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The Balance Sheets of IPCC Trajectories: Assessing the Financial Stability Properties of Canonical Mitigation Pathways and Back

Louis Daumas

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Louis Daumas. The Balance Sheets of IPCC Trajectories: Assessing the Financial Stability Properties of Canonical Mitigation Pathways and Back. Economics and Finance. École des Ponts ParisTech, 2023. English. NNT: 2023ENPC0044 . tel-04579343

HAL Id: tel-04579343

<https://pastel.hal.science/tel-04579343>

Submitted on 17 May 2024

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The Balance-Sheet of IPCC Trajectories

École doctorale N°528, Ville, Transports, Territoires (VTT)

Sciences Economiques

Thèse préparée au CIRED, UMR 8683

Thèse soutenue le 15 décembre 2023, par
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The Balance-Sheet of IPCC Trajectories

An assessment of the financial stability properties of canonical mitigation
pathways and back

Louis DAUMAS

15 décembre 2023

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Short Abstract

The low-carbon transition will lead to the depreciation of large swathes of the capital stock, which may deteriorate financial stability, possibly down to a crisis. It is therefore crucial to study these financial low-carbon transition risks. This endeavour faces many challenges. First and foremost, many transition paths exist. Hence, this PhD first aims to assess what kind of paths are most prone to transition risks, by applying a novel model to a large set of mitigation pathways. Second, many empirical and theoretical obstacles still surround the issue of transition risks. This thesis thus proposes leads to improve future assessments of transition risks: a novel representation of agents' expectations, and an empirical exploration of how financial exposures to polluting companies has evolved. Finally, since what measures to implement to alleviate transition risks is uncertain, this PhD discusses a financial policy option.

Résumé Court

La transition bas-carbone entraînera la dépréciation de pans entiers du stock de capital, ce qui peut détériorer la stabilité financière, voire conduire à une crise. Il est donc crucial d'étudier ces risques financiers de transition. Cette entreprise fait face à certains défis. Il existe d'abord de nombreuses transitions différentes. Ainsi, ce doctorat vise à évaluer quelles trajectoires sont les plus exposées aux risques de transition, en appliquant un modèle original à un large set de sentiers d'atténuation. Ensuite, des obstacles empiriques et théoriques entourent encore la question des risques de transition. Cette thèse propose donc des pistes pour améliorer leur évaluation: une nouvelle représentation des anticipations des agents, et une exploration empirique de l'évolution des expositions financières aux entreprises polluantes. Enfin, les mesures à mettre en œuvre pour atténuer les risques de transition étant incertaines, cette thèse discute une option de politique publique.

Abstract

The low-carbon transition will require the disappearance or the adaptation of economic activities that emit large amounts of greenhouse gases. Their assets may become “stranded”, *i.e.*, see their value diminish rapidly, and possibly come down to zero. These “stranded assets” include the financial assets backing these companies’ investments. The value of their equity, bond and of the loans they took may go down as the transition goes. The low-carbon transition will therefore affect financial agents. If too severe, these impacts may have adverse repercussion on financial stability, possibly down to a full-blown crisis.

This PhD tackles this issue of financial low-carbon transition risks, by focusing on its macro-financial aspects. It studies how financial instability potentials may unravel along mitigation pathways compatible with the Paris Agreement. Since there exists a multiplicity of such pathways this PhD’s main contribution is to disentangle the characteristics of pathways leading to the highest macro-financial transition risks. To do so, this PhD develops a macro-economic model amenable to simulating transition pathways while providing relevant metrics for financial fragility. However, such an exercise is fraught with theoretical, empirical, and methodological uncertainties. Hence, this PhD complements his main assessment by providing some theoretical and empirical leads that may help improve future model-based assessment of transition risks. The PhD finally provides some policy discussions by studying a radical proposal for alleviating transition risks.

This dissertation starts a critical review of the transition risk literature. This survey allowed to better map the relevant causality channels for the study of transition risks while highlighting different gaps in the literature (Chapter 1).

In a second part, the thesis answers its main question, and studies transition risks along mitigation pathways. I first propose a stock-flow model amenable to transition pathways, the Financial Asset Stranding Model – Investment in Decarbonisation (FASM-ID) framework and apply it to series of well-established scenarios dedicated to studying transition risks (Chapter 2). Then, this methodology is extended to a broader set of scenarios taken from the Intergovernmental Panel on Climate Change’s mitigation pathway database to disentangle what kind of scenarios are most prone to transition risks (Chapter 3).

In a third part, by building on previous chapters, I propose some theoretical and empirical advances for a better assessment of transition risks. A new way to model economic expectations, which have been singled out as a key factor of transition risks, is developed (Chapter 4). Second, I explore how the equity exposures of financial agents to greenhouse-gas intensive companies have evolved between the Paris Agreement and the Covid crisis. This research aims to provide a better understanding of how the distribution of transition risks across the financial system may evolve through time, which could be helpful in modelling the dynamic behaviour of the financial sector and in designing sound policies (Chapter 5).

Finally, in a final part, the dissertation proposes a case study of a radical policy in tackling transition risks: the setup of a climate bad bank. Such an institution would take those assets most at risk of stranding onto its balance sheet to abate transition risks. This chapter compares such policy with previous, regular bad banks set up during financial crises, and proposes a tentative blueprint for a climate bad bank (Chapter 6).

Résumé

La transition vers une économie décarbonée nécessitera la disparition ou l'adaptation des activités économiques émettrices de gaz à effet de serre. Leurs actifs risquent de devenir « échoués », c'est-à-dire de voir leur valeur diminuer rapidement, voire devenir nulle. Ces « actifs échoués » comprennent les actifs financiers qui soutiennent les investissements de ces entreprises. La valeur de leurs actions, obligations et prêts pourra diminuer au fur et à mesure de la transition. La transition affectera donc aussi les agents financiers. Si trop importants, ces impacts pourraient entraîner des répercussions négatives sur la stabilité financière, pouvant aller jusqu'à une véritable crise.

Ce doctorat aborde cette question des risques financiers de transition en se concentrant sur ses aspects macro-financiers. Il étudie la manière dont les risques d'instabilité financière peuvent émerger le long des trajectoires d'atténuation compatibles avec l'accord de Paris. Comme il existe une multiplicité de voies, la principale contribution de ce doctorat est de démêler les caractéristiques des scénarios conduisant aux risques de transition macro-financiers les plus élevés. Il développe un modèle macroéconomique pour simuler les voies de transition permettant d'étudier la fragilité financière. Face aux incertitudes théoriques, empiriques et méthodologiques d'un tel exercice, cette évaluation est complétée par des pistes théoriques et empiriques visant à améliorer l'évaluation future des risques de transition. Enfin, ce doctorat ouvre sur une discussion de politique publique en étudiant une proposition radicale visant à atténuer les risques de transition.

Cette thèse commence par une revue critique de la littérature sur les risques de transition. Cette revue de la littérature a permis de mieux cerner les liens de causalité pertinents pour l'étude

des risques de transition tout en mettant en évidence les lacunes restantes dans la littérature (Chapitre 1).

Ce manuscrit poursuit en répondant à sa question principale et étudie les risques de transition le long des trajectoires d'atténuation. Elle propose d'abord un modèle stock-flux cohérent applicable aux trajectoires d'atténuation, le *Financial Asset Stranding Model - Investment in Decarbonisation* (FASM-ID, « Modèle d'actifs échoués financiers – Investissement et décarbonation »), et l'applique à une série de scénarios dédiés à l'étude des risques de transition (Chapitre 2). Cette méthodologie est ensuite étendue à un large set de scénarios tirés de la base de données du Groupe d'experts intergouvernemental sur l'évolution du climat pour déterminer quels scénarios sont les plus sensibles aux risques de transition (Chapitre 3).

Ensuite, en s'appuyant sur les chapitres précédents, la thèse propose quelques avancées théoriques et empiriques pour une meilleure évaluation des risques de transition. Est d'abord proposée une nouvelle façon de modéliser les anticipations économiques, identifiées comme un facteur clé des risques de transition (Chapitre 4). Ensuite, la thèse étudie l'évolution de l'exposition des agents financiers aux entreprises à forte intensité de gaz à effet de serre entre l'Accord de Paris et la crise Covid. Cette démarche vise à mieux comprendre comment la répartition des risques de transition dans le système financier peut évoluer dans le temps, afin de mieux modéliser le comportement dynamique du secteur financier et concevoir des politiques idoines (Chapitre 5).

Enfin, la dernière partie propose une étude de cas d'une politique radicale de lutte contre les risques de transition : la création d'une « *bad bank* » ou « structure de défaisance » climat. Cette institution prendrait les actifs susceptibles d'échouage dans son bilan afin de réduire les risques de transition. Ce chapitre compare cette politique avec les *bad banks* mises en place lors des crises financières, et propose une ébauche de *bad bank* climat (Chapitre 6).

Acknowledgements

*Dans mon pays, les tendres preuves du printemps et les oiseaux mal habillés sont préférés aux buts
lointains.
La vérité attend l'aurore à côté d'une bougie. Le verre de fenêtre est négligé. Qu'importe à l'attentif.
Dans mon pays, on ne questionne pas un homme ému.
Il n'y a pas d'ombre maligne sur la barque chavirée.
Bonjour à peine, est inconnu dans mon pays.
On n'emprunte que ce qui peut se rendre augmenté.
Il y a des feuilles, beaucoup de feuilles sur les arbres de mon pays. Les branches sont libres de n'avoir
pas de fruits.
On ne croit pas à la bonne foi du vainqueur.
Dans mon pays, on remercie.*

René Char, « Qu'il vive » in *Les Matinaux*, 1950

Curtain close, then. After a bit more than three years, here comes the end of quite the journey at CIRED and in Bologna, blissful moments and rocky times alike. However difficult the voyage, though, not that many experiences, I think, make you grow up like a PhD does. At least do I hope to come out of it a tiny bit closer to the kind of wisdom that colours adulthood. And such paths are, of course, hardly lone-trodden. It goes without saying, my first thanks go to my PhD advisors, Céline Guivarch and Emanuele Campiglio. Not only have they provided this work with inexhaustible advice and challenge, pushing it to the best. They have also both been two unwavering sources of encouragement, moral support and humanity when I happened to need it, sometimes probably more than they may imagine. This work and I owe them tremendously. I am particularly grateful to Céline for her availability despite her many other commitments and for teaching me the virtue of sharp writing and the art of legible figures – hardly a given for me. Emanuele, I would like to thank also for educating me on the craft of designing the right story for a paper and welcoming me into the SMOOTH ERC team. This opportunity allowed me to connect with Italy,

now home-to-be, at least for some time.

I then thank Massimo Tavoni and Peter Tankov for reviewing my PhD and Maria Nikolaidi and Romain Svartzman for being part of my jury. I also thank Franck Lecocq for having me at CIRED, as well as Antoine Godin and Philippe Quirion for agreeing to be part of my steering committee. Additional thanks go to Antoine for his guidance in improving the second chapter of this thesis. Finally, I am grateful to the *Chaire Modélisation Prospective*, and in particular to Christophe Cassen, for extending my PhD contract for three months and allowing me to finalise this PhD in the best conditions.

Thanks also go to my co-authors, Louison Cahen-Fourot, Michael Gregor Miess, Andrew Yardley, and Mathilde Salin, on top of Céline and Emanuele themselves, for their contributions to different chapters of this manuscript. Additional thanks go to Louison, who kindly and minutely proof-read the description of my SFC model.

Shout out then to my fellow Ciredians, this jolly and brilliant crowd holding abode in Paris's *Jardin d'Agronomie Tropicale*, who all make this lab of sorts a unique environment where to think, discuss and intellectually thrive. I found there this happy alchemy of rigour and benevolence that can only bloom into excellence.

Amongst the people there, I would first like to thank my office mates: Antoine, Luc, Alette, Paul and Adriana, for supporting me throughout this journey. Special thanks go to Luc's ability to talk me away from my difficulties with his everlasting good humour, banters and chat.

I further thank wholeheartedly Auriane, Mathilde, Emilien and Samuel for being the comrades I needed during this PhD. Auriane for her ability to show up in the office for the most adequate coffee break, the numerous laughs we had thanks to her radiant spirits, and for supporting me as much as she did. Mathilde, for being such a great co-author and an endless source of discussions and support. And finally, Emilien for reassuring me, being of good advice as a more senior PhD candidate and for useful feedback on one of the chapters of this thesis. And Samuel for our geeky discussions at the coffee machine and for playing the occasional tabletop RPG session with me,

Luc, and Frankie, whom I thank for being such a priceless gamemaster. To Sam, Mathilde and Auriane, I wish, with great confidence, all the best for the rest of their own PhDs.

As a matter of coffee station and lunch chats, that enter a good deal into a PhD student's mental health and productivity, additional thanks go to many other Ciredians and others: Aurélie, Laurent, Quentin, Christophe, Estelle, Morgane, Mehdi, Bruno, Maï Thi, Vincent, Dimitri, Charlotte, Rita, Fanny on her visits at CIRED and our meetings in Italy, the crazily high number of Charleses and Clements in the lab, and so many others. Finally, the CIRED's ping-pong community provided me with the right amount of sports and cheers on lunch breaks: Baptiste, Simon, Thierry, all the other contenders: thanks a lot. I would also like to give a special thanks to Naceur, Carine and Jessy for the administrative and logistic support, especially Jessy for helping me deal with the meanders of messy accounting and late bills while these lines were being written.

This PhD was also partly written at *Dipartimento di Scienze Economiche e Aziendali* of the *Università di Bologna*, which I thank for having me as a visiting PhD scholar. There, I met wonderful people who really made my time there a true delight. First and foremost, big up to Hubert Massoni, who, on top, making me discover all the beatest bars of Bologna, and *amari*, and beating me hands down at chess and risotto cooking, was a hell of a support in a difficult moment thanks to his good temper, his rigour, and the stimulating discussions we had. I do not forget the other *raghi* and *raghe*: Anatole, Ginè, Viola and Giovanni for the climbing sessions and the drinks, Alè, Cla', Marco, Maria, Giorgio, Esther, Effie, Catè and Elè for allowing me in the PhD room and, also, the occasional drinks. Also, special thanks to Laura di Sanzo for making the logistics so easy upon my two visits. *Vi ringrazio tutti e tutte.*

Within the SMOOTH team, I also met great people who provided me with all their warmth and insights and definitely deserve thanks: Chris, Jérôme, Alessandro, Francesco, Roberta, Roberto, Nicolò, Claudia, on top of Hubert, Ginè, Bhavita

and, of course, Emanuele. Finally, I am grateful to Hannah and Luca for accommodating my visits in Pisa and to Johannes Emmerling, Laurent Drouet and Severin Reissl for having me so many times at EIEE.

Of course, I do not forget all the support I got from the outside world. My fellow editors at *Regards Croisés sur l'Economie* offered me memorable discussions and drink nights that were a welcome and extremely gratifying diversion from the PhD. Special thanks go to my two partners in crime, Audrey Glass and Théo Régniez, as well as to my editor-in-chief, Marion Clerc, with whom we brought a fantastic book to completion. I am, furthermore, grateful to David Flacher for offering me the opportunity to teach a module within the EPOG Master's course, once a programme I followed. I also have a thought for my excellent students, both at EPOG and UGE, who were always full of encouragement when I occasionally told them about the doldrums of a PhD student life and who made me discover the joys of being a teacher. I also have some thoughts for my Monday team mates at *La Mie de Pain*, who have always been full of support. Finally, thanks to Nicolas Nekourouh, my old fellow from Henri IV, for offering me the opportunity to write a chapter of his handbook and for being so understanding in the last months of the PhD.

How to forget now *mes deux zouaves*, Valérian and Vincent, with whom I can always find refuge in the cool shades of our childhood memories and endless bantering? Valérian, keep being this cheerful-wise child you are. I don't know anyone who grew up better than you, being as joyful as attentive to the woes of your friends when they need it. Vincent, your friendship is the most ancient I have, and I thank you for keeping it alive until today, even though our lives are so apart. And also, of course, thanks to Tanguy and Thomas, my two Parisian mates, who have always been here. Tanguy, thanks for being so much yourself, introducing me to bouldering and prompting the most delightful afternoons playing board games. Thomas, keep being such a source of inspiration. All my thoughts go with you to the other side of the Atlantic. I also have a thought for Cata, Cécile, Hugo, and the other members of the Ulm Gang for our haphazard reunions and spot-set holiday plans, always grand

moments. I also thank the members of my *Dungeons and Dragons* group for giving me such a great pretext to take a break: Simon, Morgane, and Amaury Daumas, brother and cousins, together with Gauthier, Tanguy and Stan. I send all my thoughts to Stan for the end of his own PhD in mad-hiking Grenoble. Finally, I would like to thank my fellow EPOGers from the Kingston crew, friends amongst friends who, despite how scattered we are around the globe, have remained in my heart and mind throughout, especially on the occasional Zoom call: Luise, Matías, Dudi, Stan, Hannah, Mohib and Stan, of course.

Nothing of course, would have been possible without the unstoppable and fierce, sometimes raging support of my family. In the darkest hours, I knew I could always find insights, support and the energy I needed with you, Mom and Dad, Sandrine and Marc, and I do know how much weight I put on your shoulders at some point. This thesis owes you so very much. Special thanks to Dad for proofreading no less than three chapters of this manuscript. I also do not forget my two grandparents, Denise and Jean, who, through reminiscences of the past, book chats and the teaching of the Italian I know, have brought way more than a few stones to this work of mine. Finally, I thank the Dunglas family, Marie-Cécile, Christophe, Julie and Raphaël, and all the others, who warmly welcomed and always supported me.

I cannot but finish by thanking my Clémentine, who carried out the difficult task of living by a stress-ridden and, sometimes, more than sorrowful PhD boy. I still wonder how you could keep against you the so-painstaking man I have been over these three years. But you have. Despite the distance once forced upon us, my uneasy temper and your own tempests that you eventually vanquished. There is a lot of your strength and love in this manuscript. And for this, I will forever hold your hand and be grateful forevermore. And now that we embark on a new chapter of our journey together in Milano, you make me more than ever confident that life is going to be good. For all of this, thank you.

Introduction en français

« Prenons, par exemple, l'estimation par le GIEC d'un budget carbone qui limiterait avec une probabilité raisonnable l'augmentation de la température mondiale à deux degrés au-dessus des niveaux préindustriels. Ce budget représente entre un cinquième et un tiers des réserves mondiales attestées de pétrole, de gaz et de charbon. Même si cette estimation n'était qu'approximativement correcte, la grande majorité des réserves deviendraient "imbrûlables", c'est-à-dire que le pétrole, le gaz et le charbon ne pourraient tout simplement pas être utilisés sans une technologie coûteuse de captage du carbone, qui modifierait elle-même l'économie des combustibles fossiles. Le degré d'exposition des investisseurs britanniques à ces changements, y compris des compagnies d'assurance, est potentiellement énorme. » – Mark Carney, *The Tragedy of the Horizon* [La Tragédie de l'horizon], Discours à Lloyd's, 29 septembre 2015.¹

Mis en évidence pour la première fois par l'ancien gouverneur de la Banque d'Angleterre Mark Carney en 2015, les risques financiers de transition désignent, de manière générale, les pertes potentielles que pourraient subir les agents financiers à mesure des progrès de la transition bas-carbone, en raison de leur exposition à des activités incompatibles avec les besoins de décarbonisation. L'exemple typique de ces risques de transition est précisément développé dans la citation ci-dessus : l'argent investi par les assureurs, et au-delà, dans des entreprises de combustibles

¹Propos traduits de l'anglais par l'auteur.

fossiles dont la valeur viendra certainement frôler zéro si nous voulons atteindre les objectifs de Paris. Néanmoins, la portée et les conséquences finales de ces pertes financières, que ce soit sur la macroéconomie, la stabilité financière ou la transition elle-même, sont loin d'être évidentes. Pleine d'incertitudes, la question des risques de transition mérite d'être examinée attentivement afin de guider au mieux les décideurs politiques dans l'atténuation des conséquences potentiellement néfastes de notre nécessaire transition vers une économie décarbonée.

Cette thèse entend aborder ces questions en mettant l'accent sur les aspects macro-financiers des risques de transition le long de trajectoires d'atténuation de long terme. Plus précisément, son objectif est d'évaluer la faisabilité des voies de transition vers une économie décarbonée du point de vue de la stabilité financière, en soulignant comment différents types de transition peuvent entraîner une plus grande fragilité financière, voire exercer une pression insoutenable sur les systèmes financiers. Afin d'effectivement étudier le « bilan financier » des trajectoires d'atténuation, cette thèse rassemble et propose des extensions à trois littératures liées mais isolées : (i) la recherche émergente sur les risques de transition proprement dits, principalement proposée par les institutions de régulation, (ii) le courant énergie-économie-environnement (E3) développé autour du Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC) et (iii) la littérature post-keynésienne sur la dynamique financière et la modélisation macroéconomique Stock-Flow Cohérente (SFC) issue des travaux de Wynne Godley et Marc Lavoie (2007). Sur la base d'une première revue de la littérature, cette thèse développe un modèle SFC à part entière permettant d'étudier les risques de transition dans le cadre de scénarios de décarbonisation. Plus précisément, cette thèse utilise l'approche SFC comme plateforme pour rassembler les préoccupations des volets de recherche réglementaire et E3. S'appuyant sur la revue initiale de la littérature, elle propose également quelques pistes théoriques et empiriques pour mieux évaluer les risques de transition dans les modèles macroéconomiques et au-delà. Enfin, elle examine une option politique possible pour atténuer les risques de transition.

Dans cette introduction générale, je motive cette question de recherche et souligne comment y répondre contribue à l'étude des risques de transition. En commençant par une généalogie du concept de risque de transition (i), je montre comment il a donné naissance à un nouveau courant de littérature. En proie à des incertitudes théoriques et méthodologiques, le champ naissant du risque de transition a rapidement fait preuve d'une créativité méthodologique remarquable, qui a toutefois laissé inexploitées deux voies dans son approche de l'analyse de scénarios et de la construction de cadres de modélisation non standard (ii). Cette thèse s'efforce de combler ces lacunes en utilisant un paradigme alternatif, la méthodologie stock-flux cohérente, comme interface entre le courant E3 et la littérature sur le risque de transition. Toutefois, cette approche n'est pas sans limites, car de nombreuses lacunes subsistent dans le traitement des risques de transition (iii).

Risques, finance et transition vers une économie à faibles émissions de carbone

Etendre le domaine de la transition bas-carbone

Pour limité qu'il fût, on doit bien mettre au crédit de l'Accord de Paris une attention renouvelée à la question du changement climatique de la part de la communauté internationale. Après l'échec de Copenhague et les turbulences financières du début des années 2010, qui ont relégué l'agenda climatique à l'arrière-plan de la politique mondiale (Geels 2013), la dernière décennie a vu un regain d'intérêt pour l'avenir de la planète. Face à des événements climatiques extrêmes de plus en plus marquants (IPCC 2021), qui ont confronté même les pays développés aux conséquences des changements climatiques (voir par exemple Hoffman et al. 2022), l'urgence d'une action climatique n'a probablement jamais été aussi évidente. Des activistes climatiques aux politiciens traditionnels en passant par le grand public, il est difficile aujourd'hui de ne pas trouver au moins un relai de discours sur la nécessité de s'attaquer au

changement climatique, entre autres enjeux écologiques. Même si ce renouveau s'est accompagné d'une opposition farouche et des conflits sur les modalités précises de cette bien urgente transition (Kamali Saraji and Streimikiene 2023).

Parallèlement, cette prise de conscience s'est accompagnée d'inquiétudes croissantes. L'urgence climatique est un élément du discours public depuis très longtemps, à commencer par les premiers appels des communautés scientifiques dans les années 1980 (J. Hansen 1988). Cependant, nous sommes en train de prendre conscience collectivement que, d'une incantation abstraite et peut-être lointaine, la nécessité de s'engager rapidement et résolument sur la voie de la transition s'impose désormais à nous (UNEP 2022). L'inaction relative des quarante dernières années a laissé place à une prise de conscience aiguë de la nature radicale et perturbatrice des évolutions nécessaires pour rester à l'intérieur des limites planétaires (Rockström et al. 2009). Une action qui aurait pu être engagée lentement et progressivement dans les années 1990 a été, pour l'essentiel, repoussée jusqu'à aujourd'hui, nous plaçant à la croisée des chemins (IPCC 2022b). Pire, notre fenêtre d'opportunité, chaque jour plus petite, se réduit maintenant à l'appréhension politiquement clivante d'un changement sans précédent (Charbonnier 2020; Douenne and Fabre 2022), qui pourrait bien nécessiter un passage à une économie de guerre (P. Jacques et al. 2023). C'est donc légitimement que la question des coûts de cette transition tardive s'est assez rapidement posée dans le sillage de l'Accord de Paris.

Cette question n'est pourtant pas nouvelle. Les coûts associés à la transition bas-carbone ont été au cœur de l'approche économique du sujet. Depuis les travaux pionniers de Nordhaus sur l'économie du climat (voir Nordhaus 2013, pour un aperçu complet), la lutte contre le changement climatique a le plus souvent été présentée, à juste titre ou non, comme un choix entre subir des coûts aujourd'hui en investissant contre le changement climatique ou subir plus tard des dommages climatiques (Pottier 2016). Une abondante littérature économique a ensuite exploré un large éventail de dimensions liées à ces coûts, comme leur étendue ou l'équité de leur répartition dans le temps et l'espace. Il s'agit notamment de la littérature sur l'énergie,

l'économie et l'environnement (E3) qui gravite autour du GIEC, lequel a également fourni de nombreuses estimations de ces « coûts des politiques » d'atténuation du changement climatique en utilisant des « modèles d'évaluation intégrée » (*Integrated Assessment Models*, IAM) aujourd'hui bien établis (IPCC 2015; Köberle et al. 2021). En dépit des premières estimations de Nordhaus, qui ont conduit à tempérer la nécessité d'actions climatiques précises (Nordhaus 1992), cette littérature a démontré qu'une fois améliorée la représentation des dommages climatiques, des préférences et des options technologiques, les coûts politiques de l'atténuation se sont avérés faibles ou, à tout le moins, ne devraient pas être un prétexte pour retarder l'action climatique, étant donné l'incommensurabilité des dommages climatiques à subir en cas d'inaction (Weitzman 2011; Fillon, Guivarch, and Taconet 2023).

Toutefois, ces résultats découlent de modèles et d'approches présentant de nombreuses limites dans leur représentation des systèmes économiques, malgré leur complexité formelle (Keppo et al. 2021). Ainsi, la plupart des mesures de coûts étaient soit très agrégées (pertes de PIB pour l'ensemble de l'économie), soit très stylisées (Köberle et al. 2021). De plus, des dimensions entières de l'économie, essentielles à la réussite de la transition, n'étaient tout simplement pas représentées, comme le secteur financier (Mercure, Knobloch, et al. 2019), ainsi que nous le verrons plus loin. D'où, par exemple, la (re)découverte tardive, et parfois douloureuse, des conséquences distributives de la politique climatique (Ravnigné, Gherzi, and Nadaud 2022), bien illustrées par le mouvement des Gilets jaunes (Douenne and Fabre 2022) ; ou des impacts très différenciés de la transition selon les secteurs économiques (Cahen-Fourot, Campiglio, Godin, et al. 2021). En définitive, et comme on pouvait s'y attendre, même si le coût de la transition elle-même était relativement faible d'après les résultats des modèles, la mise en œuvre concrète de la politique climatique et du passage à une société écologique se sont rapidement révélés confrontés à des obstacles et à des coûts additionnels, que les cadres conceptuels traditionnels avaient du mal à prendre en compte.

L'estimation des « coûts réels » de la transition est donc rapidement devenue une

tâche complexe, nécessitant un inventaire minutieux de ses impacts sectoriels et distributifs (Cahen-Fourot, Campiglio, Godin, et al. 2021; Ohlendorf et al. 2018). Elle a fini par rassembler un nombre croissant de parties : de nouveaux agents et institutions, voire des arènes politiques, se sont penchées sur le thème des coûts de la transition bas-carbone (e.g. Pisani-Ferry and Mahfouz 2023). Cette question a donc quitté les seuls champs de l'économie du climat, de l'énergie et de l'environnement pour s'étendre vers les domaines beaucoup plus vastes de la macroéconomie et de l'économie industrielle. Ce changement a également fait suite à un mécontentement croissant envers le cadre traditionnel des modèles d'évaluation intégrée (Hafner et al. 2020). Des appels à de nouveaux appareils conceptuels et de nouvelles techniques de modélisation ont ainsi été lancés tout au long des années 2010 (T. Jackson and Victor 2015), appelant à s'écarter des méthodologies fondées sur l'optimalité et à mieux prendre en compte les dimensions macroéconomiques telles que l'inflation, la croissance, l'emploi et la dynamique financière (Mercure, Knobloch, et al. 2019). Dès lors, de nouvelles branches de l'économie sont venues apporter un éclairage nouveau sur des dimensions autrement peu explorées liées à la transition bas-carbone. Celles-ci vont des macroéconomistes académiques, mainstream (Carattini, Heutel, and Melkade 2021) ou plus hétérodoxes (Cahen-Fourot, Campiglio, Godin, et al. 2021), aux praticiens des ministères (Ens and Johnston 2020) et, ce qui nous intéressera le plus, aux banques centrales et aux autorités de régulation.

Embarquer la finance

C'est dans ce contexte que l'ancien gouverneur de la Banque d'Angleterre, Mark Carney, a prononcé un discours fondateur lors d'un dîner de gala organisé par le célèbre assureur britannique, Lloyd's. À cette occasion, le banquier central a développé un cadre conceptuel pour étudier la transition bas-carbone sous l'angle des risques économiques et financiers en opposant trois types de dangers. Tout d'abord, les « risques physiques » sont ceux liés aux dommages climatiques et menacent directement les activités économiques. Le deuxième type de risque est appelé « risque de

responsabilité » et désigne la possibilité pour les agents économiques ou les États-nations de demander une compensation aux agents pollueurs une fois subits les dégâts climatiques qu'ils auront contribué à aggraver.

Le troisième type de risque a été baptisé « risques de transition » et se rapporte directement aux coûts de transition évoqués dans la littérature E3. Cependant, Carney a donné à cette idée une toute nouvelle tournure en la reliant directement à la question des risques financiers systémiques. En avançant l'idée d'un « moment Minsky climatique », où des politiques climatiques très rapides et décisives pourraient mettre en danger la viabilité du système financier, Carney a réussi un tour de force conceptuel et rhétorique. Alors que les ombres du krach financier mondial et de la crise de la dette souveraine européenne s'éloignaient, Carney a donné au thème des crises financières une nouvelle incarnation au travers du prisme de la transition bas-carbone, joignant ainsi deux des préoccupations les plus importantes de l'époque : la stabilité financière et la stabilité climatique.

Le discours de Mark Carney est particulièrement important pour au moins deux raisons. D'une part, il a porté la question de la transition sobre en carbone devant l'élite financière, et plus encore, en la formulant dans un langage directement attrayant et acceptable pour cette communauté. D'autre part, il a justifié le positionnement institutionnel des banques centrales et des régulateurs financiers sur la transition bas-carbone, en montrant que les risques liés au climat relèvent effectivement de leur mandat. Ce faisant, le gouverneur a envoyé un message clair à la communauté financière pour qu'elle prenne également position sur le sujet, soit dans son propre intérêt, soit pour éviter des réglementations strictes. L'intervention de Carney a jeté les bases de nouveaux efforts réglementaires et de nouvelles recherches axées sur les conséquences macro-financières de la transition vers une économie à faibles émissions de carbone.

Initialement mis en œuvre au sein de la Banque d'Angleterre, le programme de Carney est aujourd'hui principalement incarné par le Network for Greening the Financial System (NGFS). Basé à la Banque de France, ce consortium a notamment étendu et

rendu opérationnelle la grille d'analyse de Carney dans un cadre englobant destiné aussi bien aux autres régulateurs financiers qu'aux institutions supervisées. Il fournit notamment un ensemble de scénarios de transition de référence qui peuvent être utilisés par les agents dans leurs mesures de risque internes et qui servent de référence dans les exercices réglementaires officiels (Clerc, Diot, et al. 2020; Alogoskoufis et al. 2021). Les travaux menés dans le cadre du NGFS ont notamment consisté, à ce jour, à évaluer les risques de transition et les risques physiques de ces scénarios en utilisant divers cadres de modélisation intégrant le système financier et les interactions sectorielles.

Un éloignement de ses racines intellectuelles

Il est intéressant de noter que les racines intellectuelles du discours de Carney remontent à la littérature E3 et du GIEC elle-même, qui avait commencé, au tournant des années 2010, à remettre en question l'importance de l'inertie des infrastructures dans la prise en charge des coûts supplémentaires liés à la transition².

Meinshausen et al. (2009) ont suggéré pour la première fois que les réserves actuelles d'hydrocarbures étaient si abondantes que leur épuisement nous conduirait bien au-delà du plafond de 2°C avancé par le GIEC (2014). Parallèlement, Davis, Caldeira, and H. D. Matthews (2010), suivi par Guivarch and Hallegatte (2011), ont étendu l'intuition de Meinshausen et al. au capital bâti et aux infrastructures existantes à forte intensité de gaz à effet de serre. Ces articles ont donné une nouvelle vie au concept d'« actifs échoués » (« *stranded assets* »), destiné à désigner cette partie du stock de capital vouée à une dépréciation quasi-totale au fur et à mesure de la transition. Ces nouveaux concepts ont ouvert la voie à de nombreuses recherches, notamment pour mieux comprendre la dynamique des actifs échoués (Baldwin, Cai, and Kuraltbayeva 2020; Campiglio, Dietz, and Venmans 2022; Coulomb, Lecuyer, and Vogt-Schilb 2019) et pour adapter les outils politiques à cette nouvelle préoccupation

²L'on pourrait même se référer à l'idée d'Unruh (2000) de « *carbon lock-in* », selon laquelle les systèmes économiques à forte intensité de carbone sont complexes à changer en raison de l'existence de nombreux types d'inertie.

(Rozenberg, Vogt-Schilb, and Hallegatte 2020).

Alors que ces nouveaux développements auraient pu rester confinés au monde académique, la notion d'actifs échoués est allée plus loin en étant annoncée par d'autres types d'institutions, ce qui lui a donné une orientation plus financière, alors que le monde académique stricto sensu et la littérature E3 laissaient cet aspect de côté. L'ONG Carbon Tracker Initiative a notamment proposé le concept de « bulle carbone » (« *Carbon Bubble* ») (Leaton 2011), selon lequel les réserves à forte teneur en carbone étaient surévaluées sur les marchés financiers en raison des efforts de décarbonisation inévitables à l'avenir. Parallèlement, le chercheur Ben Caldecott (Caldecott, Kruitwagen, et al. 2016) de l'Oxford Smith School a étendu la notion d'actifs échoués en lui donnant un nouveau sens : parce que les dépréciations affectait les bilans des entreprises, et parce que la décarbonisation impliquait des investissements non performants, les actifs échoués pouvaient avoir des implications financières, potentiellement systémiques (Mercure, Pollitt, N. R. Edwards, et al. 2018). C'est à partir de ces deux impulsions, parmi beaucoup d'autres (Generation Foundation 2013), que les questions des actifs échoués et du « carbone imbrûlable » (« *Unburnable carbon* ») ont été portées au débat public. À partir de là, elles ont vécu leur propre vie, loin de leurs racines E3, jusqu'à ce qu'elles soient finalement adoptées par les banquiers centraux et les régulateurs financiers. La référence de Mark Carney à l'échouage d'actifs se rapporte à cette réinterprétation du concept à travers une lentille financière, l'amenant sur des territoires inexplorés.

Un champ émergent et innovant

Créativité et innovations méthodologiques

Au cours de ce processus, le nouveau champs des risques de transition s'est rapidement rendu compte des incertitudes majeures auxquelles il était confronté.

Tout d'abord, l'établissement d'un lien entre l'immobilisation d'actifs et l'évolution de la transition et les risques financiers potentiels ne reposait pas sur des bases théoriques

solides aux niveaux micro et macroéconomiques. Les théories traditionnelles de choix de portefeuille étant construites sur des facteurs et des indicateurs économiques bien définis, l'introduction de dimensions non économiques se sont avérées représenter des défis empiriques et théoriques majeurs (Bingler, Colesanti Senni, and Monnin 2020). D'un point de vue plus macro-financier, l'établissement d'un lien entre l'échouage d'actifs et les crises potentielles constituait une déviation majeure par rapport aux approches traditionnelles de l'instabilité financière, qui mettaient davantage l'accent sur le potentiel déstabilisateur d'une confiance excessive dans de nouveaux types d'investissements que sur celui d'industries destinées à disparaître à la suite de changements structurels à long terme (Semieniuk, Campiglio, et al. 2021). Les canaux de causalité entre la disparition de ces industries en déclin et l'instabilité financière sont nombreux. Ceci rend ardue l'identification précise de la forme et de la temporalité des chocs liés au risque de transition. De plus, les données manquaient, entraînant un effort considérable de construction de séries d'émissions de gaz à effet de serre à une échelle suffisamment désagrégée. De plus, quel type d'outils à utiliser pour mesurer ces risques de manière adéquate n'était pas tout à fait clair, étant donné les limites des cadres existants (Hafner et al. 2020). Enfin, comme il n'existe aucun exemple de transition impliquant l'abandon des combustibles fossiles, il n'est pas possible de s'appuyer sur les approches rétrospectives traditionnelles des risques financiers, ce qui appelle à un renouvellement des approches prospectives fondées sur des scénarios (Baudino and Svoronos 2021).

Les défis des analyses en scénarios

Cette absence de bases solides sur lesquelles s'appuyer a contraint ce nouveau domaine à innover dans de nombreuses directions.

Sur le plan empirique, de nouvelles données sont apparues sur le contenu en carbone des actifs financiers et l'intensité en gaz à effet de serre de certaines entreprises, ce qui a permis de renouveler l'économétrie financière en étudiant la manière dont les investisseurs traitaient les risques liés à la transition (Bolton and Kacperczyk 2021).

La modélisation appliquée n'a pas été en reste. Les modèles macroéconométriques à grande échelle ont été adaptés à l'étude de la transition bas-carbone, tandis que le domaine en plein essor des réseaux de production a rapidement accueilli les contributions de l'économie de l'environnement (Devulder and Lisack 2020). En outre, le domaine a fait preuve dès le départ d'une certaine ouverture à des approches moins standard de l'économie climatique et financière. Les méthodes en réseaux financiers sont devenues l'une des méthodes majeures du domaine (Battiston, Mandel, et al. 2017), tandis que de nombreux chercheurs hétérodoxes des communautés post-keynésienne (P. Jacques et al. 2023) et agent-basée (Lamperti, Bosetti, et al. 2019) ont été rapidement associés au champ. Par exemple, le modèle macroéconométrique post-keynésien E3ME a ouvert la voie à la recherche sur les conséquences financières de l'échouage d'actifs (Semieniuk, Holden, et al. 2022), tandis que d'autres cadres, comme EIRIN (Monasterolo and Raberto 2018) ou DEFINE (Dafermos, Nikolaidi, and Galanis 2017) ont été discutés parallèlement aux méthodologies établies par les banques centrales elles-mêmes.

Cependant, la plus grande avancée méthodologique du champ a probablement été la systématisation des scénarios d'utilisation, en s'appuyant sur une méthodologie ayant bénéficié d'un regain d'intérêt après les grands krachs financiers des années 2000-2010: les *stress tests*. Les *stress tests* consistent généralement en l'application d'un choc violent mais plausible sur un modèle économique, soit au niveau macroéconomique, soit au niveau microéconomique, afin de mesurer la résilience d'un système (Cartellier 2022). Face aux risques de transition et plus généralement aux risques liés au climat, les régulateurs financiers ont étendu cette approche à l'étude de la perturbation potentielle des chocs de transition. Ce processus s'est accompagné de défis méthodologiques spécifiques. Les *stress tests* climatique à court terme ont nécessité des narratifs précis afin de distinguer les chocs de transition possibles, allant de la mise en œuvre de la politique climatique aux développements technologiques rapides (Vermeulen et al. 2021). Cependant, le plus grand défi concernait l'horizon d'analyse des risques liés à la transition. Étant donné que la transition vers une économie

sobre en carbone s'étendra sur plus d'un demi-siècle, de nouveaux types de scénarios, permettant une évaluation à long terme des transitions, ont dû être construits. Cet effort a été principalement fourni par le NGFS (Bertram, Jérôme Hilaire, et al. 2020; NGFS 2020b; NGFS 2021b; NGFS 2022), qui a fourni une grille d'analyse des risques de transition basée sur une distinction entre trois types de transitions. Les scénarios « Maison qui brûle » (*Hot House World*), caractérisés par des efforts de transition inexistantes ou très timides, conduisent à réchauffement dépassant les 3°C. De telles hausses de températures entraîneraient des dommages climatiques importants, susceptibles de déclencher des évolutions financières particulièrement nefastes. Les « Transitions ordonnées », quant à elles, se caractérisent par une mise en œuvre harmonieuse des politiques climatiques et des technologies à faible teneur en carbone, ce qui permet d'atteindre les objectifs climatiques tout en évitant des perturbations financières majeures. Enfin, les « Transitions désordonnées » décrivent des trajectoires sur lesquelles la politique climatique est retardée, mal mise en œuvre ou non coordonnée entre les régions du monde, ou avec un développement limité des technologies bas-carbone. Ces facteurs pouvant entraîner d'importantes turbulences financières, ces scénarios ont fait l'objet d'un examen minutieux.

Ces trois récits ont été mis en œuvre dans des exercices multi-modèles à grande échelle. Ces derniers permettent une étude fine de l'exposition à la transition et de la vulnérabilité tant au niveau macroéconomique que microéconomique, grâce à des données de plus en plus désagrégées au niveau de l'entreprise et de l'agent financier. Très innovants et pragmatiques, grâce à l'utilisation de nombreux cadres de modélisation différents, ces exercices, réalisés pour la plupart par des équipes de recherche au sein d'institutions de régulation, constituent le fer de lance de l'évaluation des risques de transition à long terme.

Un dialogue manqué ?

Il est intéressant de noter que pour élaborer ces scénarios, le NGFS a fait appel à des membres bien établis de la communauté E3 pour établir ces projections, semblant

ainsi renouer avec les origines intellectuelles de la littérature sur le risque de transition. Cependant, la collaboration entre les deux communautés n'est guère allée au-delà de l'élaboration des scénarios. Les projections fournies par la communauté E3 n'étaient que la première étape de l'ensemble du dispositif NGFS qui, par la suite, a développé sa propre méthodologie avec ses propres outils et préoccupations. Du côté de la communauté E3, les scénarios NGFS ont été examinés comme tous les autres dans l'*Assessment Report 6* du GIEC. Parallèlement, le champ a développé ses propres discussions sur la stabilité financière, notamment en s'interrogeant sur la possibilité de l'intégrer dans les modèles d'évaluation intégrée (Curtin et al. 2019; Keppo et al. 2021). Au final, cette interface d'un temps entre les deux domaines n'a pas donné lieu à des collaborations et des discussions plus profondes et plus systématiques. Par conséquent, la littérature sur le risque de transition ne s'est guère appuyée sur les denses débats épistémologiques et méthodologiques sur l'utilisation de scénarios et de modèles à grande échelle, qui ont été un sujet de discussion important dans la littérature E3.

En outre, en raison de son intérêt pour les questions à long terme et de son utilisation de cadres de modélisation complexes, la littérature E3 a mis l'accent sur la nécessité de s'attaquer aux incertitudes inhérentes à ses exercices (van Asselt and Rotmans 2002). Ces incertitudes se manifestent à différents niveaux. Tout d'abord, il est évident que les hypothèses intégrées dans des scénarios donnés, par exemple sur le coût et la disponibilité des technologies futures (Kriegler, Weyant, et al. 2014) ou les données macroéconomiques (Riahi, van Vuuren, et al. 2017), peuvent affecter les trajectoires de transition dans une large mesure. Ensuite, il existe une incertitude tout aussi grande sur les valeurs des paramètres des composants clés des modèles d'évaluation intégrée, par exemple les élasticités ou les taux de pénétration technologique (Gillingham et al. 2018; Marangoni et al. 2017). Enfin, les modèles d'évaluation intégrée peuvent présenter des structures et des hypothèses très différentes, ce qui peut conduire à des résultats sensiblement différents pour des narratifs de scénario similaires et des valeurs de paramètres comparables (Kriegler, Weyant, et al. 2014). Ghersi

et al. (2023) ont même suggéré un nouveau type d'incertitude « théorique », liée aux nombreuses théories et ontologies différentes (néoclassique, néo-keynésienne, post-keynésienne) utilisées pour décrire les systèmes économiques. Ces débats ont donné lieu à une vaste littérature qui considère de plus en plus les scénarios comme des outils exploratoires permettant de cartographier au mieux les incertitudes (Guivarch, Le Gallic, et al. 2022).

En revanche, ils ont été largement absentes de la littérature sur les risques de transition, ce qui est quelque peu surprenant compte tenu de la grande incertitude qui entoure cette notion. De manière assez symptomatique, le NGFS s'appuie sur un nombre relativement réduit de scénarios rarement mobilisés dans les exercices de régulation. Pire, alors que le premier millésime de la série du NGFS comprenait quelque dix-huit scénarios, y compris des variantes de mêmes scénarios, les millésimes les plus récents ont réduit le nombre de scénarios à douze. Or rien ne garantit que ces scénarios soient (i) représentatifs du large éventail de voies de transition possibles et (ii) qu'ils permettent de cartographier l'ensemble des incertitudes caractérisant la transition, qui pourraient aller bien au-delà de la temporalité de l'action climatique et de l'intensité du progrès technologique. Certes, un ensemble réduit de scénarios permet une narration claire et crée un point de référence bien établi pour les praticiens. Cette approche a également permis de familiariser la communauté du secteur financier avec les méthodologies à base de scénarios, qui étaient assez éloignées des pratiques des financiers. Cependant, elle comporte également certains risques d'un point de vue macroprudentiel, dans la mesure où certaines sources de risques de transition peuvent ne pas être cartographiées, par exemple si elles ne prévalent que dans certaines hypothèses de scénario.

Il y a donc un besoin immédiat d'élargir le portefeuille de scénarios utilisés dans les évaluations des risques de transition en portant les préoccupations de la littérature sur les risques de transition à un ensemble plus large de voies d'atténuation et en suscitant un dialogue entre les volets de recherche E3 et sur les risques de transition. C'est le premier objectif de cette thèse, qui vise à étudier le « bilan » de toutes les

trajectoires proposées par le GIEC.

Vers de nouveaux modèles

Parallèlement, tout en faisant preuve d'une certaine ouverture méthodologique et de pragmatisme, la littérature sur le risque de transition n'a pas encore utilisé de cadres de modélisation alternatifs dans ses évaluations. Plus précisément, les innovations formelles et appliquées sont restées dans des cadres standard. Par exemple, la littérature naissante sur les réseaux de production s'appuie sur les fonctions de production habituelles et les hypothèses de concurrence parfaite. Dans un autre registre, le modèle macroéconomique le plus couramment utilisé dans les évaluations des risques de transition est un modèle macroéconométrique néo-keynésien bien établi, NiGEM (NIESR 2016). Cependant, lorsque cette thèse a été entamée, les autorités de régulation n'avaient pratiquement pas mis en œuvre de cadre alternatif, comme les modèles agents-basés et les modèles stock-flux cohérents alors que la reconnaissance de leur capacité à modéliser et à étudier des interactions financières complexes va croissant (Sanders et al. 2022).

Ces deux limites des évaluations actuelles des risques de transition sous à l'origine des deux objectifs de cette thèse. Elle vise tout d'abord à introduire les discussions E3 sur l'incertitude dans le domaine, notamment en élargissant la gamme des scénarios utilisés pour l'étude des risques de transition financière. Pour ce faire, elle vise à développer un modèle stock-flux cohérent, capable d'étudier les dynamiques financières le long des trajectoires de transition tout en se prêtant à la simulation de nombreux scénarios. Avec cette double approche, qui combine l'approche stock-flux cohérente aux les scénarios préexistants fournis par la communauté E3, elle s'efforce de contribuer à une cartographie plus précise des incertitudes liées aux risques financiers de la transition vers une économie à faible émission de carbone.

Par conséquent, le deuxième objectif de cette thèse est d'utiliser l'agenda des risques de transition comme point de rencontre entre la littérature sur les risques de transition en tant que telle, la littérature E3 sur les scénarios de transition et l'approche stock-

flux cohérente.

L'approche stock-flux cohérente

Cependant, l'interface entre la communauté E3 et l'approche stock-flow consistant est loin d'être évidente, étant donné leurs fondements théoriques très différents. Principalement ancrée dans l'économie néoclassique et le paradigme de l'optimisation, la littérature E3 a, jusqu'à présent, à peine inclus des approches moins standard. On pourra noter à ce titre que le modèle d'évaluation intégré post-keynésien E3ME, bien établi, ne fournit pas les trajectoires examinées dans les rapports d'évaluation du GIEC (IPCC 2022b). Cependant, le thème du risque de transition, en raison de son orientation vers les thèmes financiers, représente une occasion stimulante de jeter un pont entre ces deux littératures, notamment en systématisant le lien entre les scénarios de transition et l'approche stock-flux cohérente.

Cette méthodologie remonte aux travaux de Wynne Godley, Gennaro Zezza et Marc Lavoie dans les années 1990 et a été formellement définie par Wynne Godley et Marc Lavoie dans leur ouvrage de -Godley and Lavoie (2007), *Monetary Economics*. Elle est aujourd'hui principalement, voire intégralement, utilisée par l'école post-keynésienne, une communauté hétérodoxe caractérisée par son insistance sur le rôle de la demande globale dans la gestion des questions de distribution dynamique de l'économie et des interactions réelles-financières. L'approche stock-flux cohérente représente aujourd'hui la plateforme d'intégration centrale pour les approches post-keynésiennes et fournit un complément précieux aux méthodes plus traditionnelles telles que les modèles macroéconométriques ou les DSGE (Burgess, Burrows, and Kinsella 2016).

Quelque peu trompeuse, l'expression « stock-flux cohérent » renvoie à la nécessité pour un cadre de modélisation de respecter les conventions de la comptabilité nationale, ce qui, aujourd'hui, est le cas de la plupart des cadres de modélisation appliqués, standards ou hétérodoxes. Cependant, pour les auteurs post-keynésiens, la cohérence stock-flux prend un sens plus profond (Nikiforos and Zezza 2017). Le projet

Table 1: Matrice générique des flux de transactions (Tirée de Godley and Lavoie (2007))

	Ménages (1)	Entreprises de production		Banques		Gouvernement (6)	Banque centrale	
		Courant (2)	Capital (3)	Courant (4)	Capital (5)		Courant (7)	Capital (8)
Transactions								
Consommation	$-C$	$+C$						
Investissement	$-I_h$	$+I$	$-I_f$					
Cons. Publique		$+G$				$-G$		
Salaires	$+WB$	$-WB$						
Profits, entreprises	$+FD_f$	$-F_f$	$+FU_f$					
Profits, banques	$+FD_b$			$-F_b$	$+FU_b$			
Profits, banque centrale					-5	$+F_{cb}$	$-F_{cb}$	
Intérêts, prêts	$-r_{l(-1)} \cdot L_{h(-1)}$	$-r_{l(-1)} \cdot L_{f(-1)}$		$+r_{1(-1)} \cdot L_{(-1)}$				
Intérêt, dépôts	$+r_{m(-1)} \cdot M_{h(-1)}$			$-r_{m(-1)} \cdot M_{(-1)}$				
Intérêts, obligations	$+r_{b(-1)} \cdot B_{h(-1)}$			$+r_{b(-1)} \cdot B_{b(-1)}$		$-r_{b(-1)} \cdot B_{(-1)}$	$+r_{b(-1)} \cdot B_{cb(-1)}$	
Taxes - Transfers	$-T_h$	$-T_f$		$-T_b$		$+T(1)$		
Flux de fonds								
Variation, prêts	$+\Delta L_h$		$+\Delta L_f$		$-\Delta L$			
Variation, liquidités	$-\Delta H_h$				$-\Delta H_b$			$+\Delta H$
Variation, actions	$-\Delta M_h$				$+\Delta M$			
Variation, obligations	$-\Delta B_h$				$-\Delta B_b$	$+\Delta B$		$-\Delta B_{cb}$
Variation, actions	$-(\Delta e_f \cdot p_{ef} + \Delta e_b \cdot p_{eb})$		$+\Delta e_f \cdot p_{ef}$		$+\Delta e_b \cdot p_{eb}$			
Σ	0	0	0	0	0	0	0	0

intellectuel de Godley et Lavoie était, grâce à une comptabilité minutieuse des flux et des stocks au sein des systèmes économiques, de comprendre comment les flux et les stocks financiers interagissaient avec les flux et les stocks réels. Alors que la plupart des cadres traditionnels se concentrent uniquement sur les variables réelles ou introduisent une séparation claire entre les quantités monétaires et non monétaires, les modèles post-keynésiens stock-flux cohérents établissent un lien systématique entre la finance et le reste de l'économie. Ils soulignent notamment comment la structure des contrats financiers, notamment le crédit, peut influencer la dynamique économique à court et à long terme.

Formellement, un modèle stock-flux cohérent représente l'économie comme un réseau de bilans imbriqués appartenant généralement, mais pas exclusivement, aux secteurs institutionnels de l'économie figurant dans les comptes nationaux (ménages, entreprises non financières, entreprises financières). Ces bilans sont liés principalement par des flux monétaires qui influencent l'évolution des stocks réels et financiers. En fin de compte, l'économie réelle et le système financier s'influencent mutuellement de manière intégrée.

En termes visuels, les modèles stock-flux cohérents peuvent être résumés par deux

tableaux illustrant les exigences de la cohérence des flux de stocks, une matrice des flux de transactions (Figure 1) et une matrice des bilans (Figure 2).

Ces deux tableaux illustrent l'importance de la cohérence stock-flux dans les modèles SFC, telle que mise en avant par Nikiforos and Zezza (2017).

- La matrice de transaction-flux représente tous les flux financiers inclus dans le modèle. Sa partie supérieure décrit les flux financiers émergeant des transactions de l'économie réelle : consommation, investissements et transferts. Sa partie inférieure montre le flux de financement de l'économie, qui inclut les flux financiers résultant de l'achat d'actifs financiers, et décrit donc la structure de l'épargne. Ce tableau illustre la première condition de la cohérence stock-flux, à savoir que tous les flux financiers doivent avoir une origine et une fin bien identifiées afin d'éviter les « fuites » dans le système. C'est pourquoi la somme de toutes les lignes doit être égale à zéro. Toutes les colonnes doivent également être égales à zéro pour illustrer la répartition entre les transactions (partie supérieure) et les flux de fonds, ou épargne (partie inférieure).
- La matrice de bilan présente la structure de l'actif et du passif de l'économie. Il montre que la cohérence stock-flux exige en outre que les actifs d'un agent soient les passifs d'un autre agent – à l'exception du capital, adossé à l'épargne dans son ensemble.
- Les matrices de transactions-flux et de bilan montrent enfin la troisième condition de la cohérence stock-flux, à savoir qu'un flux doit, en fin de compte, être imputable à une variation de stock.
- Ces trois conditions impliquent une comptabilité à quadruple entrée, dans laquelle tout flux financier doit correspondre en fin de compte à une origine, une fin, une diminution d'un stock et une augmentation d'un autre.

La spécificité de l'approche post-keynésienne de la cohérence stock-flux est que l'accent mis sur les flux comptables et monétaires lui permet d'intégrer dès le départ le système financier dans l'économie. Plus précisément, parce qu'elle

Table 2: Matrice de bilan générique (Tirée de Godley and Lavoie (2007))

	Households	Production firms	Banks	Government	Central bank	Σ
Tangible capital	$+K_h$	$+K_f$				$+K$
Obligations	$+B_h$		$+B_b$	$-B$	$+B_{cb}$	0
Liquidités	$+H_h$		$+H_b$		$-H$	0
Dépôts	$+M_h$		$-M$			0
Prêts	$-L_h$	$-L_f$	$+L$			0
Actions, firmes	$+E_f$	$-E_f$	$-E_b$		0	$-K$
Actions, banques	$+E_b$		$-NW_b$	$-NW_g$	0	0
Richesse Nette	$-NW_h$	$-NW_f$	$-N$	0	0	0
Σ	0	0	0	0		

représente explicitement les stocks d'actifs financiers, qui sous les sous-jacents des dépenses d'investissement, elle donne un rôle au système financier au-delà du rôle d'amplificateur de choc qu'il assume dans la plupart des modèles traditionnels qui l'intègrent (Nikiforos and Zezza 2017). En outre, parce que la méthode modélise explicitement le comportement d'épargne de tous les secteurs de l'économie, elle permet une étude pertinente des équilibres financiers et des positions de prêt nettes. L'approche post-keynésienne stock-flux cohérente comprend enfin quelques aspects théoriques. S'appuyant notamment sur les enseignements de Keynes et de Kalecki, la plupart, sinon tous les modèles SFC post-keynésiens sont des modèles guidés par la demande, dans lesquels l'investissement est régi par une fonction indépendante et où l'épargne est déterminée *a posteriori* par les dépenses d'investissement. Ce bouclage par la demande est généralement un corollaire d'une approche endogène de la création monétaire, selon laquelle les banques peuvent créer du pouvoir d'achat sur demande pour s'adapter aux fluctuations de l'économie. Dans un tel régime, « les prêts font les dépôts » et l'investissement n'est pas limité par un montant préexistant d'épargne monétaire. Cette approche de la création monétaire, jugée plus réaliste par les banquiers centraux (Jakab and Kumhof 2015; Jakab and Kumhof 2018), resserre les liens entre le système financier et l'économie en éloignant l'investissement de financement du comportement de lissage intertemporel de la consommation des modèles néoclassiques. Ceci, à son tour, invite à une modélisation complète et sophistiquée

du système financier, avec des hypothèses comportementales dédiées sur le choix du portefeuille et l'octroi de prêts. Enfin, il convient de noter que la plupart des modèles SFC reposent très rarement sur des comportements d'optimisation et qu'ils supposent le plus souvent des attentes adaptatives.

Ces aspects des modèles stock-flux cohérents en font des outils adaptés à l'étude des risques de transition à plusieurs égards. L'accent mis sur les variables monétaires, la plasticité qu'ils offrent dans la modélisation du système financier et leur représentation plus réaliste des flux financiers en font un candidat idéal pour cette entreprise. En outre, l'habituel bouclage par la demande, qui permet des résultats plus keynésiens, peut constituer un complément précieux à la plupart des outils existants. Enfin, son rejet des procédures d'optimisation permet de s'éloigner des approches trop rationnelles de la transition à faible émission de carbone, ce que la littérature appelle de ses vœux depuis longtemps (Hafner et al. 2020).

En effet, de nombreux cadres stock-flux cohérents ont été proposés pour étudier les questions écologiques au sens large : FALSTAFF de Peter Jackson (T. Jackson and Victor 2015), DEFINE de Dafermos et al. (Dafermos, Nikolaidi, and Galanis 2017), EIRIN de Monasterolo et al. (Monasterolo and Raberto 2018), ou, plus récemment, TEMPLE, de P. Jacques et al. (2023).

Tous ces modèles ont abordé les conséquences macroéconomiques d'une transition bas-carbone, avec, dans certains cas, un regard sur les variables financières. Dans la plupart des cas, si ce n'est tous, la transition bas carbone est simulée par un changement exogène de la part d'énergie bas carbone dans le mix ou de capital bas carbone, avec des trajectoires censées être cohérentes avec les objectifs de décarbonisation. Les modèles SFC ont donc été principalement conçus comme des plateformes permettant de simuler des trajectoires de transition prédéfinies et d'en explorer les conséquences. Toutefois, ces voies de transition sont généralement très peu nombreuses et laissées à la discrétion du modélisateur. Cette pratique présente deux inconvénients. D'une part, elle empêche d'explorer différentes formes de transition à faible intensité de carbone, alors que de nombreuses possibilités existent, en fonction de la disponibi-

ité de certaines technologies, des hypothèses sur la vitesse de leur déploiement ou de la forme prise par les politiques climatiques. Deuxièmement, elle peut conduire à supposer des voies de transition indûment rigoureuses, qui ne sont peut-être pas concevables en raison de l'inertie des infrastructures et de l'économie.

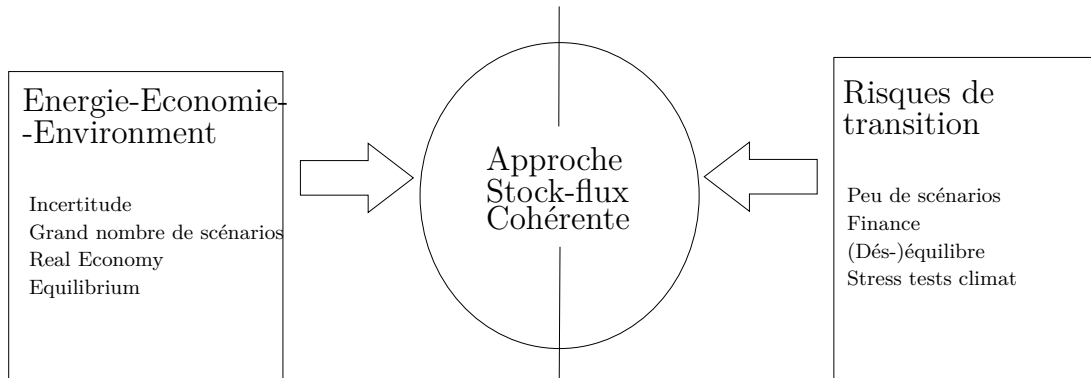
C'est précisément là qu'une interface fructueuse pourrait être établie avec la littérature E3. Étant donné que cette dernière fournit de nombreuses voies de transition, qui dessinent autant de chemins vers la décarbonisation, on pourrait créer un lien entre les caractéristiques de ces voies de transition et les données nécessaires pour simuler les transitions dans les modèles SFC. Par conséquent, des modèles SFC adéquats axés sur la transition pourraient être utilisés comme plateformes pour caractériser les propriétés d'instabilité financière de ces voies. Plus précisément, ils peuvent servir de point de rencontre efficace entre la littérature sur le risque de transition et la communauté E3 en fournissant des mesures précieuses pour les risques macro-financiers tout en aidant à répondre aux incertitudes que la littérature E3 a soulignées à maintes reprises.

Ce programme de recherche, schématisé dans la Figure 1, sera l'objet de cette thèse. En utilisant un modèle SFC comme outil pour explorer les incertitudes autour des risques de transition, son but est d'aider à compléter les approches existantes dans la littérature sur les risques de transition tout en misant sur le grand nombre de scénarios fournis par la littérature E3. En un mot, étudier le bilan des trajectoires du GIEC.

Explorer d'autres frontières

Cette contribution est toutefois essentiellement méthodologique. En tant que telle, elle n'aborde que partiellement les incertitudes liées aux risques de transition. Elle se concentre sur celles liées à la forme des trajectoires de transition et aux hypothèses sous-jacentes des modèles utilisés pour générer les trajectoires de référence. Cependant, comme nous l'avons esquissé plus haut, le domaine des risques de transition

Figure 1: Résumé de l'approche de la thèse



est également perçu d'incertitudes théoriques qui requièrent autant d'innovations formelles et de modélisation. En s'appuyant sur un état de l'art de la littérature et sur les obstacles rencontrés en suivant le programme de recherche ci-dessus, cette thèse entend fournir des pistes préliminaires pour améliorer la théorie des risques de transition. Deux axes de travail ont été explorés : la modélisation des anticipations et la compréhension du secteur financier.

L'importance des anticipations

Comme le soulignent les littératures des actifs échoués (van der Ploeg and Rezai 2020b) et du risque de transition (Battiston, Monasterolo, Riahi, et al. 2021), les anticipations des agents économiques seront un facteur crucial dans la détermination de l'ampleur des perturbations macro-financières soulevées par la transition bas-carbone. Des politiques climatiques bien anticipées et des attentes correctes sur les développements technologiques futurs permettraient une transition plus douce, les agents économiques étant en mesure de se préparer et d'orienter leurs investissements de manière adéquate. Dans le cas contraire, des réactions rapides aux déplacements technologiques ou à la mise en œuvre de politiques climatiques pourraient entraîner des ajustements macroéconomiques et financiers difficilement soutenables (Carney 2015).

Peut-être plus encore que pour d'autres concepts, la représentation adéquate des an-

anticipations en matière de transition nécessite de ménager (i) l'incertitude radicale qui l'entoure et (ii) le fait que les résultats pertinents de la transition s'étendent sur de vastes horizons temporels. Les modélisateurs économiques ont pour la plupart abordé cette question en s'appuyant sur certaines versions des anticipations rationnelles, soit des anticipations parfaites, soit une connaissance préalable des résultats possibles et des probabilités correspondantes (van der Ploeg and Rezai 2020b; Lemoine and Traeger 2016). Le problème de cette approche est qu'elle dote les agents d'un niveau de rationalité très élevé, qui minimise mécaniquement l'ampleur des risques liés à la transition, tout en renonçant à l'incertitude radicale qui lui est inhérente (Battiston, Dafermos, and Monasterolo 2021). D'autres approches s'appuient sur des anticipations rétrospectives, dans lesquelles les agents sont soit myopes, soit adaptent leurs estimations de manière séquentielle. Ces approches, bien qu'elles reconnaissent l'incertitude radicale, ne sont pas nécessairement plus satisfaisantes, car les agents ne peuvent pas formuler de points de vue prospectifs sur la transition et ne peuvent pas tenir compte des évolutions possibles. Enfin, dans les deux cas, les agents sont censés avoir des structures d'attentes alignées ou similaires, alors que l'on pourrait s'attendre à ce que les attentes soient très hétérogènes.

Ces deux traitements extrêmes appellent à trouver un juste milieu. Les agents devraient être en mesure de formuler des attentes prospectives tout en laissant une place à l'incertitude radicale. En outre, dans l'idéal, le modélisateur devrait inclure l'hétérogénéité des anticipations, qui sera cruciale pour façonner les évolutions de la transition – par exemple, les différents paris sur les évolutions technologiques – et les ajustements des prix des actifs sur les marchés financiers. Des propositions récentes ont été faites à ce sujet (Campiglio, Lamperti, and Terranova 2023; Dunz, Naqvi, and Monasterolo 2021), afin de mieux comprendre le déroulement de la transition en présence de structures d'anticipations alternatives. Cette thèse s'inscrit dans cette démarche en proposant une méthode de modélisation des anticipations axée sur leur hétérogénéité. Cette méthode serait, en principe, portable à des modèles macroéconomiques de grande taille.

Comprendre le secteur financier

Une meilleure compréhension et modélisation du secteur financier, notamment de ses interactions internes, est également une voie de recherche porteuse. Alors que les approches en réseau des *stress tests* climatique sont devenues un fer de lance de ce domaine, une représentation fidèle du secteur financier dans des modèles macroéconomiques plus dynamiques doit encore être proposée. Les *stress tests* climatiques réglementaires font généralement appel à plusieurs modules pour obtenir une représentation compréhensive des variables financières. Toutefois, ces modules ne rétroagissent pas sur l'économie "réelle" et ne tiennent que rarement compte des interactions au sein du secteur financier. Paradoxalement, l'approche stock-flux cohérente ne va pas très loin à cet égard non plus. Bien que les économies réelle et financière soient intégrées, le système financier est souvent réduit aux banques, la finance de marché étant attribuée aux ménages. Cette approche ne rend pas compte de la diversité des agents financiers et, par conséquent, de la manière dont l'exposition aux risques financiers peut changer de mains. Encore plus curieusement, les études empiriques ne se sont pas beaucoup développées sur cette question non plus, la plupart des efforts économétriques étant centrés sur le comportement de choix de portefeuille au lieu d'étudier comment les actifs se déplacent d'un agent à l'autre.

Cette thèse aborde cet aspect à deux égards. Premièrement, le modèle SFC qu'elle développe propose une représentation désagrégée du secteur financier en différenciant les agents non bancaires et les agents bancaires, et en les faisant interagir. Il tient également compte des interactions entre ces deux types d'agents. Deuxièmement, il reviendra sur les données afin de mieux comprendre quels types d'investisseurs ont eu le plus de chances d'augmenter leur exposition aux entreprises à forte intensité de carbone, afin de mieux informer la représentation du secteur financier dans des travaux futurs.

Conception des politiques

Un troisième domaine d'incertitude concerne les politiques à mettre en œuvre pour faire face aux risques de transition. À cet égard, le programme de Mark Carney n'a guère été radical en matière de réglementation macro-financière. Ses propositions, qui se sont incarnées dans la Task Force for Climate Disclosure (TCFD), considèrent principalement la question des risques climatiques comme une lacune en matière d'information. Les investisseurs n'étant pas en mesure d'évaluer les performances climatiques des entreprises dans lesquelles ils investissent, ils ne peuvent ni réorienter leurs fonds vers des alternatives plus écologiques, ni couvrir les risques potentiels. En guise de réponse, la TCFD a proposé des lignes directrices pour la divulgation d'informations sur les performances environnementales des entreprises, l'objectif ultime étant que ces éléments puissent améliorer le *pricing* des risques liés au climat.

Bien qu'elle ait donné lieu à des efforts importants pour améliorer la divulgation (TCFD 2020) et à des mesures politiques concrètes et fructueuses (Mésonnier and B. Nguyen 2021), cette approche s'est trouvée sous le feu des critiques. Elle s'est d'abord heurtée au scepticisme de nombreux observateurs, qui ont estimé que le simple fait d'informer les agents financiers ne modifierait pas intrinsèquement leur motivation de profit et leur attitude face au risque (Christophers 2017). Une autre critique a suggéré que les événements liés au climat sont par essence caractérisés par une incertitude radicale, rendant inutiles les méthodes traditionnelles d'évaluation des actifs. Chenet, Ryan-Collins, and van Lerven (2021) a préconisé à cet égard une approche « précautionnelle » des risques climatiques par laquelle les régulateurs financiers et les banques centrales orienteraient activement les marchés financiers par le biais d'incitations, comme des exigences de réserve différenciées pour les prêts à forte ou faible intensité de carbone ou même une politique de crédit active visant à réorienter les fonds vers des projets compatibles avec la transition.

Cette thèse participe également à ces débats en discutant d'une option politique qui s'inscrirait dans le cadre de l'approche précautionnelle. Alors que la plupart des propositions dans ce domaine se concentrent sur un pilotage actif des

marchés financiers, les politiques qui pourraient contenir les risques de transition et l'immobilisation d'actifs sur les marchés financiers ont été relativement peu discutées. Cette thèse examine donc l'option de la création d'une « *climate bad bank* », qui libérerait les bilans des agents financiers de leurs actifs risqués intenses en carbone.

Plan de la thèse

Cette thèse est composée de six chapitres. Le Chapitre 1 commence par une revue de la littérature théorique et appliquée dans le domaine des risques de transition. Elle couvre la littérature sur les actifs échoués, les travaux fournissant des estimations des potentiels d'instabilité financière et l'économétrie financière de la transition bas-carbone. L'étude souligne en particulier que ces trois littératures se sont développées de manière relativement isolée les unes des autres. Elle appelle à une meilleure intégration des résultats et des intuitions tirées des différents champs. En outre, elle identifie plusieurs pistes de recherche dans l'estimation des risques de transition, comme l'utilisation de cadres de modélisation non standard en conjonction avec un large éventail de scénarios de décarbonisation, une meilleure modélisation des structures d'anticipations et de la dynamique du secteur financier, et, enfin, un meilleur lien entre l'échouage d'actifs dans l'économie réelle et le potentiel d'instabilité financière. Le reste de la thèse s'appuie sur ces enseignements.

Le Chapitre 2 développe un modèle stock-flux cohérent pour l'étude des risques de transition, appelé FASM-ID (*Financial Asset Stranding Model - Investment in Decarbonisation*) (Modèle d'Actifs Echoués Financiers – Investissement et Décarbonation). FASM-ID innove par rapport aux cadres existants en proposant une modélisation explicite de l'étranglement des actifs, une désagrégation du secteur financier en deux types d'agents, les banques et les agents non-bancaires, qui interagissent entre eux, et en étant capable d'émuler les voies de transition existantes afin d'explorer leurs implications en termes d'instabilité financière. FASM-ID est appliquée à l'ensemble des scénarios du NGFS pour fournir le premier *stress test* sur les risques de transition

avec un modèle stock-flux cohérent. Le modèle montre notamment que les agents financiers non bancaires sont intrinsèquement plus fragiles que les agents bancaires, avec des tensions significatives qui peuvent émerger de la dépréciation des actifs sur les marchés financiers. Il montre également que les risques de transition ne se limitent pas à des ajustements à court terme, mais peuvent apparaître à moyen et long terme. Enfin, parce qu'il est appliqué à plusieurs variantes d'un même scénario, le modèle montre que la forme et le rythme précis de la transition peuvent avoir une importance significative pour la dynamique des risques de transition vers une économie décarbonée, ce qui invite à envisager un large éventail de scénarios.

Le Chapitre 3, co-écrit avec Céline Guivarch, s'engage précisément dans cette voie en étendant cette méthodologie à l'ensemble de la base de données des scénarios du GIEC. Nous commençons par regrouper les scénarios du GIEC en cinquante groupes, dont nous tirons un meilleur représentant que nous considérons comme la référence de ce groupe. Nous simulons ensuite les cinquante meilleurs représentants avec FASM-ID sur de nombreux étalonnages différents. En particulier, nous nous appuyons sur le cadre Shared Socio-Economic Pathways (Riahi, van Vuuren, et al. 2017) pour construire cinq « mondes macroéconomiques » utilisés pour simuler les scénarios. Cette approche nous permet de caractériser les configurations de scénarios les plus risquées. Nous constatons que l'efficacité de la politique climatique dans la réalisation des objectifs climatiques est essentielle pour déterminer les risques de transition, les scénarios les plus risqués étant ceux dont les objectifs climatiques sont dans le milieu de la distribution et dont les prix du carbone sont élevés.

Le Chapitre 4 répond à l'appel à une meilleure modélisation des anticipations en proposant une nouvelle façon de les représenter. Ce travail conjoint avec Louison Cahen-Fourot, Emanuele Campiglio, Michael Gregor Miess et Andrew Allan Yardley modélise les croyances des investisseurs individuels sur les futurs échouages d'actifs carbonés comme des déviations idiosyncrasiques par rapport à une norme centrale ayant cours sur marché. En appliquant ce cadre à un modèle simple de choix d'investissement, nous montrons notamment qu'une plus grande dispersion autour

de la norme peut réduire les investissements à faible émission de carbone et ralentir considérablement la transition.

Le Chapitre 5 offre un aperçu empirique du comportement des marchés financiers concernant la transition vers une économie bas-carbone. Il étudie comment différentes catégories d'investisseurs ont modulé leur exposition aux entreprises les plus intensive en gaz à effet de serre dans le monde. En s'appuyant sur les données d'actionnariat fournies par Refinitiv Eikon, l'article reconstruit les poids des portefeuilles correspondant aux 100 entreprises les plus émettrices de gaz à effet de serre pour environ 30 000 investisseurs. À l'aide d'un modèle logit, l'étude caractérise les types d'investisseurs et les nationalités et les tailles de portefeuille qui ont été les plus enclins à augmenter leur exposition à ces entreprises. On constate notamment que, à l'exception des investisseurs européens, la plupart des agents financiers ne se sont pas désengagés de manière significative des entreprises à forte intensité de GES et que les investisseurs des pays en développement ont été les plus enclins à augmenter leur exposition. L'article montre également que les agents les plus ouverts ont augmenté leur exposition sont les fonds négociés en bourse (« *Exchange-Traded Funds* »), qui comptent parmi les institutions les moins réglementées, et les fonds de pension. Ce dernier résultat est particulièrement inquiétant compte tenu de l'approche à long terme des fonds de pension en matière d'investissement, car il suggère que la plupart de ces agents négligent les risques de transition de long terme.

Le Chapitre 6, co-écrit avec Mathilde Salin, avant la conclusion, se termine par une évaluation d'une proposition politique radicale visant à atténuer les risques de transition. Les « *bad banks* climat » ont été envisagées comme un moyen de réduire le poids des actifs à forte teneur en carbone dans les bilans financiers. À l'instar des *bad banks* traditionnelles (ou « structures de défaisance »), une *bad bank* climat prendrait en charge les actifs financiers risquant de s'échouer sur son bilan afin d'alléger la charge pesant sur les institutions financières. En s'appuyant sur un examen historique des *bad banks* passées et après avoir examiné les défis en matière d'efficacité, d'éthique et de gouvernance auxquels ces institutions sont confrontées, nous proposons un schéma

de *bad bank* climatique.

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Introduction

*“Take, for example, the IPCC’s estimate of a carbon budget that would likely limit global temperature rises to two degrees above pre-industrial levels. That budget amounts to between one fifth and one third world’s proven reserves of oil, gas and coal. If that estimate is even approximately correct it would render the vast majority of reserves “stranded” – oil, gas and coal that will be literally unburnable without expensive carbon capture technology, which itself alters fossil fuel economics. The exposure of UK investors, including insurance companies, to these shifts is potentially huge.” – Mark Carney, *The Tragedy of the Horizon*, Speech at Lloyd’s September, 29th, 2015.*

Highlighted first by former Governor of the Bank of England Mark Carney in 2015, low-carbon transition risks for finance designate, broadly speaking, the potential losses that could be incurred by financial agents as the low-carbon transition unravels due to their exposures to activities incompatible with decarbonisation efforts. The prime example of these transition risks is precisely developed in the quote above: money invested by insurers and beyond in fossil fuel companies whose value will certainly get close to zero if we are to achieve the Paris targets. Nevertheless, the final span and consequences of these financial losses, be they on the macroeconomy, financial stability or the transition itself, are far from obvious. Fraught with uncertainties, the issue of transition risks deserves careful scrutiny to best guide policymakers in alleviating the potentially adverse consequences of our necessary transition to a low-carbon economy.

This thesis intends to address these issues with a particular focus on the macro-financial aspects of transition risks over long-run mitigation pathways. More precisely, its goal is to assess the feasibility of low-carbon transition paths from the standpoint of financial stability by highlighting how different kinds of transition pathways may entail greater financial fragility, even put unsustainable pressure on financial systems. To effectively study the “balance sheet” of mitigation pathways, it brings together and proposes some extensions to three related but ultimately isolated literatures: (i) the emerging research on transition risks proper, mainly put forward by regulatory institutions, (ii) the Energy-Economy-Environment (E3) strand developed around the Intergovernmental Panel on Climate Change (IPCC) and (iii) the Post-Keynesian literature on financial dynamics and macroeconomic Stock-Flow Consistent (SFC) modelling originating in the works of Wynne Godley and Marc Lavoie (2007). Building on an initial literature review, this thesis develops a fully-fledged SFC model amenable to studying transition risks along decarbonisation scenarios. More precisely, this thesis uses the SFC approach as a platform to bring together concerns from the regulatory and E3 research strands. Building on the initial literature review, it also proposes some theoretical and empirical ways forward to better assess transition risks within macroeconomic models and beyond. Finally, it discusses a possible policy option to alleviate transition risks.

In this general introduction, I motivate this endeavour and highlight how it contributes to the study of transition risks. Starting with a genealogy of the transition risk concept (i), I show how it gave birth to a new strand of literature. Plagued with theoretical and methodological uncertainties, the nascent transition risk field soon exhibited a remarkable methodological creativity, which, however, left open two avenues in its approach to scenario analysis and the construction of non-standard modelling frameworks (ii). This dissertation endeavours to bridge these gaps by using such an alternative paradigm, the stock-flow consistent methodology, as an interface between the E3 and the transition risk literature. However, this approach is not without limitations, as many research gaps remain in the treatment of low-carbon transition risks

(iii).

Risks, finance, and the low-carbon transition

Stretching the realm of the low-carbon transition

The Paris Agreement, revered or reviled, cannot but be considered as a catalyst of global attention on the issue of climate change. After the Copenhagen failure and the financial turmoils of the early 2010s, which pushed the climate agenda in the background of global politics (Geels 2013), the past decade has witnessed a revival of interest in the future of the planet. Amid increasingly salient extreme weather events (IPCC 2021), that have confronted even the developed world with the consequences of climate changes (*e.g.* Hoffman et al. 2022), the emergency of climate action has probably never been as obvious. From climate activists to mainstream politicians through the broader public, it is hard today not to find at least a modicum of discourse on the need to tackle climate change and other ecological issues. Even if it means fierce opposition and conflicts on the precise modalities of this pressing transition (Kamali Saraji and Streimikiene 2023).

In parallel, this realisation has come with growing worries. Climate emergency has been an element of public discourse for very long, starting with the first calls from the scientific communities in the 1980s (J. Hansen 1988). However, we are now collectively coming to the sense that, from an abstract and maybe distant incantation, the need to embark rapidly and decisively on a transition path now looms upon us (UNEP 2022). The slumber of relative inaction of the past forty years has given way to an acute awareness of the sweeping and disruptive nature of the evolutions necessary to remain within planetary boundaries (Rockström et al. 2009). An action that could have been started slowly and progressively in the 1990s has been largely postponed until now, leaving us at a crossroads (IPCC 2022b). Worse, our small and shrinking window of opportunity now reduces to an intense and politically divisive embrace of change (Charbonnier 2020; Douenne and Fabre 2022) that could well require a shift

to a war economy (P. Jacques et al. 2023). Quite legitimately, then, the question of the costs of this belated transition has arisen quite quickly in the aftermath of the Paris Agreement.

This is not to say that this issue had never been raised before. The costs associated with the low-carbon transition have been at the heart of the economic approach to the matter. Ever since Nordhaus's pioneer works on climate economics (see Nordhaus 2013, for a comprehensive overview), the fight against climate change has always been framed, rightly so or not, as a choice between incurring costs today by investing against climate change or suffering later from climate damage (Pottier 2016). A lengthy economic literature has subsequently explored a wide array of dimensions related to these costs, like their extent or the fairness of their distribution across time and space. This included the Energy-Economy-Environment (E3) literature revolving around the IPCC, which has also provided numerous estimates of these "Policy Costs" of climate change mitigation through the use of well-established "Integrated Assessment Models" (IAMs) (IPCC 2015; Köberle et al. 2021). In spite of Nordhaus's first estimates, which led to temper the need for definite climate actions (Nordhaus 1992), the bottom line of this literature is straightforward: once improved the representation of climate damage, preferences and technological options, policy costs to mitigation were mild, or, at the very least, should not be a pretext to delay climate action, given the incommensurability of climate damage (Weitzman 2011; Fillon, Guivarch, and Taconet 2023).

However, these results flowed from models and approaches with many limits in their representation of economic systems, despite their formal complexity (Keppo et al. 2021). Hence, most of the cost metrics were either highly aggregated (whole-economy GDP losses), or very stylised (Köberle et al. 2021). Entire dimensions, key to the success of the transition, were simply not represented, like, as will be crucial later, the financial sector (Mercure, Knobloch, et al. 2019). Hence, for instance, the late, and sometimes painful, (re)discovery of the distributional consequences of climate policy (Ravigné, Gherzi, and Nadaud 2022), well-illustrated by the Yellow Vest movement

(Douenne and Fabre 2022); or of the highly differential impacts of the transition on distinct economic sectors (Cahen-Fourot, Campiglio, Godin, et al. 2021). All in all, as could have been expected, even though the cost of the transition itself were relatively low based on model outcomes, the concrete implementation of climate policy and of the shift to an ecologically friendly society quickly turned out to face additional obstacles and costs that traditional conceptual frameworks hardly took into account. Estimating the “true costs” of the transition thus became quickly a complex task, necessitating a careful inventory of possible sectoral and distributional impacts (Cahen-Fourot, Campiglio, Godin, et al. 2021; Ohlendorf et al. 2018). It ended up gathering a growing number of parties: new agents and institutions, even political arenas, have investigated the theme of the costs of the low-carbon transition (*e.g.* Pisani-Ferry and Mahfouz 2023). Hence, this issue left the sole fields of climate, energy and environmental economics to transition towards the much larger realms of macro- and industrial economics. This shift also followed growing discontent with the traditional setting of integrated assessment models across the board (Hafner et al. 2020). Calls for new conceptual apparatuses and modelling techniques were emerged throughout the 2010s (T. Jackson and Victor 2015), appealing to departures from optimality-based methodologies and for a better accounting of macroeconomic dimensions like inflation, growth, employment, and financial dynamics (Mercure, Knobloch, et al. 2019). From then on, new branches of economics came to the table to shed new light on otherwise little-explored dimensions related to the low-carbon transition, ranging from academic macroeconomists, mainstream (Carattini, Heutel, and Melkadze 2021) or more heterodox (Cahen-Fourot, Campiglio, Godin, et al. 2021), to practitioners in Ministries (Ens and Johnston 2020) and, as will interest us most, Central Banks and related regulatory authorities.

Bringing finance on board

It is in this context that former Governor of the Bank of England Mark Carney, delivered a speech at a gala dinner held by the famous British insurer, Lloyd’s. On

this occasion, the central banker developed a conceptual framework to study the low-carbon transition from the standpoint of economic and financial risk by contrasting three types of dangers. First, physical risks are those related to climate damage and threaten economic activities directly. The second type of risk was dubbed “liability risks”, and designated the possibility that economic agents or Nation-States may ask polluting agents for compensation in fuelling physical risks.

The third type of risk was named “transition risks” and relates directly to the transition costs discussed by the E3 literature. Yet, Carney gave this idea a whole new spin by linking it directly to the issue of systemic financial risks. By pushing forward the idea of a “Climate Minsky Moment”, whereby very rapid and decisive climate policies could endanger the viability of the financial system, Carney achieved a conceptual and rhetorical *tour de force*. As the shadows of the Global Financial Crash and of the European Sovereign Debt Crisis were receding, Carney gave the theme of financial crises a new embodiment through the lens of the low-carbon transition, hereby putting together two of the most significant concerns of the time: financial stability and climate stability.

Carney’s speech is most significant for at least two reasons. On the one hand, he brought the issue of the low-carbon transition right before the financial elite; even more, by framing it in a language directly appealing and palatable to this community. Second, he justified an institutional positioning of central banks and financial regulators on the low-carbon transition, showing that climate-related risks effectively fall within their mandate. In doing so, the Governor sent the pristine message to the financial community that it should also take a stance on the matter, either for their own sake or to avoid strong regulations. Carney’s intervention laid the groundwork for more regulatory efforts and for new strands of research centred around the macro-financial consequences of the low-carbon transition.

Initially carried out around the Bank of England, Carney’s agenda is today mainly embodied by the Network for Greening the Financial System (NGFS). Based at *Banque de France*, this consortium has notably extended and made Carney’s grid

of analysis operational within an overarching framework destined for other financial regulators but also for regulated institutions. It notably provides a body of reference transition scenarios that can be used by agents in their in-house risk measures and that serves as benchmarks in official regulatory exercises (Clerc, Diot, et al. 2020; Alogoskoufis et al. 2021). NGFS-based work has, as of today, notably consisted of transition and physical-risk assessments of said scenarios through the use of various modelling frameworks incorporating the financial system and sectoral interactions.

Deviating from its intellectual roots

Interestingly, though, the intellectual roots of Carney’s speech trace back to the E3 and IPCC literature itself, which had started, at the turn of the 2010s, to question the importance of infrastructural inertia in bearing additional costs for the transition.³

Meinshausen et al. (2009) first suggested that current hydrocarbon reserves were so abundant that exhausting them would lead us far beyond the 2°C ceiling put forward by the IPCC (2014). In parallel, Davis, Caldeira, and H. D. Matthews (2010), followed by Guivarch and Hallegatte (2011), expanded Meinshausen et al.’s intuition to built capital and existing greenhouse gas-intensive infrastructures. By doing so, they revived the concept of “stranded assets”, meant to designate this portion of the capital stock doomed to almost complete depreciation as the transition would go. These new concepts paved the way for stimulating research, notably to better understand the dynamics of stranded assets (Baldwin, Cai, and Kuralbayeva 2020; Campiglio, Dietz, and Venmans 2022; Coulomb, Lecuyer, and Vogt-Schilb 2019) and how to adapt policy tools to this new concern (Rozenberg, Vogt-Schilb, and Hallegatte 2020).

While these new developments could have remained confined to the academic world, the notion of stranded assets went beyond by being advertised by other kinds of institutions, which gave it a more finance-oriented focus, while the academic world *stricto*

³One could even refer to Unruh’s (2000) idea of “carbon lock-in”, whereby high-carbon economic systems are complex to change due to the existence of many types inertia.

sensu and the E3 literature were leaving this aspect aside. NGO Carbon Tracker Initiative notably proposed the concept of “Carbon Bubble” (Leaton 2011), according to which high-carbon reserves were overvalued on financial markets in view of inevitable decarbonisation efforts in the future. In parallel, Oxford Smith School’s researcher Ben Caldecott (Caldecott, Kruitwagen, et al. 2016) extended the notion of stranded assets by giving it a new meaning: because depreciations occurred on balance sheets, and because decarbonisation implied non-performing investments, stranded assets could have financial implications, potentially systemic (Mercure, Pollitt, N. R. Edwards, et al. 2018). From these two impulses, among many others (Generation Foundation 2013), the issues of stranded assets and unburnable carbon were brought to the public debate. From there, they lived a life of their own, away from their E3 roots, until being eventually adopted by central bankers and financial regulators. Carney’s reference to asset stranding pertains to this reinterpretation of the concept through a financial lens, bringing it to uncharted territories.

A New, innovative field

Methodological creativity and innovations

In this process, the new field of transition risks quickly realised that it was facing major uncertainties.

To start with, linking asset stranding and transition developments to potential financial risks lacked strong theoretical underpinnings at the micro- and macro-economic levels. Traditional portfolio choice theories being built on well-defined factors and economic indicators, introducing non-economic dimensions represented key empirical and theoretical challenges (Bingler, Colesanti Senni, and Monnin 2020). From a more macro-financial standpoint, linking asset stranding to potential crises was a major deviation from traditional approaches to financial instability, which had more emphasised the destabilising potential of excessive confidence in new kinds of investments than that of industries meant to disappear through long-run structural change

(Semieniuk, Campiglio, et al. 2021). Causality channels from the disappearance of such “sunset” industries to financial instability are numerous, making it difficult to pinpoint the precise shape and timing of transition risk shocks. Then, reliable data was scarce, leading to a significant effort in the reporting of carbon emissions at a sufficiently disaggregated scale. Similarly, the kind of tools to be employed to measure these risks adequately was not fully clear, given the limitations of existing frameworks (Hafner et al. 2020). Finally, because no example of transitions away from fossil fuels exists, traditional backward-looking approaches to financial risks could not be relied on, calling for a renewal of forward-looking approaches based on scenarios (Baudino and Svoronos 2021).

The challenges of scenario-based analyses

This lack of strong basis to build on forced the new field into innovating in many directions.

In empirics, new data emerged on the carbon content of financial assets and the greenhouse gas intensities of particular companies, allowing for a renewal of financial econometrics in studying how investors dealt with transition risks (Bolton and Kacperczyk 2021). Applied modelling also had its leaps forward. Large-scale macroeconomic models were adapted to the study of the low-carbon transition, while the booming field of production networks quickly welcomed environmental economics contributions (Devulder and Lisack 2020). Furthermore, the field displayed right from the outset a certain openness to less standard approaches to climate and financial economics. Network-based methods came to become a workhorse in the field (Battiston, Mandel, et al. 2017), while many heterodox scholars from the Post-Keynesian (P. Jacques et al. 2023) and agent-based (Lamperti, Bosetti, et al. 2019) communities became quickly associated with the field. For instance, the Post-Keynesian macroeconomic model E3ME pioneered research on the financial consequences of asset stranding (Semieniuk, Holden, et al. 2022), while other frameworks, like EIRIN (Monasterolo and Raberto 2018) or DEFINE (Dafermos, Nikolaidi, and Galanis 2017), came to be

discussed alongside established methodologies from central banks themselves.

However, the greatest methodological advance of the transition risk methodology has probably been the systematisation of the use scenarios, building on a methodology that had become highly fashionable after the Great Financial Crashes: stress tests. Stress tests generally consist in the application of a strong but plausible shock on an economic model, either at the macro- or at the microeconomic level, to gauge the resilience of the corresponding system to high disturbances (Cartellier 2022). In the face of transition risks and climate-related risks more generally, financial regulators extended this approach to study the potential disruptiveness of transition shocks. This process came with methodological challenges of its own. Short-run climate stress tests required precise narratives in order to disentangle possible transition shocks, ranging from climate policy implementation to rapid technological developments (Vermeulen et al. 2021). Yet, the greatest challenge belonged to the horizon of analysis of transition risks. Because the low-carbon transition will span over more than half a century, new kinds of scenarios, allowing for a long-run assessment of transitions, had to be considered. This endeavour was mostly carried out by the NGFS (Bertram, Jérôme Hilaire, et al. 2020; NGFS 2020b; NGFS 2021b; NGFS 2022), who provided a grid of analysis for the analysis of transition risks based on a distinction between three kinds of transitions. “Hot House Worlds”, featuring no or very timid transition efforts, led to a world beyond 3°C warming, characterised by high climate damage, which may trigger adverse financial developments. “Orderly transitions”, on the other hand, feature smoothly implemented climate policies and low-carbon technologies, allowing for the achievement of climate targets while avoiding major financial disruptions. Finally, “disorderly transitions” depict courses of events in which climate policy is delayed, badly implemented or uncoordinated across world regions, or with a disruptive development of low-carbon technologies. These factors possibly leading to important financial turmoils, these disorderly transition scenarios were placed under close scrutiny.

These three narratives were implemented in large-scale, multi-model exercises, al-

lowing for a fine-grain study of transition exposures and vulnerability both at the macroeconomic and microeconomic scales, thanks to more and more disaggregated data at the company and financial agent level. Highly innovative and pragmatic, due to the use of many modelling frameworks, these exercises, mostly carried out by research teams in regulatory institutions, represent the spearhead of long-run transition-risk assessments.

A missed dialogue?

Interestingly, to build these scenarios, the NGFS called upon well-established members of the E3 community to build these projections, seemingly connecting back with the intellectual origins of the transition risk literature. However, the collaboration between the two communities hardly went beyond this scenario construction. The projections provided by the E3 community were only the input of the first step of the whole NGFS apparatus, which, in the following, developed its own methodology with its own tools and concerns. On the side of the E3 community, NGFS scenarios were reviewed as any other in the IPCC's Assessment Report 6. In parallel, the field developed discussions on financial stability separately, notably questioning the possibility of embedding it into Integrated Assessment Models (Curtin et al. 2019; Keppo et al. 2021). In short, this interface between the two fields has hardly given rise to deeper and more systematic collaborations and discussions. As a result, the transition risk literature has hardly built on the dense epistemological and methodological discussions on the use of scenarios and large-scale models, which has been an important subject of discussion within the E3 literature.

Furthermore, because of its interest in long-run matters and its use of complex modelling frameworks, the E3 literature has emphasised on the need to tackle the uncertainties inherent to its exercises (van Asselt and Rotmans 2002). Such uncertainties play out at various levels. First, obviously, the assumptions embedded in given scenarios, for instance, on the cost and availability of future technologies (Kriegler, Weyant, et al. 2014) or macroeconomic data (Riahi, van Vuuren, et al. 2017), can

affect transition paths to a significant extent. Next, there is equally high uncertainty on the parameter values for key components of integrated assessment models, for instance elasticities or technological penetration rates (Gillingham et al. 2018; Marangoni et al. 2017). Finally, large-scale integrated assessment models can exhibit very different structures and assumptions, which may lead to significantly different results for similar scenario assumptions and comparable parameter values (Kriegler, Weyant, et al. 2014). Ghersi et al. (2023) even suggested a new kind of “theoretical” uncertainty, relating to the many different theories and ontologies (neoclassical, neo-Keynesian, post-Keynesian) used to describe economic systems and which cannot be firmly disentangled. These discussions have given rise to a wide literature increasingly taking scenarios as exploratory tools to map uncertainties as best as possible (Guivarch, Le Gallic, et al. 2022).

By contrast, these discussions have been largely absent from the literature on transition risks, which is somewhat surprising given the high uncertainty surrounding the notion. Quite symptomatically, the NGFS builds on a relatively reduced number of scenarios rarely mobilised altogether in regulatory exercises. Worse, while the first vintage of the NGFS’s series included some eighteen scenarios, including variants of the same scenarios, the most recent vintages have reduced the number of scenarios to twelve. At the same time, nothing warrants that these scenarios are (i) representative within the wide range possible transition pathways and (ii) allow to map the full range of uncertainties characterising the transition, which could go far beyond the timing of climate action and the intensity of technological progress. True, a reduced set of scenarios allows for a clear narrative and creates a well-established benchmark for practitioners. It has also been useful in familiarising the financial sector’s community with scenario-based methodologies, which, until now, had been quite estranged to the practices of financiers. However, it also represents some risks from a macroprudential standpoint, in that some sources of transition risks may not be mapped, for instance if they only prevail under some scenario hypotheses.

There is, therefore, an immediate need for an expansion of the scenario portfolio used

in transition risk assessments by bringing the concerns of the transition risk literature to a broader set of mitigation pathways and prompting a dialogue between the E3 and transition risk research strands. It is the first goal of this dissertation, which intends to study the “balance sheet” of all IPCC pathways.

Towards new models

In parallel, while displaying a certain methodological openness and pragmatism, the transition risk literature has not yet used of alternative modelling frameworks in its assessments. More precisely, formal and applied innovation has remained within standard frameworks. For instance, the growing production-network literature builds on usual production functions and perfect-competition assumptions, and the most commonly used macroeconomic model used in transition-risk assessments is a well-established New-Keynesian macroeconometric model, NiGEM (NIESR 2016). However, when this dissertation was started, regulatory authorities had hardly implemented any alternative framework, like agent-based and stock-flow consistent models, while their ability to model and study complex financial interactions has been increasingly recognised (Sanders et al. 2022).

These two limits of current transition-risk assessments motivate the two endeavours of this dissertation. It first intends to bring E3 discussions on uncertainty to the field, notably by expanding the range of scenarios used for the study of financial transition risks. For this purpose, it aims to develop a stock-flow consistent model able to study financial dynamics along transition paths while being amenable to the simulation of many scenarios. With this double approach, which combines the stock-flow consistent approach with the pre-existing scenarios provided by the E3 community, it endeavours to contribute to a more precise mapping of uncertainties related to financial low-carbon transition risks.

Therefore, this dissertation’s second goal is to use the transition risk agenda as a meeting point between the transition-risk literature *per se*, the E3 literature on transition scenarios, and the stock-flow consistent approach.

The stock-flow consistent approach

However, the interface between the E3 community and the stock-flow consistent is far from obvious, given their very different theoretical underpinnings. Primarily anchored in neoclassical economics and the optimisation paradigm, the E3 literature has, so far, barely included less standard approaches. As an illustration of these limited discussions, it may be noted that the well-established post-Keynesian Integrated Assessment Model E3ME does not provide trajectories reviewed in IPCC's assessment reports (IPCC 2022b). Yet, the transition risk theme, because of its orientation towards financial themes, represents a stimulating occasion for building a bridge between these two literatures, notably by systematising the link between transition scenarios and stock-flow consistent approaches.

The stock-flow consistent methodology traces back to the works of Wynne Godley, Gennaro Zezza and Marc Lavoie in the 1990s and was formally laid down by Wynne Godley and Marc Lavoie in their -Godley and Lavoie (2007) *Monetary Economics*. It is today mainly, if not integrally, used by the post-Keynesian school of economics, a heterodox community characterised by its emphasis on the role of aggregate demand in running economic dynamic distributional matters and real-financial interactions. The stock-flow consistent approach represents today the central integrative platform for post-Keynesian approaches and provides a valuable complement to more traditional methods like macroeconometric models or DSGEs (Burgess, Burrows, and Kinsella 2016).

Somewhat a misnomer, "Stock-Flow Consistent" relates to the necessity for a modelling framework to abide by the conventions of national accounting, which, today, is the case for most applied modelling frameworks, standard or heterodox. However, stock-flow consistency for post-Keynesian authors takes a more profound sense (Nikiforos and Zezza 2017). Godley and Lavoie's intellectual project was, thanks to a careful accounting of stocks and flows within economic systems, to understand how *financial* stocks and flows interacted with *real* stocks and flows. While most traditional frameworks only focus on real variables or introduce a clear separation

Table 1: Generic Transaction-Flow Matrix (Borrowed from Godley and Lavoie (2007))

	Households (1)	Production firms		Banks		Government (6)	Central Bank	
		Current (2)	Capital (3)	Current (4)	Capital (5)		Current (7)	Capital (8)
Transactions								
Consumption	$-C$	$+C$						
Investment	$-I_h$	$+I$	$-I_f$					
Govt. exp.		$+G$				$-G$		
Wages	$+WB$	$-WB$						
Profits, firms	$+FD_f$	$-F_f$	$+FU_f$					
Profits, Banks	$+FD_b$			$-F_b$	$+FU_b$			
Profits, central Bank					-5	$+F_{cb}$	$-F_{cb}$	
Loan interests	$-r_{l(-1)} \cdot L_{h(-1)}$	$-r_{l(-1)} \cdot L_{f(-1)}$		$+r_{1(-1)} \cdot L_{(-1)}$				
Deposit interests	$+r_{m(-1)} \cdot M_{h(-1)}$			$-r_{m(-1)} \cdot M_{(-1)}$				
Bill interests	$+r_{b(-1)} \cdot B_{h(-1)}$			$+r_{b(-1)} \cdot B_{b(-1)}$		$-r_{b(-1)} \cdot B_{(-1)}$	$+r_{b(-1)} \cdot B_{cb(-1)}$	
Taxes - transfers	$-T_h$	$-T_f$		$-T_b$		$+T(1)$		
Flow of Funds								
Change in loans	$+\Delta L_h$		$+\Delta L_f$		$-\Delta L$			
Change in cash	$-\Delta H_h$				$-\Delta H_b$			$+\Delta H$
Change, deposits	$-\Delta M_h$				$+\Delta M$			
Change in bills	$-\Delta B_h$				$-\Delta B_b$	$+\Delta B$		$-\Delta B_{cb}$
Change, equities	$-(\Delta e_f \cdot p_{ef} + \Delta e_b \cdot p_{eb})$		$+\Delta e_f \cdot p_{ef}$		$+\Delta e_b \cdot p_{eb}$			
Σ	0	0	0	0	0	0	0	0

between monetary and non-monetary quantities, post-Keynesian stock-flow consistent models draw a systematic link between finance and the rest of the economy. They notably highlight how the structure of financial contracts, notably credit, can influence economic dynamics in the short and long run alike.

Formally, a stock-flow consistent model depicts the economy as a network of nested balance sheets, usually, but not exclusively, belonging to the institutional sectors of the economy found in national accounts (households, non-financial firms, financial firms). These balance sheets are linked primarily by monetary flows, which, ultimately, influence the evolution of real and financial stocks. In turn, the real economy and the financial system influence each other in an integrated way.

In visual terms, stock-flow consistent models can be summarised with two tables illustrating the requirements of stock-flow consistency, a Transaction-Flow matrix (Figure 1) and a Balance-Sheet matrix (Figure 2).

These two tables illustrate the importance of stock-flow consistency in SFC models, as put forward by Nikiforos and Zezza (2017).

- The transaction-flow matrix depicts all financial flows included in the model.

Table 2: Generic Balance-Sheet Matrix (Borrowed from Godley and Lavoie (2007))

	Households	Production firms	Banks	Government	Central bank	Σ
Tangible capital	$+K_h$	$+K_f$				$+K$
Bills	$+B_h$		$+B_b$	$-B$	$+B_{cb}$	0
Cash	$+H_h$		$+H_b$		$-H$	0
Deposits	$+M_h$		$-M$			0
Loans	$-L_h$	$-L_f$	$+L$			0
Equities	$+E_f$	$-E_f$	$-E_b$		0	$-K$
Equities	$+E_b$		$-NW_b$	$-NW_g$	0	0
Net worth	$-NW_h$	$-NW_f$	$-N$	0	0	0
Σ	0	0	0	0		

Its top section displays financial flows emerging from real-economy transactions: consumption, investments, and transfers. Its bottom part shows the flow-of-fund of the economy, which includes the financial flows arising from the purchase of financial assets, and therefore depicts the structure of savings. This table illustrates the first requirement of stock-flow consistency, namely that all financial flows must have a well-identified origin and well-identified end to avoid “leaks” in the system. This is why all rows should sum to zero. All columns should also sum to zero to illustrate the dispatch between Transactions (upper part) and Flow of funds (lower part).

- The balance sheet reports the asset-liabilities structure of the economy. It shows that stock-flow consistency further requires that the assets of one agent must be the liabilities of another agent – except for capital, backed by savings as a whole.
- The Transaction-Flow Matrix and the Balance Sheet together finally show the third requirement of stock-flow consistency, *i.e.* that a flow must, ultimately, be attributable to a change in stock.
- These three requirements imply a quadruple entry bookkeeping, whereby any financial flow must be matched ultimately by an origin, an end, a decrease in a stock, and an increase in another.

The specificity of the post-Keynesian stock-flow consistent approach is that this em-

phasis on accounting and monetary flows allows it to embed the financial system within the economy right from the outset. More precisely, because it explicitly represents stocks of financial assets, which back investment expenses, it gives a role to the financial system beyond the role of shock-amplification it assumes in most of the traditional models that include it (Nikiforos and Zezza 2017). Furthermore, because the method explicitly models the saving behaviour of all sectors in the economy, it allows for a meaningful study of financial balances and net lending positions.

The post-Keynesian stock-flow consistent approach finally includes some theoretical aspects. Building notably on the teachings of Keynes and Kalecki, most, if not all post-Keynesian SFC models are demand-led models, whereby investment is ruled by an independent function and where savings are determined ex-post by investment expenditures. This demand-led closure is usually a corollary of an endogenous money approach to money creation, whereby banks can create purchasing power on demand to accommodate the fluctuations of the economy. Under such a regime, “loans make deposits”, and investment is not constrained by a pre-existing amount of money savings. This approach to money creation, judged more realistic by central bankers (Jakab and Kumhof 2015; Jakab and Kumhof 2018), tightens the links between the financial system and the economy by shifting the funding investment away from the intertemporal consumption smoothing behaviour of neoclassical models. This, in turn, invites to model the financial system in a comprehensive and sophisticated way, with dedicated behavioural assumptions on portfolio choice and loan-making. Finally, it is worth noting that most SFC models are “behavioural” in a broad sense, in that they very rarely rely on optimising behaviours and most often assume adaptive expectations.

These aspects of stock-flow consistent models make them suitable tools for the study of transition risks in several respects. The emphasis on monetary variables, the plasticity it offers in modelling the financial system makes, and its more realistic depiction of financial flows make it a perfect candidate for this endeavour. Furthermore, the usual demand-led closure, which allows for more Keynesian outcomes, may offer a

valuable complement to most existing tools. Finally, its rejection of optimisation procedures allows for a shift from over-rational approaches to the low-carbon transition that has been long called for in the literature (Hafner et al. 2020).

And indeed, many stock-flow consistent frameworks have been put forward to study ecological matters broadly: Peter Jackson's FALSTAFF (T. Jackson and Victor 2015), Dafermos et al.'s DEFINE (Dafermos, Nikolaidi, and Galanis 2017), Monasterolo et al.'s EIRIN (Monasterolo and Raberto 2018), or, more recently, TEMPLE, by P. Jacques et al. (2023).

All these models have touched upon the macroeconomic consequences of a low-carbon transition, with, in some instances, an eye on financial variables. In most, if not all cases, the low-carbon transition is simulated through an exogenous change in the share of low-carbon energy in the mix or of low-carbon capital, with trajectories meant to be consistent with decarbonisation objectives. SFC models have, therefore, been mostly built as platforms to simulate pre-decided transition paths and explore the latter's consequences. However, these transition pathways are usually very few and at the discretion of the modeller. This practice comes with two shortcomings. On the one hand, it bars the possibility of exploring different shapes of low-carbon transition, while many possibilities exist, depending on the availability of some technologies, assumptions on the speed of their deployment, or the form taken by climate policies. Second, it can lead to assuming unduly stringent transition pathways, which may not be conceivable due to infrastructural and economic inertia.

It is precisely where a fruitful interface could be drawn with the E3 literature. Because the latter provides many transition pathways, which draw as many roads to decarbonisation, one could create a link between the characteristics of these transition pathways and the inputs necessary to simulate transitions in SFC models. As a result, adequate transition-oriented SFCs could be used as platforms to characterise the financial instability properties of such pathways. More precisely, it can serve as an effective meeting point between the transition risk literature and the E3 community by providing valuable metrics for macro-financial risks while at the same time

helping address the uncertainties the E3 literature has repeatedly emphasised.

This research programme, schematised in Figure 1, will be the endeavour of this dissertation. By using an SFC model as a tool to explore uncertainties around transition risks, its aim is to help complement existing approaches within the transition risk literature while, at the same time, bank on the large number of scenarios provided by the E3 literature. In a word, study the balance sheet of IPCC trajectories.

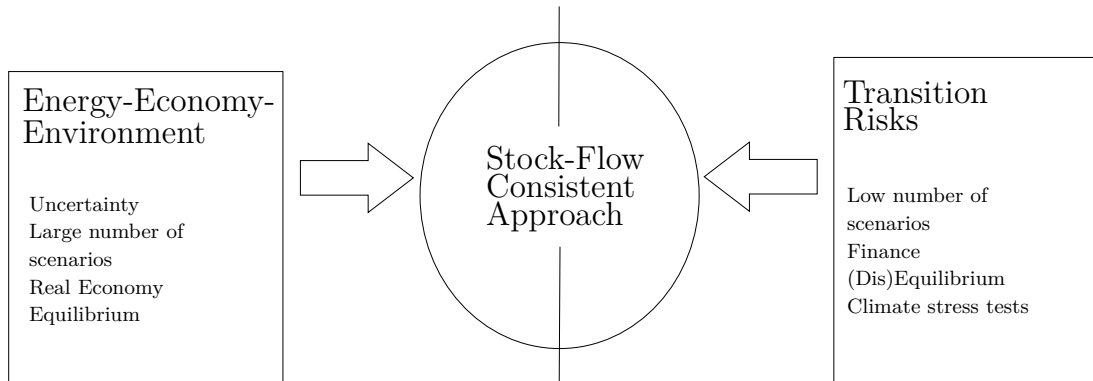
Exploring other frontiers

This contribution, however, is primarily methodological. As such, it only partly addresses the uncertainties around transition risks. It focuses on those that relate to the shape of transition pathways and the underlying assumptions of models used to generate reference trajectories. However, as sketched above, the transition risk field is also fraught with theoretical uncertainties that require as many formal and modelling innovations. By building on a state-of-the-art of the literature and on the obstacles encountered while following the above research programme, this dissertation intends to provide preliminary steps to improve the theoretics of transition risks. Two main lines of work were explored: the modelling of expectations and the understanding of the financial sector.

The importance of expectations

As emphasised by the stranded asset (van der Ploeg and Rezai 2020b) and transition risk (Battiston, Monasterolo, Riahi, et al. 2021) literatures, the expectations of economic agents will be a crucial factor in shaping the extent of the macro-financial disturbances raised by the low-carbon transition. Well-anticipated climate policies and correct expectations on future technological developments would allow for a smoother transition, economic agents being able to prepare and orient their investment adequately. In the opposite case, brisk reactions to technological displacements

Figure 1: Summary of the dissertation's three-tier approach



or climate policy implementations could result in sharp macroeconomic and financial adjustments (Carney 2015).

Maybe even more than for other economic outcomes, adequately representing transition expectations requires dealing with (i) the radical uncertainty that surrounds it and (ii) the fact that relevant transition outcomes span over large time horizons. Economic modellers have mostly tackled this question by relying on some versions of rational expectations, either perfect foresight or a prior knowledge of possible outcomes and corresponding probabilities (van der Ploeg and Rezai 2020b; Lemoine and Traeger 2016). The problem with this approach is that it endows agents with too-high a level of rationality and mechanically downplays the extent of transition risks, while waiving the radical uncertainty inherent to the transition (Battiston, Dafermos, and Monasterolo 2021). Other approaches have relied on backwards-looking expectations, whereby agents are either myopic or sequentially adapt their guesstimates. These approaches, although they do acknowledge radical uncertainty, are not necessarily more satisfying since agents cannot formulate forward-looking views on the transition and cannot make for possible developments. Finally, in both cases, agents are supposed to have aligned or similar expectation structures, while one could expect expectations to be highly heterogeneous.

These two extreme treatments call for a middle ground. Agents should be able to formulate forward-looking expectations while, at the same, leaving room for radical

uncertainty. Also, ideally, the modeller should include heterogeneity in expectations, which will be crucial in shaping transition developments – for instance, various bets on technological developments – and asset price adjustments in financial markets. Some recent proposals have been made on the matter (Campiglio, Lamperti, and Terranova 2023; Dunz, Naqvi, and Monasterolo 2021), in order to better understand the unravelling of the transition in the presence of alternative expectation structures. This dissertation will walk in these steps by proposing a way to model expectations focusing on their heterogeneity. This method would be, in principle, portable to large macroeconomic models.

Understanding the financial sector

A better understanding and modelling of the financial sector, notably of its internal interactions, is also an open and stimulating research avenue. While network approaches to climate stress tests have become a workhorse in the field, a sound representation of the financial sector within more dynamic macroeconomic models is yet to be proposed. Regulatory climate stress tests typically resort to multiple modules to allow for a comprehensive picture of financial outcomes. However, these modules do not feed back on the economy, and rarely capture within-finance interactions. The stock-flow consistent approach, quite paradoxically, does not go very far in this respect either. Although the real and the financial economies are integrated, the financial system is often reduced to banks, with market finance being attributed to households. This approach fails to capture the diversity of financial agents and, therefore, how exposures to financial risks could change hands. Strangely enough, empirics have not developed much on this question, most econometric endeavours being centred around portfolio choice behaviour instead of studying how assets move from agent to agent.

This thesis tackles this aspect in two respects. First, the SFC model it will develop proposes a disaggregated representation of the financial sector by differentiating across non-bank and banking agents. It further accounts for interactions between

these two agent types. Second, it will get back to the data in order to better understand what kind of investors have had the most chances to increase their exposure to high-carbon companies in order to better inform the representation of the financial sector in future works.

Designing policies

A third area of uncertainty relates to the policies to implement in dealing with transition risks. In this respect, Carney hardly laid out a highly radical agenda regarding macro-financial regulation. His proposals, which took shape in the Task Force for Climate Disclosure (TCFD), mostly considered the issue of climate risks as an information gap. Because investors are not able to assess the climate performances of the companies they invest in, they can neither reorient their funds towards more ecologically friendly alternatives, nor hedge potential risks. As an antidote, the TCFD proposed some guidelines for disclosing information on the environmental performances of firms, with the ultimate objective that this information could improve the pricing of climate-related risks.

Although it led to major efforts in improving disclosure (TCFD 2020) and concrete and successful policy moves (Mésonnier and B. Nguyen 2021), this approach came under fire. It first encountered the skepticism of many observers, who posited that merely informing financial agents would not intrinsically change their profit motive and risk attitudes (Christophers 2017). Another critique suggested that climate-related events are by essence characterised by radical uncertainty, rendering traditional asset pricing methods useless. Chenet, Ryan-Collins, and van Lerven (2021) advocated a “precautionary” approach to climate risks whereby financial regulators and central banks would actively steer financial markets through incentives, like differential reserve requirements for high- or low-carbon loans or even an active credit policy aimed at reorienting funds away from high-carbon companies.

This dissertation also participates in these debates by discussing a policy option that would fall within the precautionary approach. While most proposals in this realm

focus on active financial market steering, policies that could contain transition risks and asset stranding on financial markets have been comparatively little discussed. This thesis thus discusses the option of setting up a climate bad bank, which would free financial agents' balance sheets of their risky high-carbon assets.

Dissertation layout

This dissertation is composed of six chapters. Chapter 1 opens by providing a review of the theoretical and applied literatures in the field of low-carbon transition risks. It reviews the stranded asset literature, works providing estimates of financial instability potentials and the financial econometrics of the low-carbon transition. The review highlights in particular that the three literatures have developed in relative isolation from each other. It calls for a better integration of findings and insights. Furthermore, it identifies several avenues of research in the estimation of transition risks, like the use of non-standard modelling frameworks in conjunction with a large array of decarbonisation scenarios, a better modelling of expectation structures and of the dynamics of the financial sector, and, finally, a better linking of asset stranding in the real economy and financial instability potential. The remainder the dissertation builds upon these teachings.

Chapter 2 develops a stock-flow consistent modelling framework for the study of transition risks along transition pathways, named FASM-ID (Financial Asset Stranding Model – Investment in Decarbonisation). FASM-ID innovates compared to existing frameworks by proposing an explicit modelling of asset stranding, a disaggregation of the financial sector into two agent types, banks and non-banks, which interact within the financial sector, and by being able to emulate existing transition pathways to explore their financial instability implications. I apply FASM-ID to the NGFS's scenario set and provide the first transition-risk stress test powered by a stock-flow consistent model. The model notably shows that non-bank financial agents are intrinsically more fragile than bank agents, with significant tensions that can emerge from asset

depreciation in financial markets. It also shows that transition risks are not confined to short-run adjustments but can emerge in the medium to long run. Finally, because it is applied on several variants of the same scenario, the model shows that the precise shape and pace of the transition can matter significantly for the dynamics of low-carbon transition risks, inviting to consider a wide array of scenarios.

Chapter 3, written with Céline Guivarch, precisely embarks on this endeavour by expanding this methodology to the whole IPCC scenario database. We start by clustering IPCC scenarios into fifty groups, from which we draw a best representative that we consider as the benchmark of this group. We then simulate all fifty best representatives with FASM-ID on many different calibrations. In particular, we build upon the Shared Socio-Economic Pathways (Riahi, van Vuuren, et al. 2017) framework to build five “macroeconomic worlds” used to simulate the scenarios. This approach allows us to characterise the riskiest scenario configurations. We find that the efficiency of climate policy in achieving climate targets is key in determining transition risks, the riskiest scenarios being those with mid-range climate targets and high carbon prices.

Chapter 4 builds on the call for a better modelling of expectations by providing a novel way to represent forward-looking expectations. This joint work with Louison Cahen-Fourot, Emanuele Campiglio, Michael Gregor Miess and Andrew Allan Yardley models individual investors’ beliefs on future high-carbon capital stranding as idiosyncratic deviations from a central market norm. By applying this framework to a simple investment choice model, we notably show that higher dispersion around the norm can lower low-carbon investment and significantly slow down the transition.

Chapter 5 offers empirical insights into the behaviour of financial markets with respect to the low-carbon transition. It studies how different investor categories have modulated their exposures to the most GHG-intensive companies around the globe. By building on ownership data provided by Refinitiv Eikon, I build portfolio weights in the top 100 most GHG-intensive companies for around 30,000 investors. Using a logit model, I characterise what investor types and nationalities have been more prone

to increase their exposure to these companies. I notably find that, except for European investors, most financial agents have not significantly disengaged from GHG-intensive companies and that the investors from developing countries have been most prone to increase their exposure. I also document that the agents most prone to increase their exposures are Exchange-Traded Funds, which are amongst the least regulated kinds of institutions, and Pension Funds. This latter feature is particularly worrying in view of Pension Funds' long-term approach to investments, as it suggests that most of these institutions waive long-run transition risks.

Chapter 6, written with Mathilde Salin, before the conclusion, closes by offering an evaluation of a radical policy proposal aimed to alleviate transition risks. Climate bad banks have been contemplated as a means to reduce the burden of high-carbon assets on financial balance sheets. Similarly to traditional bad banks or asset management companies, a climate bad bank would take financial assets at risk of stranding onto its balance sheets in order to alleviate the burden put on financial institutions. By relying on a historical review of past bad banks and after examining the efficiency, ethics and governance challenges faced by these institutions, we propose a conceptual climate bad bank blueprint.

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Chapter 1

Financial stability, stranded assets and the low-carbon transition – A critical review of the theoretical and applied literature¹

¹This paper is a slightly modified version of Daumas, L. (2023), Financial stability, stranded assets and the low-carbon transition – A critical review of the theoretical and applied literatures, *Journal of Economic Surveys*.

Abstract

Transitioning to a low-carbon economy will entail sweeping transformations of energy and economic systems. A growing research body has raised concerns about the effect of such strain on financial stability. This literature on “financial transition risk” has highlighted that the conjunction of climate policy, technological change and shifts in consumption patterns may propagate to financial markets. In extreme cases, these dynamics may result in a “Climate-Minsky” moment with systemic implications. The field has developed quickly, covering many methods and research questions. While this expansion in literature is advantageous when studying a complex issue like the low-carbon transition, it also comes with downsides. The large number of methods found in the literature hampers result comparison and the integration of research designs. It also makes it difficult to provide a synthetic view of results in the literature as well as identify remaining uncertainties. To bridge these gaps, I propose a critical review of the literature. I examine three sub-fields: the asset stranding literature, the direct assessment of transition risks through prospective models and the financial empirics of the low-carbon transition. I expound their main results, critically assess underlying methodologies and propose a framework to compare results. The review ends by suggesting some avenues for future research.

Keywords: Review, Stranded assets, Financial Stability, Transition Risks

Acknowledgements

The author is grateful to Thibault Briera, Emanuele Campiglio, Régis Gourdel, Céline Guivarch, Esther Marie Shears and three anonymous referees for helpful suggestions and comments. All possible remaining errors are mine.

Introduction

As the latest IPCC report (IPCC 2022a) made clear, decarbonisation is becoming urgent. While the effects of climate change are increasingly salient, our window of opportunity to achieve a 1.5–2°C warming is shrinking. Reaching net-zero by 2050 will require a yearly 3%–5% reduction of our greenhouse gas emissions. This target was only achieved during the Covid crisis. This fact alone provides a sense of the immense scale of the necessary changes to bring about decarbonisation.

How decarbonisation could affect financial stability was first explored in the early 2010s. The “carbon bubble” hypothesis put forward by Carbon Tracker Initiative (CTI) (Leaton 2011) conjectured that fossil reserves were overvalued given decarbonisation targets. Former Governor of the Bank of England, Mark Carney addressed the issue in a landmark speech at Lloyd’s in 2015. He suggested that a rapid transition to a low-carbon economy carried risks for the financial system, possibly down to systemic implications – what he dubbed a “Climate Minsky Moment”. The newly coined “financial transition risk” concept has provided an intellectual basis for studies on the links between financial stability and the low-carbon transition.

Yet, the financial transition risk research agenda has faced daunting methodological, theoretical, and empirical challenges. The low-carbon transition is a multi-faceted phenomenon. It includes economic dimensions, like stopping further fossil extraction projects (SEI et al. 2021). It also encompasses societal elements, like climate policies, the design of new institutions, and possibly far-reaching lifestyle changes toward sufficiency (IPCC 2022a). Transition risks will be of many kinds, acting at various levels and brought about by several drivers (Semieniuk, Campiglio, et al. 2021). They will impact the real economy and the financial system through many causality channels (Basel Committee 2021b), which are difficult to disentangle. Further, because the links between structural change and financial instability are understudied, the relative importance of these drivers and channels poses acute theoretical issues (Semieniuk, Campiglio, et al. 2021). This lack of firm theoretics, together with the radically uncertain nature of the transition (Kriegler, Weyant, et al. 2014), has plagued the

literature with methodological and empirical uncertainties.

Many approaches to transition risks have been proposed, with various foci. The stranded asset literature has intended to quantify balance sheet losses emerging from premature decommission and redundant high-carbon capital. It presents financial crises as a possible outcome of these balance sheet losses (Leaton 2011). Yet, the field has hardly gone beyond quantifying financial value losses along transition paths without linking them to financial agents or financial instability (Curtin et al. 2019). Finance-oriented approaches have bridged this gap by providing insights into financial agents' exposures and possible financial disturbances. These two fields have extensively developed forward-looking methodologies based on transition scenarios. Its main current difficulties revolve around the representation of how agents, notably financial, will react, adapt, and reorganise around transition paths. The empirical literature on financial markets, which I will cover last, provides insights into this matter by measuring financial investors' expectations and how they could react to transition developments.

While this diversity is undoubtedly a strength, it has also introduced difficulties regarding study comparability and clarity. Hence, there lacks a synoptic view of current results and difficulties in identifying research needs, especially on the systemic relevance of transition risks.

Having a clear view of financial transition risks is critical in two respects. Instability along a transition path may reset policy agendas away from decarbonisation, like after the 2008 crisis (Geels 2013). Second, even if they do not come down to a crash, higher volatility or financial disturbances along a transition path could represent a brake on transition dynamics. Finally, the negative consequences of instability on economic dynamics should be avoided. Hence, it is crucial to understand how instability can arise along decarbonisation to design policies able to smooth out dynamics and ensure sustained decarbonisation efforts.

This article critically reviews the current state-of-the-art focused on financial low-carbon transition risks. It synthesizes existing methodologies and proposes an ana-

lytical grid to facilitate the interpretation of results, how they relate to instability potentials, and systemic risks and how to link them to each other.

The financial system will not only be affected by the low-carbon transition. Mark Carney highlighted two other climate-related risks. Physical risks are financial losses associated with climate damage, while liability risks are the costs of compensating agents affected by climate damage.

However, the literature on liability risks is very scarce (Barker, Dellios, and Mulholland 2021). Further, the literatures on physical and transition risks face close but ultimately distinct methodological challenges. Hence, I focus on transition risks to allow for a comprehensive picture of the field.² This review contributes to the literature on transition risks in several respects. It adopts an encompassing view of the transition risks highlighted by the three strands mentioned above and streamlines a very diverse literature through a unified analysis grid.

It complements other reviews. Some have focused on specific topics like asset stranding (Curtin et al. 2019; Fisch-Romito et al. 2021; A. Jackson 2018), or particular sectors (van Benthem et al. 2022). Others have explored theoretical and methodological considerations only (van der Ploeg and Rezai 2020a; Campiglio and Ploeg 2021; Cartellier 2022; Salisu and Oloko 2023) or summarised the empirical literature on asset pricing (Breitenstein et al. 2022; Campiglio, Daumas, et al. 2023). Others, like Kouwenberg and Zheng (Kouwenberg and C. Zheng 2023) adopt a bibliometric approach to the climate finance corpus. The review also brings together both a quantitative and a methodological assessments of the literature.

The three branches above have developed in relative isolation, with little cross-fertilization and integration of findings. Despite immediate connections, the stranded asset and finance-oriented approaches are yet to be linked consistently. Indeed, it is ultimately still unclear how stranded assets could lead to financial disturbances. Similarly, modelling studies should incorporate the results from the empirical literature, notably through a better representation of investors' perceptions and expectations.

²An exception will be the discussion of the interactions between transition and physical risks (Monasterolo, 2020b).

The literature is also yet to account for uncertainties inherent to forward-looking methodologies. Relatedly, the modelling of the interactions between the financial system and the real economy along transition paths must be deepened. Regarding results, the literature points to possibly high losses for high-carbon companies along transition paths, although their impact on financial instability is still uncertain. The literature seems nonetheless to agree on the risks associated with “disorderly” transitions, whereby climate policies are ill-conceived or introduced late.

Section 1 will present theoretical elements on transition risks, provide a first overview of the literature and propose a framework for the study of results. Section 2 will describe the applied literature on stranded assets, which has studied exposures of non-financial companies’ (NFCs) balance sheets. Section 3 will critically assess the diversity of finance-based approaches mobilised by the literature. Section 4 will cover the empirical literature on investors’ attitudes and asset pricing that provides measures for investor expectations. Section 5 will conclude by summarizing the review’s findings and providing some research avenues.

1 Understanding transition risks

1.1 Definition and Scope

1.1.1 Transition risks

The intuition of transition risks originates from Meinshausen et al.’s (2009) analysis of 2 °C-consistent carbon budgets and their incompatibility with the use of existing fossil reserves. The concept received a financial spin through NGO Carbon Tracker Initiative’s “carbon bubble” hypothesis (Leaton, A. Grant, et al. 2015; Leaton 2015), whereby fossil reserves left “unburnt” could lose value and bear systemic implications (Schoenmaker and van Tilburg 2016).

Former Governor of the Bank of England Mark Carney (2015) coined the “transition risk” term. In a landmark speech at Lloyds’, he highlighted that climate change

and the low-carbon transition posed three main risks to financial stability. “Physical risks” designate climate damage (Bolton, Després, et al. 2020). “Liability risks” refer to the possible compensations some entities and countries may ask for after suffering climate damage (Golnaraghi 2018). “Transition risks,” which are the focus of this review, are defined broadly as:

The threats, possibly systemic, posed by the transition to a low-carbon economy to financial stability (Carney, 2015).

Carney (2016) highlighted a trade-off between physical and transition risks. Going slow would endanger financial stability through higher climate damage (Carney 2015). However, transitioning fast or in a disorderly manner may trigger devaluations in some sectors and propagate to financial systems (Papandreou 2019). Transition risks will depend on the stringency of climate policies (Batten, Sowerbutts, and Tanaka 2016) and the pace of the low-carbon transition (Grubb, Drummond, and Hughes 2020).

The literature has focused on transition risks emerging from “sunset”, high-carbon industries (van der Ploeg 2020; Semieniuk, Campiglio, et al. 2021), that is, on how the high-carbon structure of our economic systems may endanger financial instability.³ This concern has brought to the forefront the notion of stranded assets.

1.1.2 Stranded assets

A general definition of stranded assets was provided by van der Ploeg and Rezai (2020a), building on Caldecott, Kruitwagen, et al. (2016) and Generation Foundation (2013):

Stranded assets in the context of the low-carbon transition are assets whose profit expectations will be drastically reduced compared to when economic agents had first invested in them when the economy decarbonises. This phenomenon emerges

³Comparatively, financial instability arising from greater risk-taking in “sunrise”, low-carbon industries has barely been covered (see Nauman (2021)). I will, therefore, focus on sunset industries in the remaining of this article.

because of costly reallocation or transaction costs preventing these assets to be easily put to other uses or liquidated.

Stranded assets fit three categories (see Figure 1). Stranded resources refer to the losses incurred from untapped fossil resources (Leaton 2011) or unexploited forests and agricultural lands (Caldecott, Howarth, and McSharry 2013; Rautner, Tomlinson, and Hoare 2016). Stranded capital designates production assets that will lose value or require costly reconversion (Hambel, Kraft, and van der Ploeg 2020). Caldecott, A. Clark, et al. (2021) extend the definition beyond carbon assets to encompass biodiversity losses, broader climate damage and environmental litigation issues. Expected losses on stranded resources and capital imply stranded paper, *i.e.*, devaluations on the asset side of financial companies' balance sheets (Curtin et al. 2019). Reciprocally, expectations of paper stranding might worsen capital or resource stranding if the financial sector disengages too quickly from concerned activities (TCFD 2017).

Part of, if not all, the value of stranded assets would be written off the books of their owners, with possible adverse consequences on financial markets (van der Ploeg 2020). Financial disturbances could emerge because future transition developments are uncertain, notably regarding the climate policy stance and future technological progress (van der Ploeg and Rezai 2020a). Once uncertainty is resolved, *i.e.* when the transition starts (or is credibly announced), agents realize that past and current high-carbon investments may fall short of expected returns (van der Ploeg and Rezai 2020a). Hence possibly sharp asset devaluations, all the more severe if climate policies are stringent (Rozenberg, Vogt-Schilb, and Hallegatte 2020), if the transition is rapid with respect to capital depreciation (Edenhofer et al. 2020; A. Jackson 2018; Mercure, Salas, et al. 2021) or if reallocation costs are high (Baldwin, Cai, and Kuralbayeva 2020).

The literature has tightly linked asset stranding to premature⁴ decommissioning (Caldecott, Kruitwagen, et al. 2016; Lin et al. 2020; Mercure, Salas, et al. 2021; Rautner, Tomlinson, and Hoare 2016; Reddy and Anbumozhi 2017), asset under-

⁴Defined with respect to economic lifetime.

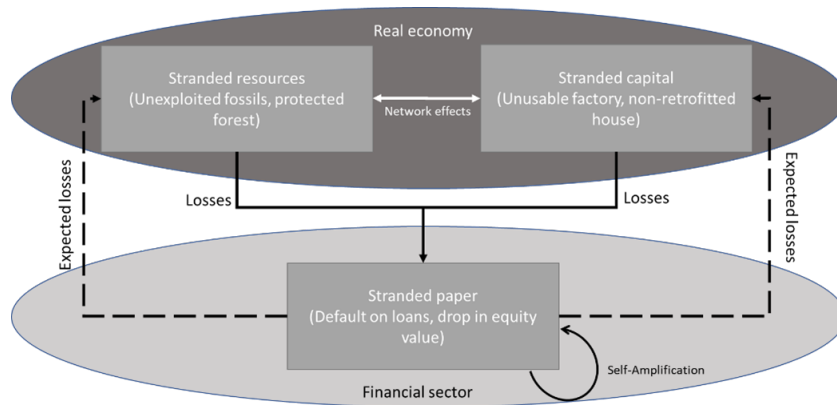


Figure 1: Categorisation of stranded assets and interactions.

utilisation (Caldecott 2017; Mercure, Salas, et al. 2021; Rozenberg, Vogt-Schilb, and Hallegatte 2020) or active disinvestment (Campiglio, Daumas, et al. 2023). Premature decommissioning, capital underutilisation or active disinvestment need not give rise to financial disturbances or sharp asset devaluations if they are provisioned for (van der Ploeg and Rezai 2020b). However, they are indicators for potential asset stranding (see Section 2).

Based on these definitions, the literature has identified causality channels through which financial transition risks and stranded assets may affect financial stability.

1.2 Theoretical mechanisms

The impact of transition risks on financial instability will depend on the extent of the expectation realignment when the transition kicks in. “Disorderly transitions” (van der Ploeg and Rezai 2020a), whereby sweeping adjustments are likely to occur, have been the main focus of the literature.⁵

1.2.1 Transition drivers and financial risks

Semieniuk, Campiglio, et al. (2021) identify three transition risk drivers: climate policy, technological change and changes in consumer preferences.

⁵A smaller strand of the literature has studied the impact of “orderly” transition pathways on portfolio values in which policies are expected and introduced early (Mercer 2015).

Like research on asset stranding, the broader transition risk literature has focused on time-inconsistent (Kalkuhl, Steckel, and Edenhofer 2020), non-credible (Bretschger and Soretz 2021; van der Ploeg and Rezai 2020b) or unanticipated policies (Rozenberg, Vogt-Schilb, and Hallegatte 2020). Such ill-designed policies would lead to a sudden change in the policy stance, which may lead to a brisk reassessment of prospects and sweeping adjustments in financial markets (Batten, Sowerbutts, and Tanaka 2016). Some works have studied the effects of rapid technological penetration (T. Jackson and Victor 2020). If disruptive enough, it could lead to sizeable losses for high-carbon businesses (Mercure, Pollitt, N. R. Edwards, et al. 2018). Shifts in consumer preferences have comparatively been underexplored (Basel Committee 2021b; Caldecott, A. Clark, et al. 2021).

Beyond these elements, the precise identification of transmission channels for transition risks poses daunting theoretical challenges (Semieniuk, Campiglio, et al. 2021). The issue of asset stranding has led the literature to focus on “sunset industries” meant to disappear as the economy decarbonises. This focus stands at odds with existing theories and empirics on financial stability that have underscored the role of ascending dynamics, exhilaration, and speculation in fostering financial crises (Minsky 1986; Nikolaidi 2017; Perez 2002; Wolfson 1990). It calls for a careful inventory of possible transmission channels.

1.2.2 Transmission channels

1.2.2.1 From drivers to financial risks A first distinction is between flow and stock effects (Campiglio and Ploeg 2021).

Flow effects will harm companies’ income statements (profitability) and cash flow statements (liquidity) through reduced proceeds, higher costs, or lower access to funding (A. Jackson 2018; TCFD 2017). It will diminish firms’ ability to meet financial commitments and increase their default propensity. Second, lower expected profitability may increase refinancing costs (Basel Committee 2021b), hamper access to credit and market funding and force firms to rely on shorter-term, more unstable

funding (Ivanov, Kruttli, and Watugala 2020). Reputational issues and the stigmatization of some sectors can also prove harmful (TCFD 2017). Regarding households, lower incomes due to carbon taxes or costlier energy may reduce their ability to pay back loans, notably mortgages, whose interactions with financial instability are well-known (Jordà, Schularick, and A. Taylor 2015; Schularick and A. M. Taylor 2012). These channels are summarised in Table 1.

These flow effects may transfer to financial institutions at the microeconomic level (Basel Committee 2021b; Bolton, Després, et al. 2020; Wilkins 2018) through usual financial risk channels summarised in Table 2.

Market risks refer to asset depreciation in financial markets that may lead to balance sheet losses. Credit risks imply higher default probability, which is problematic if leverage is high or cash flows are weak (Cathcart et al. 2020). Liquidity risks describe the reduced ability to exchange assets and to get refinanced in the short run. Insurance risks relate to the possible under-pricing of derivatives. Wilkins (2018) extends the list to two other kinds of risks. Reputational risks are signal effects that may lead partners or customers not to renew their contracts (Karwowski and Raulinajtys-Grzybek 2021). Litigation risks tackle the exposure of agents to legal actions due to failures to achieve climate goals or respect environmental norms (Barker, Dellios, and Mulholland 2021; Owens 2021).

Stock shocks affect balance sheets, possibly down to technical bankruptcy if the shock is too strong (Semieniuk, Campiglio, et al. 2021). For households, the low-carbon transition may devalue housing assets (Muldoon-Smith and Greenhalgh 2019). Such devaluations could eventually affect financial agents through collateralization (Basel Committee 2021a; Comerford and Spiganti 2022; Alogoskoufis et al. 2021).

Stock and flow effects are not isolated. Reduced cash flows have valuation effects. Because the value of an asset is the discounted sum of expected cash flow, lower income than expected will result in its depreciation, as would be the case for stranded assets (Botte et al. 2021). Similarly, worse financials after a balance sheet hits and stranded assets may increase risk premia on debt and equity, making refinancing

Table 1: Transition risks and potential impacts on non-financial agents

Transition risk	Description	Flow effect	Stock effect
Market Conditions	Degradation of market conditions	Reduced demand and revenues Higher production costs (energy, inputs)	Repricing of assets Asset stranding
Technological change	Emergence of competing, low-carbon technologies	Higher expenses for changing production technology (R&D, investment)	Asset stranding
Policy Regulation	Introduction of carbon tax Phase-in of regulation	Changes in production costs Lower demand due to tighter regulation	Asset stranding
Reputation	Stigmatisation Divestment Change in consumer preferences	Reduced revenues	Reduced capital availability

Adapted from Bolton, Després, et al. (2020) and Basel Committee (2021b).

more difficult (TCFD 2017). Recent theoretical inquiries through Dynamic Stochastic General Equilibrium (DSGE) models⁶ have confirmed the importance of financial frictions and balance sheet constraints in generating instability along transition pathways⁷ (Carattini, Heutel, and Melkadze 2021; Diluio et al. 2021; van den Bijgaart and Smulders 2018).

Drivers can also influence financial institutions through macroeconomic channels (Basel Committee 2021a; Semieniuk, Campiglio, et al. 2021). The transition to a low-carbon economy carries GDP costs (NGFS 2020a), unemployment and possibly current account imbalances (Semieniuk, Campiglio, et al. 2021; Valdecantos 2021), which may increase financial fragility. Resource-dependent Global South countries would be sensitive to such shocks (Bos and Gupta 2019; Magacho et al. 2021). Drivers will thus affect countries and regions according to their fundamentals (Basel Committee 2021a).

Finally, transition risks may trigger macroeconomic policy responses, with possible adverse effects (Diluio et al. 2021; Vermeulen et al. 2021), for instance if central banks increase base rates to thwart transition-induced inflation.

Because of lower energy returns on investment (Capellán-Pérez, Castro, and Zamora-

⁶See Annicchiarico et al. (2021) for a review.

⁷Note, however, that because these models are focused on short-term macroeconomic developments, their insights would mostly be relevant for the direct aftermaths of climate policy introduction.

Table 2: Typology of financial transition risks

Financial risk	Transition-risk example
Market risk	Decrease in fossil company share prices
Credit risk	Increase in default probability of carbon-intensive firms
Liquidity risk	
Position	Increased risk premium on short-term debt to carbon-intensive firms
Market	Strong decrease in demand for securities from carbon-intensive firms
Insurance risk	Important obligations on high-carbon firm derivatives, or transition-sensitive commodities (fossil fuels)
Reputation risk	A fund known for its high-carbon investment or having greenwashed high-carbon commitment may find difficulties to get financed
Litigation risk	A financial firm not complying or defrauding on disclosure

Adapted from Bolton, Després, et al. (2020) and Basel Committee (2021b).

Verdejo 2021; Delannoy et al. 2021) and the penetration of more intermittent energy sources (Hall, J. G. Lambert, and Balogh 2014), the low-carbon transition may entail higher energy prices. Small open economies may be particularly sensitive to such “greenflation” whereby the low-carbon transition significantly increases energy costs in the short run (Airaudo, Pappa, and Seoane 2022), and even possibly in the long run (P. Jacques et al. 2023). Sers and Victor (2018) and A. Jackson and T. Jackson (2021) highlighted the macroeconomic risks associated with higher energy costs, which is also a usual precursor of financial crises (Hamilton 2009; Hamilton 2013).

The impact of the low-carbon transition on government finance (Semieniuk, Campiglio, et al. 2021) could also entail transition risks (Basel Committee 2021b) because of the reliance on government bonds as risk-free and liquid assets and their role in repo operations (Gabor 2020). Countries where public companies exploit large reserves⁸ (Heede and Oreskes 2016) may face increased sovereign risks. Nation-states also often hold significant stakes in energy utilities, especially in developing countries (Huxham, Anwar, and Nelson 2019). Higher sovereign risk finally increases the probability of capital reversals, sudden stops and exchange rate crises (Conte and

⁸Although, as noted by Leaton (2015), private companies own the highest-cost reserves. It suggests that reserves held by Nation-states would be exploited for longer but would have to close shop all the same. A caveat is that some of these companies may hold highly polluting oil fields that would need to be closed early to increase chances of meeting mitigation targets (Coulomb, Henriot, and Reitzmann 2021).

Meglioli 2021; Gomez-Gonzalez, Valencia, and Sánchez 2021), which can ripple to other jurisdictions (Magacho et al. 2021).

1.2.2.2 Amplifiers and mitigators The literature has further identified amplifying factors that may worsen the effect of the low-carbon transition on financial stability (Basel Committee 2021a).

Contagion effects in production networks could harm NFCs or financial companies (FCs) not initially exposed to transition risks (Cahen-Fourot, Campiglio, Godin, et al. 2021). In financial markets, amplifiers relate to systemic risk sources (Benoît et al. 2017). First, financial institutions can collectively exhibit reckless risk-taking attitudes. They can adopt correlated investment behaviours, exposing them to the same kind of risky assets. Hence, a single failure can have far-reaching effects, especially if these assets are illiquid or subject to high tail risks. Similarly, banks can increase their risk exposure along the evolution of the value of assets used as collateral (Kiyotaki and Moore 1997) or because of over-optimistic beliefs (Minsky 1986). Second, contagion can occur through financial networks (Battiston, Mandel, et al. 2017), through interactions across institutional sectors (Stolbova, Monasterolo, and Battiston 2018) or if counterparty risks are not provisioned for (Brunnermeier 2009). Finally, liquidity crises, for example, in the form of bank runs or fire sales, can amplify seemingly small initial shocks (possibly from a certain threshold), sometimes down to a complete market freeze (Guttman 2016). A brisk and uncoordinated withdrawal of funds from creditors can worsen the effect of a small shock on a debtor (Benoît et al. 2017). Financial risks category can also interact, for example, for asset classes whose liquidity depends on counterparties' creditworthiness, like bonds (Basel Committee 2021a).

Further, physical risks can amplify transition risks, like in the event of a sudden policy reaction to an adverse climate event entailing sharp adjustments (Monasterolo 2020b). Transboundary transition risks through which transition shocks in some countries may ripple off to foreign financial systems are further amplification factors

(Volz et al. 2021).

Finally, some have pointed out the risk associated with the reorganization of the financial system around seemingly smooth transition paths (Dafermos, Monserand, and Nikolaidi 2022; Degryse, Roukny, and Tielens 2022). Financial institutions may transfer risks to less solid agents in the Global South (Bos and Gupta 2019). Similarly, financial agents' withdrawals from high-carbon firms could weaken the latter (Ivanov, Kruttli, and Watugala 2020; TCFD 2017).

Mitigators can temper transition risks. Financial markets can absorb shocks if they are deep enough and offer insurance facilities (Basel Committee 2021a). They are also more resilient if volatility is low (Roncoroni et al. 2021) or if portfolios are diversified enough (Semieniuk, Campiglio, et al. 2021).

How agents will seize hedging or reconversion opportunities will also be key (TCFD 2017). It will depend on how adaptable or convertible some businesses may be, both technically and financially. The main factor will be the state of agents' expectations, which will determine business reconversion and hedging behaviours. Finally, investors' preferences for green assets ("green sentiments") may be an enabler of the low-carbon transition and transition risk hedging (Battiston, Monasterolo, Riahi, et al. 2020; Dunz, Naqvi, and Monasterolo 2021). Figure 2 provides a summary of the causality channels reviewed above.

1.3 Overview of the literature and paper selection

The literature in this study is structured around three main strands, each dealing with a subset of issues linked to transition risks (see Figure 3).

Studies have shown how transition risks could affect NFCs by quantifying potential financial losses due to asset stranding. However, their consequences on financial instability are not well-examined, except in a few studies.

Works adopting a finance-oriented view bridge this gap. Yet, these quantitative exercises remain focused on large and disruptive transition shocks and only partly

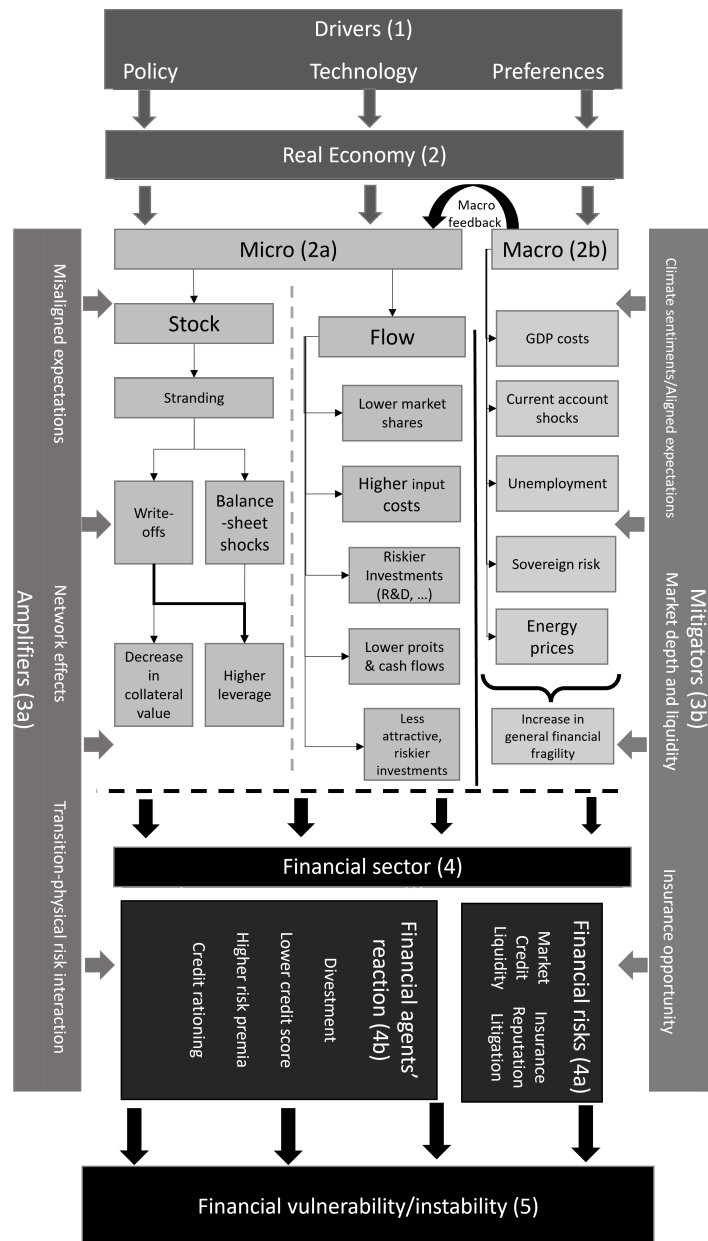


Figure 2: Summary of causality channels for low-carbon transition risks. Reading: Transition drivers (1) affect the real economy through microeconomic (2a) and macroeconomic (2b) channels. Both interact and are influenced by amplifiers (3a) and mitigating influences (3b). Micro- and macroeconomic channels as well as amplifiers and mitigating influences affect the financial sector (4), both through financial risks (4a) and the reaction of financial agents (4b). Both create vulnerability and/or instability potentials (5).

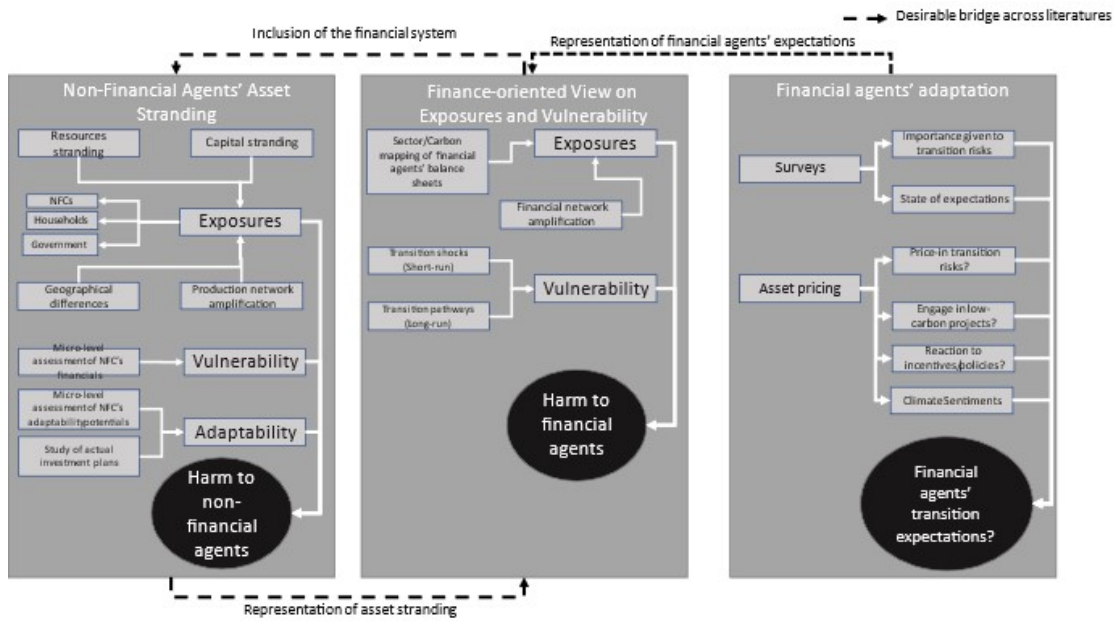


Figure 3: Structuration of the literature. Dashed arrows show desirable connections across literature strands.

represent the dynamic relations between the low-carbon transition and the financial sector.

A sound representation of the reaction of the financial sector to the transition requires checking whether financial markets account for future transition risks. Various methods have been mobilised to measure past and current financial agents' reactions to transition risks and provide hints of the current state of expectations on financial markets regarding transition risks. Insights from these three branches shed light on complementary aspects of the transition, but their results are difficult to compare. To bridge this gap, this review proposes a four-tiered grid of analysis borrowing from Cardona et al. (2012) :

- What kind of hazard can affect companies, which directly relates to the three types of transition risks (regulatory, technological, and demand-driven) mentioned above and to the kind of financial risk it can give rise to.
- How exposed agents are: how their market, regulatory and technological envi-

ronment can represent a source of shocks.

- How vulnerable they could be, that is, how much they could suffer from a given shock, which depends on the company's financial health, how carbon-intensive it is, the diversity of its supply source, etc (TCFD 2017)
- How resilient/adaptable they will be. Companies can diminish hazards, exposures and vulnerability by reorienting their businesses or reshuffling their portfolios (Nicol et al. 2017).

Which of these dimensions the three strands of literature explore is not always clear. Yet, identifying all four components is instrumental for the study of financial instability potential. Second, I will study how geographical, time, and other structural variations affect results. Finally, I will explore the merits of each literature in assessing potential systemic risks.

2 Transition risks from non-financial agents' physical and resource stranding

This section first reviews quantifications of stranded assets along transition paths at various geographical levels to provide a quantitative assessment of non-financial agents' vulnerability to transition risks. I then discuss mitigators and amplifiers to asset stranding, notably the pace of the transition and the role of network effects. I close by discussing the lack of connections between asset stranding estimates and financial instability discussions.

2.1 Stranded asset exposures: which sectors are concerned?

Initially, the stranded asset literature focused on fossil resources (Leaton 2011). The literature expanded to fossil-fuelled utilities (Caldecott, Kruitwagen, et al. 2016) and downstream fossil capital (Leaton, A. Grant, et al. 2015). Agricultural lands (Caldecott, Howarth, and McSharry 2013) and forestry (Rautner, Tomlinson, and

Hoare 2016) could also be stranded. Stranding in some sectors could also prompt asset stranding in upstream or downstream sectors due to production network effects (Cahen-Fourot, Campiglio, Godin, et al. 2021).

Mercure, Chester, et al. (2021) consider that all industries will decarbonise and suffer from stranding. Residential housing may also be stranded and affect households (Muldoon-Smith and Greenhalgh 2019).⁹ However, the core of the literature has focused on fossil fuel and power assets.

2.2 Measuring stranded assets

Most studies have relied on model-based forward-looking approaches comparing a baseline projection (business-as-usual or unambitious policies) to a policy scenario (Mercure, Pollitt, N. R. Edwards, et al. 2018). Estimates are measures of the vulnerability of a sector's capital stock to stranding for a given projection.¹⁰ Because these studies typically rely on large-scale models, what kind of hazard they study is uncertain since climate policies, technological displacement and demand shifts are modeled altogether.

2.2.1 Non-Monetary estimates

Early studies quantified “unburnable” carbon (Leaton 2011; McGlade and Ekins 2015) related to the “carbon bubble” hypothesis. Fisch-Romito et al. (2021) summarise the existing literature, stressing the variety of metrics: prematurely decommissioned capacity Binsted et al. (2020), unextracted fossil fuel quantities (Leaton 2011; McGlade and Ekins 2015), committed emissions embodied in existing fixed assets (Pfeiffer et al. 2016), underutilisation, or the age of the capital stock (Mo, Cui, and H. Duan 2021). Some studies are static and measure a year-to-year stranding potential based on a given target (Pfeiffer et al. 2016; Farfan and Breyer 2017). Because

⁹Households could also be touched through human capital (Mercure, Chester, et al. 2021). However, given the uncertainties around the estimation of human capital, I will focus on physical assets in what follows.

¹⁰Most of the literature has focused on non-financial companies (NFCS), with a handful of works tackling stranded assets for households (Muldoon-Smith and Greenhalgh 2019; Saygin et al. 2019) or States (Heede and Oreskes 2016; Jaffe 2020).

it has remained focused on quantities, this literature is silent on how stranded assets can affect finance (an exception is Leaton (2011)). In particular, it rarely discusses what shape stranding costs would take or how the valuation of those assets would change (Helm 2015). Hence the need for monetary estimates.

2.3 Monetary estimates

Most exercises provide monetary estimates at the world level with two main metrics.

- Book loss captures the economic value of existing fixed high-carbon assets to be decommissioned or left underground before the end of their expected economic lifetime to respect a carbon budget (N. Johnson et al. 2015). It explicitly measures the burden of past irreversible investments (Fisch-Romito et al. 2021).¹¹
- Foregone streams¹² designates the ongoing loss of financial inflows that transition-exposed companies will have to incur in the event of the low-carbon transition. Under the hypothesis that the value of fixed assets is the discounted sum of future profits (or other income streams, like rent or revenue), this metric is a proxy for balance sheet losses (Mercure, Pollitt, N. R. Edwards, et al. 2018).

I report estimates in Tables A.1 and A.2 in Appendix.¹³ To provide orders of magnitude, I follow Mercure, Pollitt, N. R. Edwards, et al. (2018) and relate estimates to the initial \$US250 billion shock on financial value during the subprime crisis. For better comparability, wherever possible, results are displayed undiscounted.

Across metrics, the financial costs can be a multiple and sometimes a power of the GFC's initial loss. Regarding stranded resources, oil bears the highest losses because

¹¹Mercure, Chester, et al. (2021) refine it with a Stranded Value-at-risk metric by weighting book value loss estimates by the distance to natural retirement age. It allows them to avoid overestimating stranding by setting aside assets close to their retirement age.

¹²“Stream” here refers to any monetary inflow: revenue, income, profit, or rent. Which measure is used in what study is detailed in Tables A.2 and A.4.

¹³For readability purposes, all tables are in Appendix. Coverage is meant to be as exhaustive as possible, based on queries on Google Scholar, Scopus and Web of Science.

of its higher extraction costs—although it represents a lesser share of future abatement efforts (T. A. Hansen 2022; Nelson, Hervé-Mignucci, Goggins, Szambelman, et al. 2014). Variations depend first on sectoral scope: the more sectors accounted for, the higher the estimate. They also depend on scenario hypotheses. Delayed action (Saygin et al. 2019), continued fossil investment (Mercure, Chester, et al. 2021), and more climate-ambitious¹⁴ scenarios (N. Johnson et al. 2015; Kefford et al. 2018) yield higher stranding. By contrast, scenarios with more negative emission technology availability (McGlade and Ekins 2015; Pradhan et al. 2021) or lesser political constraints (Löffler et al. 2019) exhibit lower stranding.

For stranded resources, price trajectory hypotheses are key. Low fossil fuel prices—which can also denote lower demand—decrease the viability of high-cost extraction sites (Leaton, A. Grant, et al. 2015; Mercure, Pollitt, N. R. Edwards, et al. 2018). Hence, assuming low prices over the transition entails more stranding. For other sectors, assumptions about the technical lifetime of existing assets affect results. Assuming quicker depreciation yields less stranding (IRENA 2020b; Zacarias and Grubert 2021). Finally, assumptions about the agents' farsightedness are crucial. For the same scenario and model, shorter foresight tends to increase stranding because firms invest more in high-carbon projects in the short run (Löffler et al. 2019). Yet, perfect-foresight models can also reach high estimates if scenarios are stringent (Saygin et al. 2019).

2.3.1 Geographical distribution and developing countries' exposures

However, due to their economic specialization and level of development, countries and regions will be variably exposed to asset stranding (Ansari and Holz 2020). It calls for more geographical disaggregation.

Tables A.3 and A.4 report country or regional estimates. Europe will likely not incur significant power and resource asset stranding due to its increasing reliance on alternative energy sources and lack of fossil fuels (Mercure, Pollitt, N. R. Edwards,

¹⁴This notably implies higher carbon prices putting many fixed assets below their cutoff profitability point (Leaton, A. Grant, et al. 2015).

et al. 2018). Yet, some specific countries, like Germany, may be more exposed than others due to their reliance on coal (Breitenstein et al. 2022; Sen and Schickfus 2020). Regarding extraction, the United States, Canada, Russia and OPEC countries are most sensitive (Mercure, Pollitt, N. R. Edwards, et al. 2018). Latin America is also exposed (Binsted et al. 2020), especially extractive countries like Venezuela (Spavieri 2019) and Mexico (Tornel, Gutiérrez, and Villarreal 2019). In Africa, some countries exhibit exposure to resource stranding (Denton 2019; Huxham, Anwar, and Nelson 2019). China and India are the most exposed to power asset stranding due to their higher reliance on coal and gas (N. Johnson et al. 2015; Kefford et al. 2018; Spencer, Berghmans, and Sartor 2017; W. Zhang et al. 2021), the relative youth of their capital stock (Fisch-Romito et al. 2021) and overcapacity (Lin et al. 2020). Yet, against GDP, stranding in China is small (Lin et al. 2020).

Finally, developing and emerging countries feature high government shareholding (Nelson, Hervé-Mignucci, Goggins, Szambelman, et al. 2014; Spencer, Berghmans, and Sartor 2017) and foreign dependence (Colenbrander et al. 2023; Manych, Steckel, and Jakob 2021) in transition-exposed sectors. Hence, asset stranding in these countries will likely be relevant for sovereign risks (Jaffe 2020) and current account imbalances (Volz et al. 2021).

2.3.2 Time distribution and stranding pace

These losses are computed over the 30–50 years of the transition (van der Ploeg and Rezai 2020b). However, the pace of asset stranding along transition paths is undetermined, as most studies only display cumulative losses. An exception is T. A. Hansen and Pollin (2020), who shows that most stranding is likely to occur in the 2020–2030 decade. The pace and timing of book value losses also depend on the implementation of climate policies and the technology considered (Saygin et al. 2019). I provide a time distribution approximation by taking the average of undiscounted losses over the term of the analysis and supposing that NFCs incur the same losses each year. Results appear in column (9) of Tables A.1 and A.3. Several studies

still exhibit potential yearly losses above the GFC threshold or representing sizeable portions of countries' GDPs.

2.4 Amplifiers and mitigators

However big, the estimates above are outcomes of models that may fall short of critical economic effects, like the amplifying role of production networks (Baqae and Farhi 2019). This subsection discusses how the estimates above could be reduced or increased due to mitigating influences or amplifiers and examine current trends in this respect.

2.4.1 Amplifiers in production networks

Studies have proposed an approach based on input-output representations of the economy, possibly including cross-border interdependencies (Cahen-Fourot, Campiglio, Godin, et al. 2021; Godin and Hadji-Lazaro 2022), depicting industrial structures as a network (Campiglio, Godin, et al. 2017).

This method quantifies how upstream or downstream activities are affected by a drop in input demand or supply from a distressed sector. It is relevant for transition-exposed sectors like mining and quarrying, which have sizeable forward linkages¹⁵ (Cahen-Fourot, Campiglio, Dawkins, et al. 2020). Stranding is quantified as capital underutilisation (Cahen-Fourot, Campiglio, Dawkins, et al. 2019; Cahen-Fourot, Campiglio, Godin, et al. 2021). This metric yields how much capital is left fallow in case of lower input availability or lower demand from another sector. It is expressed as changes in sectoral capital-output ratios. It measures the sensitivity of whole production structures to shocks to up- and downstream sectors in the short run. Godin and Hadji-Lazaro (2022) express results in foregone income per unit of non-utilized capital.

¹⁵Based on Hirschman (1958) a sector has important forward linkages when a significant amount of its output is employed by other sectors as intermediate inputs.

Results for individual countries depend on their industrial structures and integration within global value chains. Network effects can multiply initial shocks several times. Losses can propagate to surprising sectors like public administration, defence, and trade services. Immediate exposure for a given sector underestimates its total transition risk exposure due to feedback loops (Sanderson and Stridsland 2022).

2.4.2 Adaptive capacity and value creation

On the other hand, mitigators can reduce the amount of asset stranding.

2.4.2.1 Adaptive capacity First, firms could compensate for losses by adapting to the low-carbon transition (Kondrup et al. 2022). Yet, while long-run studies explored above include elements of adaptation like CDR technology installation or retrofitting (Löffler et al. 2019; Saygin et al. 2019), the subject is understudied within the asset stranding literature.

The field tends to over-emphasise losses at the expense of opportunities (Monasterolo 2020a). Asset stranding is rarely compared to possible gains in transition-relevant sectors, including energy (Linnenluecke, Han, et al. 2019). The literature has also developed in isolation from corporate discussions on adaptability (Linnenluecke and Griffiths 2013; Shimbar 2021; Venturini 2021). Finally, some studies are confined to the analysis of short-term shocks, while long-run technological evolutions could alleviate transition risks (Cahen-Fourot, Campiglio, Dawkins, et al. 2019; Cahen-Fourot, Campiglio, Dawkins, et al. 2020).

Private agents or NGOs have developed quantitative approaches to adaptive capacity (Bingler, Colesanti Senni, and Monnin 2020; Bingler and Colesanti Senni 2022; Carlin, Lonfat, and R. Fischer 2021). Thomä and Dupré (2014) proposed a discussion linking adaptability to external factors, such as scale and speed of change or the novelty of new technologies and internal factors, like firms' strategic vision, governance practices or product diversity. Academic results show that actual reconversion plans in oil majors are still missing (Cormack et al. 2020; Dietz, D. Gardiner, et al. 2021;

Radovic, Kruitwagen, and Witt 2020),¹⁶ hence possible losses for these firms (Chevalier et al. 2021).¹⁷ Finally, an emerging literature has explored the possible financial constraints to adaptation that firms may encounter (Cohen, Gurun, and Q. H. Nguyen 2022; Dafermos 2021) as the financial system hedges its exposures to transition risks (Martin, Schmitt, and Westerhoff 2021). Ivanov, Kruttli, and Watugala (2020) show that transition-exposed firms are more financially constrained. Kacperczyk and Peydro (2021) demonstrate that banks committed to decarbonisation cut lending to brown firms, with no effect on their environmental performances and with possible perverse effects in furthering greenwashing (see also Degryse, Roukny, and Tielens (2022) and Shu, Tan, and Wei (2023)). Finally, Q. Xu and T. Kim (2021) show that financially constrained firms trade abatement costs against potential liabilities, suggesting that withdrawal of the financial sector could exacerbate vulnerabilities to transition risks.

2.4.2.2 Actual adaptation from current investment plans However, despite room for mitigators, many studies have documented gaps between the requirements of the low-carbon transition and some firms' investment plans, notably in the fossil fuel sector, referenced in Table A.5. These studies suggest that, despite progress (IEA 2020b; van Benthem et al. 2022), investment plans in the fossil sector remain strongly misaligned with climate targets beyond NDCs (M. R. Edwards et al. 2022; J. Grant and Coffin 2020). For coal power assets, fast-growing Asian countries concentrate most risks (M. R. Edwards et al. 2022). Firms thus engage in "Unneeded CAPEX": useless high-carbon projects given climate targets. Crucially, because they are pipelined projects, these "Unneeded CAPEX" will represent "certain transition losses" (Leaton 2015; Leaton, A. Grant, et al. 2015) and will be relevant for financial instability.

¹⁶Note, however, that adaptation may involve important costs which may endanger the financial viability of companies or be too dear to be carried out (TCFD 2017). Asset stranding can also be measured by reconversion costs (Binsted et al. 2020; Hambel, Kraft, and van der Ploeg 2020) to highlight that assets may become un- or less profitable if they must be retrofitted to abide by climate regulation. Costly CCS retrofitting would be a case in point.

¹⁷Some studies have explored decarbonisation potentials in industries other than the power sector, like steel (Fennell, Davis, and Mohammed 2021).

2.5 From asset stranding to financial instability: A missing link?

The review of the stranded asset literature showed that the legacy of high-carbon assets could entail impressive value losses. However, although studies mention a financial crisis as a possible consequence (Curtin et al. 2019). The literature has yet to link asset stranding to financial instability.

2.5.1 Metrics and theoretical mechanisms

The presentation above illustrated the many measures of asset stranding. The notion can thus refer to different theoretical mechanisms related to financial instability.

- **Book value losses** and **Unneeded CAPEX** are stock effects. Both refer to unrecouped investment expenses in the long and short run, respectively. If not provisioned for, these losses can entail defaults on loans. They can also imply asset write-offs, increasing financial fragility through higher leverage (Cathcart et al. 2020; ECB 2021).
- **Foregone income** is a flow measure. Thus, figures are value corrections that would occur today if all agents aligned their expectations together on a transition path. It is a high bound on financial losses incurred today. It does not tell how these losses will affect financial stability over time.
- **Underutilisation** refers to stock and flow by relating a drop in output to the amount of capital. It measures the effect of shock on the economy in the short run. It may lead to lower profits with forward-looking effects on asset value. It also gives a measure of the capital to be relinquished or refurbished to return to a “normal” utilisation rate.

To relate asset stranding more systematically to financial instability, more precision in the use of the notion is required. The literature explores different types of stranded assets relevant to various horizons of analysis and economic phenomena and with distinct relationships to financial instability.

2.5.2 Link with financial instability

Further, only a few papers (Caldecott, Howarth, and McSharry 2013; Godin and Hadji-Lazaro 2022) discuss the channels that could link asset decommissions, impairments, or underutilisation to firms' financials and affect the financial sector. None of the modelling studies features the financial sector in their framework. Hence, this literature quantifies financial companies' exposures to NFCs' stranding but not vulnerabilities.

Nonetheless, some papers have intended to draw a more systematic link between asset stranding and financial instability. Leaton (2011) already provided a rough approximation of financial losses linked to unburnable carbon and discussed how relinquished reserves could affect company valuations. Godin and Hadji-Lazaro (2022) consider sectoral balance sheet data to measure the effects of stranding cascades on financials (see also Várgedo (2022)). Nelson, Hervé-Mignucci, Goggins, Szambelman, et al. (2014) and Spencer, Berghmans, and Sartor (2017) map the debt and equity exposures related to asset stranding and measure associated risks for investors. Caldecott, Kruitwagen, et al. (2016) adopt a similar method by providing project-level financial data. Huxham, Anwar, and Nelson (2019) discuss how agents could shift transition risks on each other. An emerging literature is mapping the funding or ownership of new fossil infrastructure by particular financial institutions to assess exposures to future unneeded CAPEX (Leaton 2015; Leaton 2015; Ganswindt et al. 2021; Manych, Steckel, and Jakob 2021). Finally, Semieniuk, Holden, et al. (2022) explore the ripple effect of asset stranding in the fossil fuel sector through ownership networks. It could entail up to US\$2.5 trillion loss in financial wealth, with the financial sector alone bearing a US\$1 trillion loss.

These studies, however, remain scarce within the literature, with a need to add the financial sector to the reflection more systematically. The literature concerned with exposure and vulnerability from a financial standpoint has carried out this task.

3 Finance-oriented approaches to transition risks and stranded paper

In this section, I review studies on finance-oriented approaches to transition risks. They complement the insights provided by the stranded asset literature by directly linking transition risks in the real economy to financial instability potentials. I start by reviewing exposures to transition risks. Then, I study how the literature has quantified vulnerabilities through short-run stress tests and long-run scenario-based methods.

Table 3: Emission Scopes

Scope	Description	Example
Scope 1	Direct emissions linked to production process	Combustion
Scope 2	Indirect emissions embodied in energy use	Heat, cold, electricity, steam Natural resource purchases
Scope 3	Other indirect emissions	Travel and transport emissions Life cycle of goods (<i>e.g.</i> , cars)

3.1 Mapping financial agents' exposures

Quantifying exposure requires measuring how much value in financial companies' balance sheets concerns transition-exposed counterparties (Bateson and Saccardi 2020), typically as the amount or share of assets on financial companies' (FCs) balance sheets financing transition-exposed activities. Recent works have included non-financial sectors (Monasterolo, Battiston, et al. 2017; Stolbova, Monasterolo, and Battiston 2018). However, choosing which transition activities to include as exposures poses methodological issues.

3.1.1 Choosing relevant sectors and firms

Existing sectoral nomenclatures are ill-suited to determine which sectors or firms are subject to transition risks (Monasterolo 2020a). Although some activities, like fossil

fuel extractions, can be directly considered relevant for transition risks (Baer 2021), sectoral categories can gather subsectors with high emission heterogeneity (Battiston, Mandel, et al. 2017). Firms within a sub-sector can also exhibit very different emission intensities (ECB 2021). Finally, differences exist across nations for similar sectors and activities (Jacquetin 2021). Hence, there is a need for granularity, with emissions computed at the firm scale. Yet, attributing emissions to a company is complex because not all its emissions come from its production process (EPA 2020). Emissions are split into three “scopes,” corresponding to as many business steps. Table 3 summarises the meaning and reach of each. Scope 1 (production) and 2 (energy) emissions are well-mapped (EPA 2020). Yet, calculating Scope 3 (indirect) emissions often considered the most critical indicator of transition risk exposure (Ducoulombier 2021), is more challenging (Erhard et al. 2019). Also, given the long time horizon of the transition, emissions today are not necessarily representative of future emissions (Carbone4 2018). Therefore, there is a need to account for corporate decarbonisation plans (Clerc, Bontemps-Chanel, et al. 2021) and to complement pure emission measures with other indicators (Bingler, Colesanti Senni, and Monnin 2020). Thus, criteria for transition-exposed sectors can vary significantly across studies. Early works tackled “obvious” sectors, like fossils and energy utility (Weyzig et al. 2014). Granular decompositions of usual industry classifications have encompassed more sectors (Battiston, Mandel, et al. 2017),¹⁸ followed by sophisticated metrics based on input-output analysis (Clerc, Diot, et al. 2020; Vermeulen et al. 2021). Recent stress-test exercises rank firms within a given sector based on their emissions (Alogoskoufis et al. 2021). All in all, the literature finds the following sectors are the most exposed to transition risks (Clerc, Diot, et al. 2020; Battiston, Mandel, et al. 2017; Bellrose, Norman, and Royters 2021; Alogoskoufis et al. 2021):¹⁹

- Extractive sectors (fuels and minerals);
- High-carbon energy utilities;

¹⁸See Battiston, Monasterolo, van Ruijven, et al. (2022) for a methodological discussion.

¹⁹Following Battiston, Mandel, et al. (2017), they will be labelled “Climate Policy Relevant Sectors”, CPRS here, wherever relevant.

- Energy-intensive industrial sectors (steel, cement, petrochemicals);
- Agriculture;
- Building and construction;
- Transportation.

Identifying sensitive sectors has allowed studies to quantify the exposure of financial institutions (Table B.1). Again, wherever possible, we compare losses to the \$US250 billion shock of the subprime crisis.

3.1.2 Quantitative estimates

Early studies highlighted some country heterogeneity. The United Kingdom²⁰ (PRA 2015), the United States (Bateson and Saccardi 2020), Italy (Faiella and Lavecchia 2022), and some Latin American countries (Ramírez, Thomä, and Cebreros 2020) seem particularly exposed to devaluations in the fossil and high-carbon utility sectors compared to other areas, like Australia (Bellrose, Norman, and Royters 2021). Alogoskoufis et al. (2021) found similar heterogeneity in Europe, but only for exposure to the highest emitters, with Italy, France, and Germany being particularly exposed. Some jurisdictions are also more exposed to particular asset classes due to the structure of their financial system. The United States and the United Kingdom rely more on market finance (Levine 2002). Hence, potential losses on equities provide reliable estimates of the sector's exposures (Bateson and Saccardi 2020). By contrast, continental Europe relies more on bank loans (Battiston, Mandel, et al. 2017; Baer 2021).

Within jurisdictions, there are sizeable discrepancies across individual financial institutions, with several systemic players concentrating exposures (Giraud et al. 2021), reducing the resilience of the whole financial sector (Baer 2021). Different types of financial institutions hold structurally more of some asset classes. Insurance companies

²⁰It is also worth mentioning that London is one of the chief financial hubs where fossil fuel companies levy funds. Transition-exposed companies can comprise as much as 30% of the FTSE. Hence, the UK is vulnerable to shocks to fossil fuel companies occurring everywhere in the world. I thank an anonymous referee for raising this very relevant point.

own more bonds, while pension funds invest more in equity (Baer 2021). Investment funds stand out because they invest in high-carbon sectors and hold a sizable share of these firms' assets (Monasterolo, J. I. Zheng, and Battiston 2018). Banks seem particularly exposed to coal in the Global South, especially in China, the United States, Korea, and Japan (Ball et al. 2021; Manych, Steckel, and Jakob 2021; Ganswindt et al. 2021).²¹

Despite variations, exposures are significant, often representing several times the initial GFC loss. Yet, these assets' value will unlikely collapse to zero overnight (Battiston, Mandel, et al. 2017). It is also unsure whether sizeable exposures will result in equally sizeable losses if FCs can absorb shocks. Hence, there is a need to assess vulnerability beyond exposures. It will be the object of the following subsections. I start by reviewing short-run "stress tests" analyses of vulnerabilities and finish with long-run studies.²²

3.2 Short-run stress tests

Short-run "climate stress tests" simulate an unexpected "strong but plausible shock" (Baudino and Svoronos 2021; Borio, Drehmann, and Tsatsaronis 2014), figuring "disorderly" (NGFS 2020a) or "disruptive" (Vermeulen et al. 2021) transitions. They provide an estimate of financial agents' vulnerability to transition risks understood as sudden and unanticipated changes in climate policy stance or technological developments.

3.2.1 Methods

Static stress tests (Table B.2) measure the immediate effects of violent transition shocks mainly with two methodologies: econometrics (Faiella, Lavecchia, et al. 2022; Ferentinos, Gibberd, and Guin 2023; J. Jung, Herbohn, and P. Clarkson 2018) and valuations models (Monasterolo, J. I. Zheng, and Battiston 2018). Network stress

²¹Ball et al. (2021) also insist on the pivotal role of key financial institutions that serve as anchors for the syndication of loans, mostly located in Japan and South Korea.

²²See Cartellier (2022) for a more in-depth review of stress tests.

tests (Table B.3), pioneered by Battiston, Mandel, et al. (2017), explore amplification potentials in financial networks (Acemoglu, Ozdaglar, and Tahbaz-Salehi 2015; F. Allen and Gale 2000), through the interbank market or further-round effects like fire sales (Bateson and Saccardi 2020), capital flights (Roncoroni et al. 2021), or propagation through equity ownership chains (Semieniuk, Holden, et al. 2022). The dynamic stress test (Table B.4) approach (Vermeulen et al. 2018; Vermeulen et al. 2021; ESRB 2020; see also Várgedo 2022) adds to static stress tests macroeconomic scenarios. They depict four possible disruptive transitions (Figure 4). A macroeconomic model first runs the projection. The output then enters a disaggregated sectoral module. The outcomes of both models finally feed a module yielding financial risk metrics. The ESRB includes a feedback loop from the financial sector to the broader economy.

3.2.2 Takeaways

Vulnerability to disorderly transitions is consistent with exposures. Anglo-Saxon banks seem vulnerable (Bateson and Saccardi 2020; H. Jung, Robert F. Engle, and Berner 2021), while their European counterparts look sheltered, at least from market risk (Battiston, Mandel, et al. 2017). Losses should also be related to the type of financial institution under consideration. Banks and insurance companies, because they have less own funds, are structurally more vulnerable than other financial institutions like pension funds (Weyzig et al. 2014). Households seem resilient to policy shocks, unlike small NFCs (Faiella, Lavecchia, et al. 2022). Results are sensitive to scenarios (Monasterolo, J. I. Zheng, and Battiston 2018), assumptions on market conditions (Roncoroni et al. 2021) and behavioural hypotheses on the reaction of monetary authorities (Vermeulen et al. 2018).

Transition risks are higher if they come with adverse macroeconomic consequences (Faiella, Lavecchia, et al. 2022), sweeping structural shifts over small timespans (Battiston, Mandel, et al. 2017), or entail ambitious climate targets. Yet, static stress tests show that direct vulnerability to transition risks seems contained. Adding network ef-

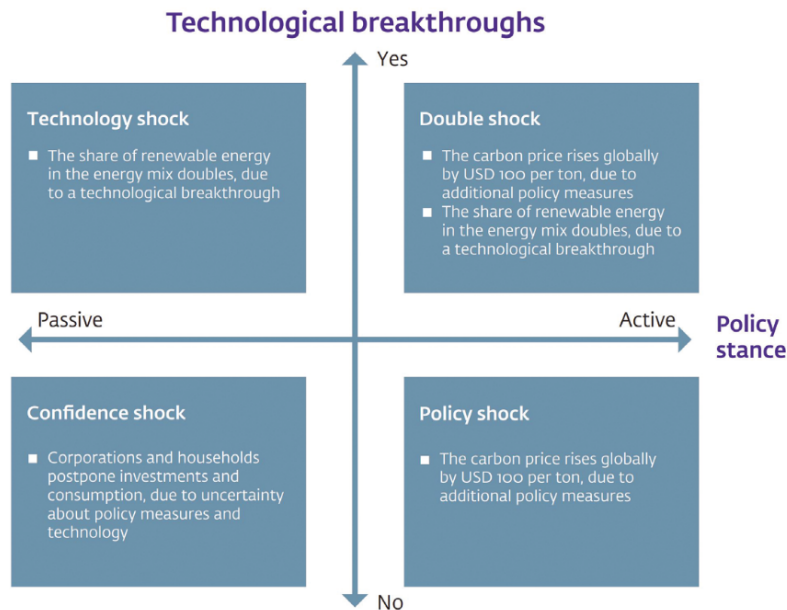


Figure 4: DNB-ESRB Disruptive-transition scenarios. Taken from Vermeulen et al. (2018).

fects, by contrast, can multiply initial shocks severalfold (Bateson and Saccardi 2020; Roncoroni et al. 2021) and include institutions with, initially, no or small exposures to transition-relevant sectors (Battiston, Mandel, et al. 2017). Finally, accounting for macroeconomic effects increases basic estimates (Vermeulen et al. 2018; ESRB 2020).

3.2.3 Sources of uncertainties

However, despite proposals (Hayne et al. 2019), there is neither a standard climate stress test method nor a unified vulnerability measure (Baudino and Svoronos 2021). Hence, there are difficulties in comparing results. Some well-established metrics, like Value-at-Risk, are inoperant in that transition outcomes cannot be given a probability distribution (Kalinowski and Chenet 2020).²³ Finally, no prudential threshold has been established for transition risks (Baudino and Svoronos 2021).

Another source of uncertainty is the “strong but plausible” nature of shocks. Borio,

²³Monasterolo et al. (2018) propose a “Climate Value-at-Risk” corresponding defined as the loss prevailing on the top-5% transition shocks in terms of magnitude.

Drehmann, and Tsatsaronis (2014) note that the structure of most economic models “shifts the burden” of producing any damage from the properties of the models to the size of the shocks, which end up being “unreasonably large” (p. 7).

Relatedly, Vermeulen et al.’s (2021) policy shock belongs to the upper tail of proposed 2020 carbon prices (Masson-Delmotte et al. 2018). Further, their technology shock is optimistic regarding low-carbon technology deployment (IRENA 2020b). Some stress tests use shock distributions from scenario databases (Battiston, Mandel, et al. 2017). However, pooling shocks occurring at very different points in time could misestimate potential losses. It would be especially the case if decarbonisation efforts mass over a particular timespan or if the shock corresponds to a late period (Roncoroni et al. 2021). More fundamentally, these works reduce the transition to an adverse shock. Yet, while it makes sense to emphasise the risk associated with brisk changes in drivers, going low-carbon will be a long-run phenomenon whose financial consequences will deploy over long timespans.

3.3 Long-run vulnerability assessments

Other strands of literature have explored these aspects, centred around two kinds of methodologies. At the microeconomic level, a growing body of literature has intended to measure portfolio losses at the investor level and the sensitivity of NFCs’ financial performances to long-run transition paths. At the macroeconomic level, the Network for Greening the Financial System (NGFS), a consortium of central bankers and regulators for the study of climate-related risks²⁴ provided a general framework to model transition risks. Transition scenarios are either drawn or adapted from well-established databases or built from scratch and run by models or a series of models accommodating financial variables.²⁵ I start by reviewing microeconomic assessments before moving on to the NGFS approach.

²⁴Some research (Bovari, Giraud, and McIsaac 2020; Bovari, Giraud, and Mc Isaac 2018; Bovari, Lecuyer, and Mc Isaac 2018; Dietz, Bowen, et al. 2016; S. Kelly et al. 2015) adopts a similar long-term view, with models capturing explicitly the financial system. However, all these works use damage functions and, therefore, do not allow to disentangle the effects of physical and transition risks. Therefore, they will not be covered in this review.

²⁵These methods are sometimes called “stress tests.” This is improper because of their long horizon of analysis (Clerc, Bontemps-Chanel, et al. 2021).

3.3.1 Long-run vulnerability assessments at the microeconomic level

Microeconomic studies typically study how much a particular agent would suffer along a transition pathway because of technical change, capital reallocation, or carbon pricing.

3.3.1.1 Investor portfolios Early pieces have studied how investor portfolios would perform along 2 °C- or even 1.5 °C-compatible trajectories (Campiglio, Daudmas, et al. 2023). This approach adopts a microeconomic focus, as it displays losses at a representative portfolio level and has explored the effects of technological displacement and structural change (Table B.5). Some studies compute changes in portfolio returns along a transition path, simulated by a forward-looking model (Mercer 2015; Mercer 2017; Mercer 2019). Results show manageable changes for diversified portfolios in expected long-term returns in the case of an orderly transition, while disorderly scenarios can prompt significant losses (Bongiorno et al. 2022). By contrast, UNEP-FI (2019) reports potential substantial losses on immediate-action pathways. It is due to their metric, which explicitly includes foregone profits and increased costs to equity, not portfolio losses. This literature highlights heterogeneity in sectoral and geographical vulnerability (Mercer 2019), suggesting that non-diversified portfolios can suffer sizeable losses (Mercer 2017).

3.3.1.2 Non-financial companies' performances Regarding NFCs, methods link cash flows under several carbon price paths to default probabilities. In the short run, evidence points to mild increases in default probabilities relative to BAU under 2 °C-compatible carbon price paths, especially under high electricity price assumptions (Cormack et al. 2020).²⁶ More stringent targets can increase short-run default probabilities (Bouchet and Le Guenedal 2020). In, Manav, et al. (2021) and Reinders, Schoenmaker, and van Dijk (2023) insist on the role of cost pass-through. In the longer run, the main factors are the hypotheses on firms' adaptation of their

²⁶However, their results are somewhat ambiguous, as their simulations fail to achieve the capacity targets laid out in 2 °C-compatible scenarios for low to medium electricity price assumptions.

capital structure. Works supposing optimal capital structure management exhibit lower transition risks (Cormack et al. 2020). On the other hand, more behavioural hypotheses yield higher estimates (Bouchet and Le Guenedal 2020). Some empirical studies have also shown a positive relationship between NFCs’ financial fragility and their carbon emissions (Capasso, Gianfrate, and Spinelli 2020). The two previous sub-fields provide valuable insights into the vulnerability of economic agents but remain incomplete without a macroeconomic scenario (Espagne 2018).

3.3.2 The NGFS’s macroeconomic approach

The NGFS’s approach (Table B.6) has bridged this gap. It relies on fully-fledged macroeconomic scenarios exploring longer-run transition risks (see Figure 5).²⁷ They intend to provide a comprehensive view of transition risks and capture as many transition risk channels as possible. The NGFS distinguishes between “orderly” and “disorderly” transitions. In the former, climate policies are implemented smoothly, and technological availability is high. “Disorderly” scenarios feature delayed policy scenarios, whereby climate action is postponed to 2030, technologically constrained scenarios or stringent climate targets (Bertram, Jérôme Hilaire, et al. 2020; NGFS 2020b). The 2021 scenario vintage (NGFS 2021b) reduced the number of scenarios and related projections more explicitly to the net-zero objective (IPCC 2022a).²⁸ These studies reproduce these scenarios in macroeconomic models to explore transition risks (T. Allen et al. 2020; ECB 2021),²⁹ for example, NFCs’ default probability or losses on equity. Various institutions have used the NGFS methodology to perform regulatory stress tests on financial institutions, with granular balance sheet data and financial health indicators (Bank of England 2020; Clerc, Diot, et al. 2020; Clerc,

²⁷Battiston and Monasterolo (2021) apply the NGFS scenarios within a microeconomic model of default probability and corporate bond valuation. They show that results are very sensitive to small changes in scenario assumptions, and invite to consider a wide range of scenarios.

²⁸In its 2022 reassessment of scenarios, the NGFS updated scenarios changes in nationally determined contribution pledges (NGFS 2022).

²⁹The literature has increasingly tended to model transition and physical risks altogether (ECB/ESRB Project Team on climate risk monitoring 2022; Alogoskoufis et al. 2021; Gourdel, Monasterolo, Dunz, et al. 2022, among others). Ens and Johnston (2020) and Fazekas et al. (2021) also build on the NGFS’s methodology and incorporate climate damage. I do not discuss them in detail here because the effects of physical and transition risks are difficult to disentangle, and because this review is focused on transition risks.

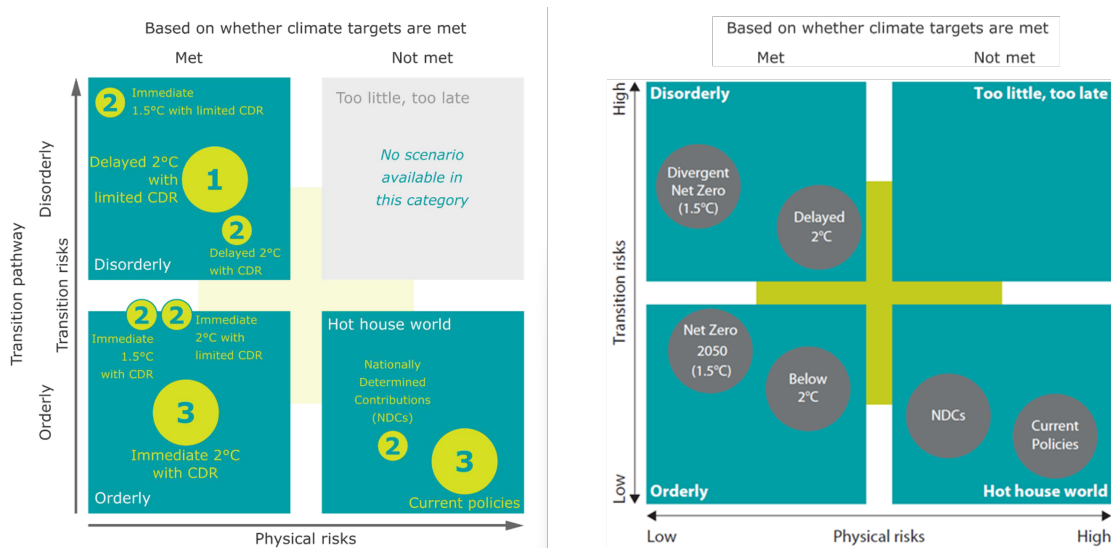


Figure 5: The NGFS scenario framework. Panel (a) displays the NGFS, 2020 vintage (Bertram, Jérôme Hilaire, et al. 2020). Figures indicate the number of models by which the scenario is generated, which represent scenario variants. Panel (b) displays the 2021 vintage (NGFS 2021b)

Bontemps-Chanel, et al. 2021; Alogoskoufis et al. 2021). Regarding results, financial transition risks seem contained, even in disorderly scenarios.³⁰ They could entail sizeable losses for transition-exposed sectors (T. Allen et al. 2020). However, the long-run physical damage due to climate change far outweighs the short-run disturbances associated with an immediate commitment to the low-carbon transition (Alogoskoufis et al. 2021). Yet, methods are still frail and uncertain. Numerous data gaps force to resort to imperfect aggregates and proxies (Lavecchia et al. 2021; ECB/ESRB Project Team on climate risk monitoring 2022; Hüttl et al. 2022), and this type of exercise is still unfamiliar to regulated institutions (Clerc, Bontemps-Chanel, et al. 2021). From a methodological standpoint, the absence of significant GDP loss differences between baselines and scenarios (unlike traditional stress tests) creates identification issues (Baudino and Svoronos 2021). It can require making heroic scenario assumptions, like the absence of any total factor productivity growth between 2025 and 2050 (T. Allen et al. 2020). It creates confusion regarding the kind of hazard under study since

³⁰Recent exercises show that financial risks in delayed-action scenarios are more driven by higher physical risks due to inaction during the 2020s than by sharp adjustments in the early 2030s (ECB/ESRB Project Team on climate risk monitoring 2022; Alogoskoufis et al. 2021).

the macroeconomic consequences of technological transition risks must be assumed prohibitively high. It may also suggest that the tools used for these assessments are ill-suited (Borio, Drehmann, and Tsatsaronis 2014; Hafner et al. 2020). Also, the choice between a “no-policy” or an “orderly transition” for the baseline is uncertain. The standard has evolved towards considering an “orderly” scenario as the benchmark (T. Allen et al. 2020; Alogoskoufis et al. 2021; ECB/ESRB Project Team on climate risk monitoring 2022). The rationale is that, from a policy perspective, it is more relevant to emphasise the costs of inaction or delayed actions compared to an efficient transition. It only holds, however, if transition risks in “orderly” transitions are low compared to a no-policy scenario that would leave aside the effects of climate.

3.3.3 Summary and link to systemic risks

The finance-oriented literature has estimated sizeable exposures. It has gone one step further than the asset stranding corpus by identifying vulnerabilities for financial and non-financial agents. Overall, financial risks seem limited for early-action, smooth transition pathways. Direct shocks imply manageable losses even in a disorderly transition. However, liability chains in financial networks may amplify initial shocks, with possibly unsustainable losses for some categories of agents. It could result in systemic risk implications in very adverse scenarios. Given the novelty of these research questions, methods are still largely nascent. Hence, many uncertainties remain regarding the financial risks linked to the low-carbon transition and their systemic implications, like the adaptive capacity of the financial sector, the consequences of its reaction to transition paths and the effect of transition risk exposures on financial agents’ own performances (see S. Li and Z. Pan (2022)). Finally, the tools employed to assess financial risks, because they require sufficiently large shocks to perform their analysis, partly dictate the focus on disorderly scenarios (Borio, Drehmann, and Tsatsaronis 2014). Hence, whether disorderly scenarios are relevant ones to explore in the first place is still a pending question. The empirical literature on financial markets’ attitude to transition risks partially answers this question. This

literature complements the previous two by providing insights into financial agents' actual attitude towards transition risks, which can be seen as a measure of their adaptive capacity. In this section, I review the survey and institutional analysis of investors' practices regarding transition risks. I follow with the financial econometrics literature studying investors' expectations by looking at asset pricing directly in the marketplace.

4 How do financial markets deal with transition risks?

4.1 Financiers and transition risks

Climate-related risks are a recent concern for finance, which questions how financiers deal with them. The survey and institutionalist literatures, which offer meaningful insights into this topic, are reviewed in the following to provide hints about how financiers as economic agents deal with transition risks. Critchlow (2015) surveyed an “irrational apathy” toward climate-related risks. More recent studies document that investors have growingly included climate risks in their business operations since the Paris Agreement (TCFD 2020). They see regulatory, technology, reputation, and litigation risks as increasingly material (Amel-Zadeh 2021; Krueger, Sautner, and Starks 2020), especially in the short run (Stroebel and Wurgler 2021). Investors consider technological risks as more material than regulatory risks and transition risks as less material than physical risks (Amel-Zadeh 2021; Ilhan, Krueger, et al. 2020). Most investors agree that the market misprices transition risks (Krueger, Sautner, and Starks 2020). They attribute this to obstacles in estimating transition risks (Amel-Zadeh and Serafeim 2018), like lack of data, adapted methodology or readily usable scientific insights (Harnett 2017; Ameli et al. 2020; Monasterolo 2020a). Finally, investors in countries or areas where environmental matters have importance, like the EU, exhibit more interest in climate-related risks (Dyck et al. 2019; Hunt

and O. Weber 2019) than in other places, like the United States (Bresnahan et al. 2020) or India (Colenbrander et al. 2023).

These findings contrast with institutional analyses of the financial system along two main lines.

Norms, routines and practices in financial markets can hamper the assessment of transition risks (Ameli et al. 2020; Caldecott and McDaniels 2014). Response biases to surveys are likely (Amel-Zadeh 2021), and still a minority of investors incorporate environmental considerations systematically in their decisions (Orsagh 2020). Christophers (2017; 2019) argues that investors will account for the environment so long as it does not contradict their fiduciary duty of profit maximization. Plus, investors will evaluate environmental concerns based on investment performances, which may limit their environmental reach (Amel-Zadeh and Serafeim 2018). Short-termism (Louche et al. 2019; Silver 2017; Thomä and Dupré 2014) and technological optimism (Ameli et al. 2020) are also norms likely to “lock in” the financial sector away from the low-carbon transition (Seto et al. 2016; Geddes and Schmidt 2020).

Finally, expecting unequivocal indicators could be illusory given the complexity of transition risks (Dafermos 2021; Kedward, Ryan-Collins, and Chenet 2022). Current synthetic ratings are faulty and inconsistent (F. Berg, J. Kölbel, and Rigobon 2022). Carbon emissions beyond scope 1 are inconsistent across third-party estimates (Busch, M. Johnson, and Pioch 2020). However, financiers may shun adopting a plurality of indicators possibly unrelated to traditional financial metrics (Harnett 2017).

Remains to check how these uncertainties and incentives faced by financiers translate into investment decisions and what they say about their expectations. The econometric literature on the pricing of transition risks tackled this issue.

4.2 Measuring investor’s expectations in financial markets

This approach measures investors’ actual investment decisions in the marketplace, which can be taken as a proxy for their expectations (Pástor, Stambaugh, and L.

Taylor 2021; Pástor, Stambaugh, and L. Taylor 2022) and could give indications about how they would react to transition risks in the future (Campiglio and Ploeg 2021). This literature has focused on policy transition risks. Studies deal with how agents manage market risks or hedge credit and reputational risks (Anginer et al. 2021; Galletta and Mazzù 2022). The literature has mainly tested two hypotheses: the green alpha hypothesis and the carbon premium hypothesis.

4.2.1 Are markets inefficient? The green alpha hypothesis

The *market inefficiency* or *green alpha* hypothesis suggests that investors misprice current risks to such an extent that they underreact to opportunities offered by low-carbon investments (Bolton and Kacperczyk 2021). It would show through abnormal positive returns on transition-shielded assets since investors would not have reaped investment opportunities. A body of literature referenced in Table C.1, based on the comparison of synthetic portfolios, supports the presence of green alphas. These studies compare the returns of different portfolios r_i over the risk-free asset's return r_0 sorted by transition exposures (policy, carbon content, etc.). They then evaluate these portfolio returns with asset-pricing models:

$$r_{i,t} - r_0 = \alpha_i + \sum_1^K \beta_{k,i} f_{k,t} + \varepsilon_{i,t} \quad (1.1)$$

where the $f_{k,t}$ are K risk factors, that is, sources of undiversifiable, systematic risks, α_i a measure of excess returns—which should be zero if markets are efficient (Fama 1970), $\beta_{k,i}$ a measure of exposure to the risk factor $f_{k,t}$ and $\varepsilon_{i,t}$ an error term. Studies document positive alphas, suggesting that investors underreact to low-carbon opportunities and do not hedge transition risks (Bernardini et al. 2021). Yet, portfolio-sorting methods are sensitive to the criterion used to build the hedging portfolio (Cheema-Fox et al. 2019; Witkowski, Adamczyk, and Franek 2021). The length of the time series is also crucial, as short time series may be noisy and bias the estimate of risk factors (Giglio, B. Kelly, and Stroebele 2020). Hence, evidence of market

inefficiencies and investor underreaction should be taken cautiously (Amenc, Esakia, and Goltz 2021). More recent results have found opposite proof that investors perceive lower investment opportunities in transition-exposed sectors (J. Choi, Jo, and H. Park 2018), with some evidence of hedging towards transition-shielded sectors (Alessi, Ossola, and Panzica 2021).

4.2.2 Measuring carbon premia

Hence, the literature has also focused on the measure of carbon premia. The carbon premium hypothesis implies a positive relationship between returns and transition exposure. High-carbon assets should be more profitable since investors ask for compensation to hold them (Bolton and Kacperczyk 2021). Other assets should bear lower returns, as investors would hold them to hedge transition risks (Alessi, Ossola, and Panzica 2021) or trade returns for non-pecuniary benefits (Pástor, Stambaugh, and L. Taylor 2021; Pástor, Stambaugh, and L. Taylor 2022). Two approaches to carbon premia stand out (Venturini 2021):

- **Bottom-up methods** consider funding cost metrics for firms and check whether transition exposures imply higher costs. It would signal higher risk premia.
- **Top-down** approaches explore the relationship between exposures and asset returns. A positive relationship between returns and exposures would signal that investors ask for a risk premium and do price transition risks.

Table C.2 gathers bottom-up methods, which show an association between funding costs and transition risk exposures. Geographical variations seem low, and larger effects are detected after the wake-up call of the Paris Agreement (J. F. Kölbel et al. 2020). Risk premia are small, notably for loans (Delis, Greiff, and Ongena 2019), which suggests mispricing.

Table C.3 shows top-down approaches. Two main methodologies have been deployed. Many studies (Alessi, Ossola, and Panzica 2021; Görden et al. 2020; Hentati-Kaffel

and Ravina 2020; Hsu, K. Li, and Tsou 2023) identify a risk factor consistent with asset pricing models (Equation (1.1)). Others (RaboResearch 2020; Bolton and Kacperczyk 2021) use panel data. Results are overall mixed, with studies either finding a positive premium (Alessi, Ossola, and Panzica 2021), not finding a premium (Görgen et al. 2020) or even a negative premium (J. Choi, Jo, and H. Park 2018).

These contradictory results are difficult to bring together due to the loose definitions of transition risk premia. Getting back to Equation (1.1), transition-risk premia can be expressed in two ways:

- If transition risks are not a new source of systematic, undiversifiable risks, higher returns should be contained in α_i , even if they are not measured with an asset-pricing model (Bolton and Kacperczyk 2021; Lioui 2019).
- If they are a new source of systematic risks affecting all assets, exposures should be a $f_{\tau,t}$, usually built from the returns on a portfolio hedging transition risks (Giglio, B. Kelly, and Stroebl 2020). A $\beta_{\tau,i}$ should be inferred in time series, measuring the sensitivity of equity into this risk factor. The corresponding risk premium should show up in cross-sections at time T as the $\gamma_{\gamma,T}$ below (Fama and MacBeth 1973):

$$r_{i,T} - r_{i,0} = \gamma_{0,i} + \sum_{k=1, k \neq \tau}^K \beta_{k,i} \gamma_{k,T} + \beta_{\tau,T} \gamma_{\tau,T} + \nu_{i,t} \quad (1.2)$$

and denote the actual realization of risk for equity i .

The literature uses these two definitions indifferently. An alpha carbon premium would denote abnormal returns or market inefficiency. It would imply that investors price transition risks imperfectly (Bolton and Kacperczyk 2021). Measuring a positive risk premium from a factor would suggest adequate pricing (Alessi, Ossola, and Panzica 2021). Detecting a factor without premium would signal an absence of pricing (Görgen et al. 2020; Hsu, K. Li, and Tsou 2023). Negative carbon premia (J. Choi, Jo, and H. Park 2018; Hentati-Kaffel and Ravina 2020; Ravina 2022) are especially difficult to interpret since they do not relate to any of the above hypotheses. One

possibility is that investors hold high-carbon assets to hedge against policy inconsistency (In, Manav, et al. 2021). Another interpretation (J. Choi, Jo, and H. Park 2018) relates to perceptions of fewer investment opportunities in transition-exposed sectors. Michael D. Bauer et al. (2022) suggest that aggregate lower returns for low-carbon stocks, which could be consistent with a negative premium, may be consistent with a positive premium if the period under study experienced a series of shocks in favour of low-carbon sectors.

Variations in results stem from different data sources and geographical focuses. Factor-based studies exhibit high geographical and data sensitivity. By contrast, Bolton and Kacperczyk's panel approach seems robust to geographical heterogeneity (Bolton and Kacperczyk 2021), but another dataset yielded different results (RaboResearch 2020). Aswani, Raghunandan, and Rajgopal (2023) show that using disclosed emissions instead of third-party estimates (as in Bolton and Kacperczyk) results in no significant link between returns and stock prices.³¹ They also highlight that results may depend strongly on retained specifications and control variables. Pástor, Stambaugh, and L. Taylor (2022) argue that samples of different lengths may yield distinct results. Further, the many metrics of transition exposure explain part of this result multiplicity. For instance, in determining their factors, Görden et al. (2020) use a combination of ESG scores incorporating transition risks and opportunities, while Alessi, Ossola, and Panzica (2021) incorporate disclosure quality. Lioui (2019) recalls that, with adequate criteria, any factor can be found statistically valid. It is, therefore, challenging to choose which factor to choose absent firm theoretical underpinnings.

Further, given the novelty of transition risks, disentangling what is priced between transition risks *per se* and the extent and quality of information disclosure is crucial. Many studies explicitly account for the valuation of disclosure (Alessi, Ossola, and Panzica 2021; Krueger 2015). However, in many cases, proxies for future transition-risk exposures could also capture the effects of disclosure quality.

³¹The authors attribute this finding to the strong correlation between estimated emissions and sales, which is one of the strongest determinants of asset returns.

Overall, empirical evidence on the pricing of transition risks in panels and cross-sections is mixed, with variability across studies.

4.2.3 Time-heterogeneity and investors' climate sentiments in the pricing of transition risks

To answer this conundrum, Lioui (2019) suggests that carbon alphas and betas (the carbon premium) are likely time-dependent (Roncalli et al. 2020; Witkowski, Adamczyk, and Franek 2021). Giglio, B. Kelly, and Stroebel (2020) further argued that carbon premia vary with investor attention and sentiments (Table C.4). If this hypothesis were true, this would cast doubt on the consistent pricing of transition risks. I review the two related literatures in the following.

Time heterogeneity relates to changes in the attention given to climate change. Attention evolves with the policy stance (Oestreich and Tsiakas 2015; Witkowski, Adamczyk, and Franek 2021), climate news (Ardia et al. 2020; Robert F Engle et al. 2020; Faccini, Matin, and Skiadopoulos 2023; Pástor, Stambaugh, and L. Taylor 2022) or natural disasters (D. Choi, Gao, and Jiang 2020). Increased perception of transition opportunities also attracts investors' attention (Sautner et al. 2023). Santi and Moretti (2021) find that countries in which attention to climate change is low do not exhibit carbon premia.

Another literature has emerged on the question of investors' "climate sentiments," showing strong correlations between surges in investor awareness and market volatility (Tran 2021; Gong et al. 2022), and between climate sentiments and overvaluations of low-carbon assets (Santi 2023). Anginer et al. (2021) show that banks toughen their lending terms to firms involved in negative climate news and attribute it to reputational risk management.

That investors react to changes in policy and announcements is also grounded in a literature using event studies or difference-in-differences methodologies (Table C.5). Event studies (MacKinlay 1997) capture abnormal returns on a single asset around an event, while difference-in-differences measure reactions of a group affected by a

measure against that of an unaffected group. Regardless of the method, investors do react to policy (Barnett 2019; Donadelli, Grüning, and Hitzemann 2019; Ilhan, Sautner, and Vilkov 2021) and technology (Byrd and Cooperman 2018) announcements. However, the precise modalities of the reaction depend on the nature of the event and the type of agent (Müller and Sfrappini 2022). It suggests that financial companies may have different strategies to cope with transition risks. They can also expect compensation for the losses that may be induced by the policy (Sen and Schickfus 2020).

Hence, the literature supports the hypothesis that short-term reactions to changes in transition risk drivers govern investors' stance regarding transition risks. They are strongly driven by changes in attention and salient events. It casts doubts on the consistent pricing of transition risks and calls for prudence in attributing fully rational, long-run expectations to financial agents.

4.2.4 Summary and relationship to systemic risk

The literature suggests that financial markets partially price transition risks. However, pricing is likely too timid (Delis, S.-J. Kim, et al. 2021), imperfect (Bolton and Kacperczyk 2021) and dependent on investors' attention and sentiments (Giglio, B. Kelly, and Stroebel 2020).

Hence, investors manage transition risks in the short run but barely hedge against longer-run developments (Faccini, Matin, and Skiadopoulos 2023). It also implies that investors hardly price transition risks but react to climate news to improve their environmental profile, suggesting that the low-carbon transition is yet to become the “new normal” and anchor investor expectations. It calls for caution in attributing far-sightedness and transition-compliant expectations to investors. It may lead to overestimating their adaptive capacities. Hence, the focus on “disorderly” transitions, in which investors are likely to react strongly, is justified.

Yet, due to its microeconomic focus, the literature cannot explore meso- or macroeconomic further-round effects like network contagion or bank run effects reviewed in

previous sections. Individual hedging strategies (Andersson 2019; Robert F Engle et al. 2020) or policy-induced divestment (Mésonnier and B. Nguyen 2021; Reghezza et al. 2022) can increase the resilience of one actor, but possibly at the expense of others. They could also be short-lived and only motivated by changes in investors' sentiments. Hence, there misses a picture of whether changes in individual exposures improve systemic resilience. For instance, a disorderly transition may thus lead to significant losses, possibly amplified if investors try to diminish their exposures simultaneously (De Brandt and Hartmann 2000). It could further trigger a liquidity crisis, especially if related assets are collateralized (Benoît et al. 2017). The likelihood of these events will depend on the magnitude of losses (including their sectoral span), the diversification of financial agents' portfolios, and the reaction of prudential and monetary authorities and agents' expectations. In this latter respect, investors seem to assume that high-carbon investments carry less systemic risk than low-carbon investments Viotto, Curcio, and Gianfrancesco (2022). Given the inefficient pricing of transition risks in financial and credit markets, investors may thus underestimate the systemic risk of some institutions exposed to transition tail risks (Reboredo and Otero González 2021a).

5 Summary and ways forward

We close this review with a summary of the results and a discussion of possible avenues for research.

5.1 Summary

Quantitatively, potential losses, either as resource, physical or financial stranded assets, are high compared to past shocks to financial values, such as the 2008 crash. Therefore, transition-risk exposures are sizeable. This aggregate picture hides sizeable heterogeneities: geographical, sectoral, and across agents. However, given the interconnectedness of agents through networks, little exposed agents could be indi-

rectly affected. Although uncertainties remain on how this interconnectedness could exacerbate exposures, and despite daunting data challenges, the literature agrees that these patterns create fragilities within the system. Whether these fragilities can degenerate into financial disturbances, possibly down to a systemic crisis, begs to interrogate how these exposures translate into vulnerabilities for economic agents' financials. It requires translating exposures into financial losses and whether they can be absorbed. The literature has shown that vulnerabilities are also heterogeneously distributed.

Despite uncertainties on methods and metrics, the literature agrees that transition risks could harm the financial system if the shift to a low-carbon path is associated with unexpectedly severe macroeconomic consequences or unanticipated structural shifts over reduced timespans. Whether such "disorderly" transitions could degenerate into systemic risks seem to rely on the strength of network effects.

This questions whether this disorderly transition pattern is a credible possibility. Facing timidly phased-in climate policies, whether financial agents anticipate future policy tightening should be questioned. The survey, institutional and asset-pricing literatures on transition risks agree that the short-termism of financial agents may represent an obstacle. Only short-term transition risks are priced and only when attention to climate change issues increases.

To summarise, the literature seems to have confirmed the theoretical intuition that disorderly transitions would likely be harmful and that these scenarios are policy-relevant. However, this picture remains incomplete without a study of the adaptability of agents to the low-carbon transition and how their reorganization around transition paths can occur smoothly.

5.2 Lack of integration

These uncertainties are also attributable to the lack of integration in the field.

The stranded asset and finance-oriented literatures could benefit from better collaborations. Forward-looking studies on financial instability do not incorporate stranded

assets (Jacquetin 2021), while they can affect financial stability. Similarly, network effects across non-financial sectors and transboundary contagion could exacerbate the exposures documented in finance-oriented studies. Not modelling stranded assets overlooks that write-offs and other impairments will be a necessary feature of the transition, with (yearly) financial losses equivalent to what the economy incurred in the outbreak of the 2008 crash. Integrating stranded assets into broader transition risk assessments could help qualify the results of this literature by accounting for financial gains linked to opportunities given by the transition.

A second aspect is the crucial issue of expectations in a situation of radical uncertainty that the empirical literature has explored. Forward-looking assessments of transition risks could benefit from integrating investors' sentiments and partial attention to climate change (Giglio, B. Kelly, and Stroebel 2020). Modelling exercises should use expectation structures beyond adaptive expectations (T. Allen et al. 2020) or perfect foresight (Saygin et al. 2019). Studying the impact of unmet technological expectations, like on CDR, would be extremely valuable.³² Regarding systemic risks, exploring how the seemingly inefficient pricing of transition risks and network contagion could interact would be a fruitful avenue. This issue is also directly connected to asset stranding, whose impact on financial systems will largely transit through expectations (van der Ploeg and Rezai 2020a). The importance of model-based prospective works in the field offers a solid platform for such an integration. Battiston, Monasterolo, Riahi, et al. (2020), Battiston, Monasterolo, Riahi, et al. (2021), Dunz, Naqvi, and Monasterolo (2021), Gourdel, Monasterolo, Dunz, et al. (2022) and Cahen-Fourot, Campiglio, Daumas, et al. (2022) works on expectations are decisive first steps.

5.3 Ways forward

Either in the asset stranding or forward-looking transition risk literature, results depend to a large extent on scenario assumptions or structural parameters. Yet, this

³²See Sers and Victor (2018), A. Jackson and T. Jackson (2021), and N. Grant et al. (2021) for first steps in this direction.

literature has worked with only a few scenarios. It may not be sufficient to map all uncertainties related to the low-carbon transition (Battiston, Monasterolo, Riahi, et al. 2021). That the NGFS’s 2021 vintage reduced the number of transition scenarios to three (NGFS 2021b) may not be a right step in the right direction. Increasing the range of projections would be more sensible and lead to a finer-grain distinction between “orderly” and “disorderly” pathways. The literature could also expand the spectrum of narratives relating transition risks to financial instability (Monasterolo, Nieto, and Schets 2023). For instance, the literature could explore “green bubble” scenarios (Borio, Claessens, and Tarashev 2021; Nauman 2021; Nikolaidi 2017). In such a case, similarly to the dot-com bubble (Guttman 2016), a craze over low-carbon assets could trigger speculative dynamics or excessive credit creation that may result in a financial crash (Semieniuk, Campiglio, et al. 2021). Envisaging such a development would put the emphasis on “sunrise” industries and offer insights into the possible adverse effects of low-carbon technology deployment. Finally, the issue of the potential effects on financial instability of low-growth scenarios and changes in consumption patterns towards sufficiency is still understudied and deserves more attention (see Dafermos, Monserand, and Nikolaidi 2022).

Further, there needs to explicitly model interactions between the financial system and low-carbon developments in the real economy over longer time horizons by modelling the adaptation of the financial system to various transition paths (ECB/ESRB Project Team on climate risk monitoring 2021; ECB/ESRB Project Team on climate risk monitoring 2022). In particular, how asset reallocations within the financial sector could strengthen or weaken systemic resilience is still pending (Dafermos 2021). It would require modelling dynamic balance sheets for financial institutions and how balance sheet interactions could influence instability. Relatedly, firms’ and financial agents’ adaptive capacities remain underexplored. Designing multi-country frameworks to study transboundary risk transmission and amplification at the macroeconomic level would also be a decisive step forward. Such research could use less standard approaches like stock-flow consistent (Sers and Victor 2018; A. Jackson and

T. Jackson 2021) or agent-based modelling (Botte et al. 2021). Sanders et al. (2022) reviewed how these promising methods and more traditional IAMs could feature more accurate representations of financial market dynamics. Third, the asset-pricing literature focuses on the marketplace, while a sound hedging strategy would be shareholder engagement to foster decarbonisation (Amel-Zadeh and Serafeim 2018; Azar et al. 2021; Benz et al. 2021; Benz et al. 2021; van Benthem et al. 2022) or disclosure (Ginglinger 2020) strategies. A remaining question is whether these strategies will be pursued steadily or relinquished if they harm profitability (Baines and Hager 2022; Christophers 2019; McDonnell, Rempel, and Gupta 2022).

Finally, the transition risk literature has focused near-exclusively on global warming. Methodological considerations have revolved around high-carbon stranded asset accounting and greenhouse gas emissions. However, the climate is only one of the nine planetary boundaries we must remain within (Rockström et al. 2009). Biodiversity losses (NGFS 2021a), ambient pollution, deforestation, and others are all relevant threats. Facing them must be considered part and parcel of a broader ecological transition. The concept of transition risks should also encompass these dimensions (Kedward, Ryan-Collins, and Chenet 2022). Related methodological challenges should be urgently faced and dealt with, as recent contributions have begun to do (Svartzman et al. 2021).

This literature review has highlighted many research avenues, making for an exciting research programme. Although it falls beyond the reach of this dissertation to embark on all possible ways forward, the following chapters will build upon these conclusions by providing contributions on four of the above calls in two distinct movements. A first movement will be dedicated to an expansion of model-based transition-risk assessments, along two lines. Chapter 2 directly answer the need to expand the modelling portfolio for transition risk assessment, while Chapter 3 provides an extension of existing scenario-based methodology by increasing the number of considered projections. In a second movement, Chapters 4 and 5 will propose ways to improve the methods used in transition risk assessments, respectively the modelling of expec-

tations, and a better understanding of the dynamics of portfolio reshuffling across heterogeneous financial agents.

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Appendices

A. Monetary Asset Stranding Estimates

Table A.1: Book Value Stranded Assets (World level)

(1) Authors (Year) Publication	(2) Methodology	(3) Reference Scenario(s) (Period)	(4) Underlying model(s)	(5) Expectation structure	(6) Exposed sectors	(7) Value in undiscounted trillion US\$ (Fraction of initial GFC loss*)	(8) Yearly undiscounted losses** in trillion US\$ (Fraction of initial GFC loss*)
Fullerton (2011) Capital Institute Blog	Extrapolation from fossil producers' market capitalisation	2°C scenario (2000-2050)	Irr.	Irr.	Fossils	20 (8000%) (8000)%	0.4 (160%) (160)%
IEA (2014) World Energy investment Outlook	Valuation of assets that will not recoup their investment costs	IEA 450 ppm Scenario (2015-2035)	World Energy Model	Perfect Fore- sight	Fossils Power Sector	0.184 (74%) 0.12 (48%)	0.0092 (4%) 0.006 (2.4%)
Johnson et al. (2015) <i>Technological Forecasting and Social Change</i>	Model runs without CSS along 8 scenarios featuring different climate-policy stringency	AMPERE Database + Homemade variants (2011-2100)	MESSAGE- MACRO	Myopic Foresight	Power Sector (Coal)	0.165-0.55 (66-220%)	0.00185-0.0618 (0.7-2%)
Kefford et al. (2018) <i>Energy policy</i>	Power Sector: Model runs 2010-2060 computation of early decommissioning and comparison to "full lifetime" use of capital	IEA 2DS Losses should be understood as lower bounds given IEA hypotheses (2014-2060)	NREAL- SAC for end-of- lifetime retirement	Irr.	Power Sector	0.541-0.773 (560-800%)	0.01-0.016 (4%-6.4%)

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Table A.1: Book Value Stranded Assets (World level) – Continued

(1) Authors (Year) Publication	(2) Methodology	(3) Reference Scenario(s) (Period)	(4) Underlying model(s)	(5) Expectation structure	(6) Exposed sectors	(7) Value in undiscounted trillion US\$ (Fraction of initial GFC loss*)	(8) Yearly undiscounted losses** in trillion US\$ (Fraction of initial GFC loss*)
Saygin et al. (2019) <i>Energy Source</i>	Baseline, delayed action, early action	IRENA ReMap scenario (2025-2050)	IRENA Model	Perfect Foresight	Power Sector	0.927 (371%)	0.026 (11%)
					Fossils	4 (1600%)	0.11 (46%)
					Real Estate	5.5 (2200%)	0.157 (63%)
					Industry [†]	0.2 (80%)	0.005 (3%)
					Total	10.627 (4251%)	0.302 (120%)
		Delayed-Action scenario (2015-2050)	IRENA Model	Perfect Foresight	Power Sector	1.8 (720%)	0.05 (21%)
					Extractive as- sets	7 (2800%)	0.2 (80%)
					Real Estate	11 (4400%)	0.314 (126%)
					Industry [†]	0.8 (320%)	0.02 (8%)
					Total	20.6 (8240%)	0.586 (234%)
Mercure et al. (2021) Working paper	Estimate of BAU utilisation rates and comparison with retirements necessary to meet Paris Agreement carbon budgets Computation of a "Value-at-Risk" (VaR) by summing the value of retirements weighted by their age relative to service life	No further fossil investment after 2020 (2020-2050)	Homemade popula- tion dynamics algo- rithm for retire- ment estimates	Myopic Foresight	Power Sector	5.7 (2280%)	0.13 (54%)
					Industry	0.5 (200%)	0.014 (5.6%)
					Total	6.2 (2480%)	0.144 (58%)
		No further fossil investment after 2025	Homemade popula- tion dynamics algorithm for re- tirement estimates	Myopic Fore- sight	Power Sector	3.7 (1480%)	0.085 (34%)
					Industry	0.2 (80%)	0.007 (2.8%)
					Total	3.9 (1560%)	0.092 (37%)

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Table A.1: Book Value Stranded Assets (World level) – Continued

(1) Authors (Year) Publication	(2) Methodology	(3) Reference Scenario(s) (Period)	(4) Underlying model(s)	(5) Expectation structure	(6) Exposed sectors	(7) Value in undiscounted trillion US\$ (Fraction of initial GFC loss*)	(8) Yearly undiscounted losses** in trillion US\$ (Fraction of initial GFC loss*)
Edwards et al (2022) <i>Environmental Research Letters</i>	Value of assets to be prematurely decommissioned in a decarbonisation scenario without additional capacity after 2020	2°C - No new coal (2020-2100)	GCAM	Perfect Fore- sight	Power (Coal)	0.537 (214%)	0.007 (2.70%)
		1.5°C - No new coal (2020-2100)				0.88 (352%)	0.01 (4.40%)
		IEA 1.8°C (2020-2040)	WEM	Perfect Foresight	Oil reserves	27 (10800%)	1.35 (540%)
					Gas reserves	4.5 (1800%)	0.225 (90%)
					Coal reserves	3.7 (1480%)	0.185 (74%)
					Total reserves	35.2 (14080%)	1.76 (704%)
					Upstream Capital (all resources)	0.3 (120%)	NA
		IEA 1.5°C (2020-2040)			Oil reserves	30 (12320%)	1.5 (600%)
					Gas reserves	9 (3600%)	0.45 (180%)
					Coal reserves	5 (2000%)	0.25 (100%)
					Total reserves	44 (17600%)	2.2 (880%)
					Upstream Capital (all resources)	0.36 (144%)	NA

Note: Irr. Stands for "Irrelevant". Monetary values are in constant currency from a given date, depending on the study. Studies selected through regularly repeated queries on Scopus, Google Scholar and Web of Science.

* US\$250\$, provided by (2018).

** The numbers are given by dividing the estimate in Column (8) by the time span of the study's scenario displayed in Column (5).

*** The author displays both discounted and undiscounted results; only undiscounted results were displayed here. **** Discounted at 10%.

† Estimate displayed in an earlier version of the paper (Agency 2017).

Table A.2: Foregone Income Stranded Assets (World Level)

(1) Authors (Year) Publication	(2) Methodology	(3) Reference Scenario(s) (Period)	(4) Discount Rate	(5) Underlying model(s)	(6) Expectation structure	(7) Exposed sectors	(8) Value in undiscounted trillion US\$ (Fraction of initial GFC loss*)	(9) Yearly undiscounted losses** in trillion US\$ (Fraction of initial GFC loss*)
Lewis et al. (2014) Kepler Chevreux Report	Estimate of the revenue losses for fossil fuel producers associated with a shift to a 450 ppm	450 ppm - Lower fossil-fuel prices and lower demand (2015-2035)	0%	Irr.	Irr.	Oil	19.3 (7720%)	0.965 (514%)
						Gas	4 (1600%)	0.2 (80%)
						Coal	4.9 (1960%)	0.245 (98%)
						Total	28.2 (11280%)	1.41 (564%)
Nelson (2014) CPI Report	Estimate of the revenue losses for fossil fuel producers associated with a shift to a 450 ppm	IEA 450 ppm scenario	8%	WEM	Perfect Foresight	Oil	18.5 (7400%)	NA
						Coal	3 (1200%)	NA
						Gas	3 (1200%)	NA
						Power	0.032 (12.80%)	NA
						Total	24.6 (9840%)	NA
Channel et al. (2015) Citi GPS Report	Foregone income between	McGlade & Ekins (2015) 2°C scenario (2020-2050)	0%	Irr.	Irr.	Fossil	100 (40000%)	3.33 (1333%)
Koehler & Bertocci (2016) UBS Report	Net present value losses under an assumption of zero cash flow from a given dates ("Cash-flow cliff")	Various assumption on cliff occurrence year and fossil fuel prices (Worst-case scenario is displayed)	Unspecified (Considered as 0%)	Irr.	Irr.	Fossils	0.573 (229%)	0.032 (38%)
N. Bauer et al. (2016) <i>Journal of Environmental Studies and Science</i>	Net present value of foregone profits due to the low-carbon transition	450 ppm (2010-2100)	5%	Irr.	Irr.	Fossils	17.5 (7000%)	NA

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Table A.2: Foregone Income Stranded Assets (World Level) – Continued

(1) Authors (Year) Publication	(2) Methodology	(3) Reference Scenario(s) (Period)	(4) Discount Rate	(5) Underlying model(s)	(6) Expectation structure	(7) Exposed sectors	(8) Value in undiscounted trillion US\$ (Fraction of initial GFC loss*)	(9) Yearly undiscounted losses** in trillion US\$ (Fraction of initial GFC loss*)
Linquiti & Cobgswell (2016) <i>Journal of Environmental Studies and Science</i>	Net present value of foregone revenues due to the low-carbon transition	IEA 450 (2014-2040) Then, extrapolations (2041-2115)	3%	WEM	Irr.	Oil	138 (55200%)	NA
						Gas	36 (14400%)	
						Coal	26 (10400%)	
						Total	200 (80000%)	
Mercure et al. (2018) <i>Nature Climate Change</i>	Model-based runs with five scenarios Losses are expressed in foregone profits	2°C scenario with downward fossil fuel price schedule against IEA baseline (2016-2035)	0%	E3ME-FTT-GENIE	Myopic Foresight	Fossils	12.4 (4960%)	0.62 (248%)
						Fossils	9.7 (3870%)	0.485 (194%)
Muldoon-Smith & Greenhalgh (2019) <i>Energy Research & Social Science</i>	Computation of the foregone rents flowing due to the illegal letting of sub-standard buildings if the entire world were to adopt the English-Welsh Minimum Energy Efficiency Standard	Irr.	Irr.	Irr.	Irr.	Residential real estate	16 (6400%)	NA
						Commercial Real Estate	10 (4000%)	NA

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Table A.2: Foregone Income Stranded Assets (World Level) – Continued

(1) Authors (Year) Publication	(2) Methodology	(3) Reference Scenario(s) (Period)	(4) Discount Rate	(5) Underlying model(s)	(6) Expectation structure	(7) Exposed sectors	(8) Value in undiscounted trillion US\$ (Fraction of initial GFC loss*)	(9) Yearly undiscounted losses** in trillion US\$ (Fraction of initial GFC loss*)
Chen et al. (2020) <i>Climate Change Economics</i>	Foregone income due to decrease in fossil extraction and coal power output through 2050	NDC	4%	EPPA	Limited foresight (5 years)	Fossil fuels	22 (8800%)	NA
		Coal power				1.25 (500%)		
		Fossil Fuels				27 (10800%)		
		Coal Power				2.2 (880%)		
		Fossil Fuels				23 (8200%)		
		Coal Power				1.7 (680%)		
		Fossil Fuels				30 (12000%)		
		Coal Power				2.25 (900%)		
	Transition						NA	
	Very late transition						NA	
	Net zero 2050						NA	

Note: Irr. Stands for "Irrelevant". Monetary values are in constant currency from a given date, depending on the study. Studies selected through regularly repeated queries on Scopus, Google Scholar and Web of Science.

* US250\$, provided by (Mercure, Pollitt, N. R. Edwards, et al. 2018).

** The numbers are given by dividing the estimate in Column (8) by the time span of the study's scenario displayed in Column (5).

Table A.3: Book value losses (Regional level)

(1) Authors (Year) Publication	(2) Geographical coverage Currency	(3) Methodology	(4) Reference Scenario(s)	(5) Underlying model(s)	(6) Expectation structure	(7) Exposed sectors	(8) Value in trillion (Fraction of country 2020 GDP)
Caldecott et al. (2016) SSE Report	Japan US\$	Cost of closing all plants at a 5-, 10- and 15-year horizon Conservative scenario for projected variables (Discount rate not mentioned)	Irr.	Irr.	Irr.	Coal Power Assets	0.0616-0.0802 (1.2-1.5%)
Löffler et al. (2019) <i>Energy Strategy Reviews</i>	European Union €	Short-term policy scenarios (2015, 2020, 2025)	No political constraint Political constraints	GENeSYSMOD	Perfect Foresight	Power Assets	0.15 (1%) 0.2-0.25 (1.5-2%)
Spavieri (2019) <i>IAEE Energy Forum Brief</i>	Venezuela US\$	Comparison of BAU fossil extraction with cuts necessary to achieve 1.5 or 2°C	CTI carbon budgets	Irr.	Irr.	Fossils	0.0018 (0.30%)
Binsted (2020) <i>Environmental Research Letter</i>	Latin America US\$	Model runs (2020-2050) computation of early decommissioning and comparison to “full lifetime” use of capital. 4 scenarios (NDCs, 1.5, 2°C)	Homemade NDC-1.5-2°C scenarios	GCAM	Perfect Foresight	Fossil power assets	0.037-0.09 (0.8-2%)

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Table A.3: Book value losses (Regional level) – Continued

(1) Authors (Year) Publication	(2) Geographical coverage Currency	(3) Methodology	(4) Reference Scenario(s)	(5) Underlying model(s)	(6) Expectation structure	(7) Exposed sectors	(8) Value in trillion (Fraction of country 2020 GDP)
Lin et al. (2020) <i>IAEE Energy Forum</i>	China CN¥	Two scenarios, computation of power plants forced to decommission prematurely in 2030	Delayed-action scenario	n.a	n.a	Coal Utilities and Genera- tion assets	0.103 (0.001%)
			Early-action sce- nario				0.04 (0.0003%)
Oshiro & Fujimori (2021) <i>Sustainability Science</i>	Japan US\$	Multiplication of stranded physical capacity by annualised investment by technology with a 5% discount rate along decarbonisation path	Homemade NDC- 1.5°C-2°C scenar- ios with different possible timelines and complemen- tary policies	AIM-Enduse	Myopic	Fossil power assets (Coal & Gas) Real Estate Trans- portation	0.04-0.09 (0.8- 1.8%)
Zhang et al. (2021) <i>Climate Policy</i>	China CN¥	Computation of prematurely decommissioned coal plants under various scenarios	No-additional ca- pacity scenario	Homemade model of asset stranding estimation	Irr.	Power (Coal)	0.382 (0.30%)
			Additional capac- ity scenarios				0.793 -3.160 (0.7-2.7%)
Hauenstein (2023) <i>Environmental Research Letter</i>	World (With regional dis- aggregation) US\$	Computation of early coal mine closures in 2030	1.5°C scenarios	COALMOD-World	Irr.	Coal mines	0.12-0.15 (Irr.) China most hit

Note: Irr. Stands for "Irrelevant". Monetary values are in constant currency from a given date, depending on the study. Studies selected through regularly repeated queries on Scopus, Google Scholar and Web of Science.

* US\$250\$, provided by (Mercure, Pollitt, N. R. Edwards, et al. 2018).

Table A.4: Foregone Income Stranded Assets (Regional level)

(1) Authors (Year) Publication	(2) Geographical coverage Currency	(3) Methodology	(4) Reference Scenario(s)	(5) Underlying model(s)	(6) Expectation structure	(7) Exposed sectors	(8) Value in trillion (Fraction of country 2020 GDP)
Nelson et al. (2014) CPI Report	US US\$	Estimate of the revenue losses for fossil fuel producers associated with a shift to a 450 ppm (8% Discount Rate)	IEA450 ppm	WEM	Perfect Foresight	Resources & Power	3.4 (15%)
	EU US\$						0.6 (3%)
	China US\$						1.6 (10%)
	India US\$						0.4 (15%)
	Brazil US\$						1.1 (61%)
	Russia US\$						2.5 (138%)
	Other Oil Producers US\$						10.5 (NA)
	Other Coal Producers US\$						1.2 (NA)
	Rest of the world US\$						3.4 (NA)
Spencer et al. (2017) Report	China US\$	Net present value of income flows from coal plants (6% discount rate)	2°C Scenario (2005-2035)	Irr.	Irr.	Coal Utilities and Generation assets	0.156 (1%)
			"Managed scenarios (2005-2035) 2°C"				

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Table A.4: Foregone Income Stranded Assets (Regional level) – Continued

(1) Authors (Year) Publication	(2) Geographical coverage Currency	(3) Methodology	(4) Reference Scenario(s)	(5) Underlying model(s)	(6) Expectation structure	(7) Exposed sectors	(8) Value in trillion (Fraction of country 2020 GDP)
		Net present value of losses	Irr.(2013-2035)	Irr.	Irr.	Fossil exporting companies	US\$0.093 (30%)
Huxham et al. (2019) Report	South Africa US\$	in fossil exports due to the low-carbon transition (Discount rate not mentioned)	"Managed 2°C" scenarios (2005- 2035)				0.097 (0.60%)

Note: Irr. Stands for "Irrelevant". Monetary values are in constant currency from a given date, depending on the study. Studies selected through regularly repeated queries on Scopus, Google Scholar and Web of Science.

Table A.5: Unneeded CAPEX (World Estimates)

(1) Authors Year Publication	(2) Geographical coverage	(3) Methodology	(4) Reference Scenario(s)	(5) Underlying model(s)	(6) Expectation structure	(7) Exposed sectors	(8) Value in US\$tn (Fraction of initial GFC loss, %)*	
Caldecott et al. (2013) Report	Australia	Study of possible write-offs due to drop in China's coal demand to Australia	World Bank, IEA	Irr.	Irr.	Extractive (Coal)	Around AU\$50bn of pipelined coal mines at risk in 2013 (N/A)	
Leaton et al. (2015) Report	World	Value of projects in surplus in 2025 compared to a low-demand scenario	IEA/Shell	IEA/Shell	Irr.	Energy (Gas)	0.283 (113.20%)	
Leaton (2015) Report	World	Unneeded CAPEX to remain within Carbon Budget	IEA 450 Scenario IEA 2°C scenario	World Model	Energy	Perfect foresight	Extractive (Coal)	0.2 (80%)
							Extractive (Gas)	0.5 (200%)
							Extractive (Oil)	1.3 (520%)
							Total	2 (800%)
CERES (2015) Report	World	Value of capex deferred or cancelled in 2014	Irr.	Irr.	Irr.	Extractive (Gas/Oil)	0.2 (80%)	
Muttit (2016) Report	World	Lists future decommissioned existing and to-be-built plants in excess of carbon budget and without CCS development	IEA (2014-2035)	Unclear	Irr.	Extractive Transportation of fossil fuels	10 (4000%) 4 (1600%)	
Leaton et al. (2018) Report	World	Value of sanctioned and expected business-as-usual CAPEX going beyond a 2°C carbon budget	IEA 450 Scenario for carbon budget	Irr.	Irr.	Extractive (Oil and gas)	2.3 (920%)	
Grant and Coffin (2019) Report	World	Value of CAPEX sanctioned in 2018-2019 inconsistent with carbon budget	IEA "Beyond 2°C" scenario	Irr.	Irr.	Extractive (Oil)	0.05 (20%)	
			BAU: IEA NDC scenario IEA 2°C scenario			Extractive (Oil)	1.5 (600%)	
			BAU: IEA NDC scenario IEA "Beyond 2°C" scenario			Extractive (Oil)	2.3 (920%)	
Edwards et al. (2022) <i>Environmental Research Letter</i>	World	Costs associated with pipelined coal plants compared to decarbonisation trajectories without new coal plants	2°C	GCAM	Perfect Foresight	Power (Coal)	1 (400%)	
			1.5°C				1.4 (560%)	

Note: Irr. Stands for "Irrelevant". Monetary values are in constant currency from a given date, depending on the study. Studies selected through regularly repeated queries on Scopus, Google Scholar and Web of Science.

* US\$250\$, provided by Mercure et al. (2018)

B. Finance-oriented methods

Table B.1: Financial Institutions' Exposure to Fossil Fuel-Related Assets

(1) Authors (Date) Publication	(2) Location of Financial Institutions (Period) Currency	(3) Assets' Sectors Choice criterion	(4) Exposed financial sectors	(5) Assets classes (Financial risk)	(6) Exposure in currency unit (Proportion of total assets, %, when available)
Leaton et al. (2011) Report	Australia, Brasil, Toronto, Russia United Kingdom (2010) US\$	Fossil	All	Stocks	30% of market capitalisation
	China, France, Hong-Kong, South Africa US\$				10% of market capitalisation
Weyzig et al. (2014) EU Parliament Report	EU (2014) €	Fossil	Banks		0.46-0.48 (1.3-1.36%)
			Pension Funds	All (All)	0.26-0.33 (5-6%)
			Insurance Companies		0.3-0.4 (3.9 - 5.14%)
			Total		1.02-1.21 (0.8 - 1%)
Prudential Regulation Authority (2015) Report	World (2014) US\$	Fossil fuel companies		Equity (Market)	6 (8%)
				Bonds (Market/Credit)	3 (4%)
				Loans (Credit)	0.3 (0.40%)
				Total	9.3(12.40%)
				Equity (Market)	9.2 (12%)
		Carbon-Intensive sectors	Insurance Companies	Bonds (Market/Credit)	3.5 (4.50%)
				Loans (Credit)	Loans: 0.5 (0.70%)
				Total	13.2 (17.20%)
				Equity (Market)	17.2 (20%)
				Bonds (Market/Credit)	6.5 (8.50%)
Total		Loans (Credit)	0.8 (1.1%)		
		Total	22.5 (29.60%)		

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Table B.1: Financial Institutions' Exposure to Fossil Fuel-Related Assets – Continued

(1) Authors (Date) Publication	(2) Location of Financial Institutions (Period) Currency	(3) Assets' Sectors Choice criterion	(4) Exposed financial sectors	(5) Assets classes (Financial risk)	(6) Exposure in currency unit (Proportion of total assets, %, when available)		
ESRB (2016) ESRB Report	EU (2015) €	Fossil fuel companies, carbon-intensive sectors	Banks	Equity (Market)	0.098 (0.00%)		
				Loans & Bonds (Market/Credit)	0.365 (1%)		
				Total	0.463 (1.30%)		
			Pension Funds	Equity (Market)	0.196 (0.38%)		
				Loans & Bonds (Market/Credit)	0.06 (0.01%)		
				Total	0.256 (5%)		
			Insurance Companies	Equity (Market)	0.109 (1.40%)		
				Loans & Bonds (Market/Credit)	0.233 (3%)		
				Total	0.342 (4.40%)		
			Schotten (2016) DNB Report	Netherlands (2015) €	Climate Policy Relevant sectors	Banks	0.19 (9.70%)
						Insurance Companies	0.034 (4.40%)
						Pension Funds	0.0866 (12.40%)
Total	0.3106 (9%)						
Battiston et al (2017) <i>Nature</i>	World (2015) US\$	Climate Policy Relevant sectors	Largest banks**	JPMorgan Chase: 0.15 Lazard: 0.03			
			Largest investment funds**	Blackrock: 0.25 Schroders PLC: 0.02			
			All investment funds	4			
			All banks	2			
			All Other Finan- cial Institutions	2			
Prudential Regulation Authority (2018) Report	UK (2018) £	Automotive	Banks	Loans & Bonds (Market/Credit)	0.02		

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Table B.1: Financial Institutions' Exposure to Fossil Fuel-Related Assets – Continued

(1) Authors (Date) Publication	(2) Location of Financial Institutions (Period) Currency	(3) Assets' Sectors Choice criterion	(4) Exposed financial sectors	(5) Assets classes (Financial risk)	(6) Exposure in currency unit (Proportion of total assets, %, when available)
Delgado (2019) Banco de España <i>Revista de Estabilidad Financiera</i>	Spain (2010s) €	All	Deposit-taking institutions	Loans (Credit)	20-25% of total assets
	US (2014) US\$				0.505
	EU (2014) US\$				0.702
Nieto (2019) <i>Journal of Financial Regulation and Compliance</i>	China (2014) US\$	All	Banks	Syndicated Loans (Credit)	0.069
	Japan (2014) US\$				0.301
	Switzerland (2014) US\$				0.058
	Total (2014) US\$				1.637
Ramírez (2020) 2ii Report	Colombia (2019) US\$	Oil & gas, coal mining, power utilities, aviation, shipping, cement and steel Restriction to top emitters in each sector, covering 90% of emissions in average portfolio	Insurance companies	All	0.0015 (10.50%)
Battiston et al. (2020) <i>OeNB Financial Stability Report 40</i>	Austria (2019) US\$	Climate Policy Relevant sectors	Banks	Loans and Bonds (Market/Credit)	0.228 (28%)
Ramírez et al. (2020) IDB Technical Note	Argentina Brazil Colombia Chile Mexico (2020) US\$	Highest emitters in Fossil, Material and Buildings, Transportation and Power	Individuals Pension funds Investment Funds	Equity & Bonds (Market/Credit)	20 to 50% of market capitalisation significantly exposed to transition risks
Baer (2021) CEENRG Working Paper	World (2018) US\$	Fossil	All	Bonds (Market/Credit)	0.21
				Equity (Market)	2.6
				Total	2.8
Bellrose et al. (2021) Report	Australia US\$	All	Banks	Loans (Credit)	20-25% of bank loans extended to top-50% emitters

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Table B.1: Financial Institutions' Exposure to Fossil Fuel-Related Assets – Continued

(1) Authors (Date) Publication	(2) Location of Financial Institutions (Period) Currency	(3) Assets' Sectors Choice criterion	(4) Exposed financial sectors	(5) Assets classes (Financial risk)	(6) Exposure in currency unit (Proportion of total assets, %, when available)
Avgouleas et al. (2021) Report	EU €	All	Banks	Loans (Credit)	30-35% of loans exposed to high transition risks Homogenous across countries Top 10% most polluting banks mostly located in Italy, France and Germany
Manych et al. (2021) <i>Environmental Research Letters</i>	Global (2015) US\$	Fossil Infrastructures	All	Loans (Credit)	0.469
				Underwriting	1.321
				Bonds (Market/Credit)	0.038
				Equity (Market)	0.239
Marques & Carvalho (2021) Banco de Portugal Occasional Paper	Portugal (2019) €	Fossils Transportation Buildings Agriculture Scope 1 & Scope 3 emissions with sub-sectoral disaggregation based on carbon intensity	All	All	0.021-28%
Ganswindt et al. (2021) Report	Global (2016-2020) US\$	Fossil infrastructures	Banks	Loans (Credit)	3.8 (n. a)
Ferrer et al. (2021) Banco de España Report	Spain (2021) €	Climate Policy Relevant sectors	Banks	Loans (Credit)	n. a-3.50%
Alessi & Battiston (2022) <i>International Review of Financial Analysis</i>	EU (2020) €	Choice criterion based on EU taxonomy: share of sectors that does not comply with the taxonomy	Banks	Investment Funds	0.57 (6.10%)
				Equity & Bonds (Market/Credit)	0.077 (1.70%)
				Insurance companies	0.44 (5%)
				Money Market Funds	0.018 (3.30%)
D'Orazio et al. (2022) Working Paper	Germany (2008-2018) €	All	Banks	Loans (Credit)	0.260-0.440 (20-30%)
Faiella & Lavecchia (2022) <i>Journal of sustainable finance and investment</i>	Italy (2018) €	Climate Relevant Sectors	All loan-making institutions	Loans (Credit)	0.474 (12.90%)
		Above-median emitters			0.364(14.40%)
		First quintile of the average ranking of borrowers and emitters			0.528 (14.40%)

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Table B.1: Financial Institutions' Exposure to Fossil Fuel-Related Assets – Continued

(1) Authors (Date) Publication	(2) Location of Financial Institutions (Period) Currency	(3) Assets' Sectors Choice criterion	(4) Exposed financial sectors	(5) Assets classes (Financial risk)	(6) Exposure in currency unit (Proportion of total assets, %, when available)
Kirsch et al. (2022) Report	Global (2021) US\$	Fossil infrastructures (New Financing)	Banks	Loans & Underwriting(Credit)	0.1459 (n. a)
Colenbrander et al. (2023) <i>Global Environmental Change</i>	India (2021) Indian Rupee (₹)	Carbon-Intensive sectors (UNFCC classification)	Banks	Loans	13.03 (12%)

Note: Monetary values are in constant currency from a given date, depending on the study. Studies selected through regularly repeated queries on Scopus, Google Scholar and Web of Science.

Table B.2: Static stress-tests

(1) Stress-test type	(2) Authors (Year) Publication	(3) Geographical Coverage (Period)	(4) Depreciated Assets' class (Financial risk)	(5) Exposed financial sectors	(6) Assets' Sectors	(7) Methodology	(8) Transition driver	(9) Scenario(s)	(10) Underlying model(s)	(11) Metric	(12) Findings
Scenario	Weyzig et al. (2014) EU Par- liament Report	EU (2014)	All	Banks	Fossil	Top-20 financial institutions by portfolios then extrapolation to the whole sector	Technology	Low-carbon breakthroughs (Heavy losses on fossil assets, including equity)	Irr.	Shock to total assets	0.40%
				Pension Funds							2.5-3.4%
				Insurance Compa- nies							2%
Model-Based	Monasterolo et al. (2018) China and World Economy	China (2018)	Syndicated loans (Credit)	Two main develop- ment banks	Energy & Utility	Stress-test based on different IPCC scenario assumptions, with a shock in 2020-2030.	Technology	LIMITS Database	GCAM, WITCH	Share of asset at Climate Value at Risk*	4%-22%
											US\$0.7bn - 3.8bn
Model-Based	Battiston & Monas- terolo (2018) OeNB Confer- ence Paper	Austria (2018)	All	Central Bank (OeNB)	Energy, Utility & Sovereign	Stress-test based on IPCC scenario, with shock in 2020-2030. Risk premium of sovereign bonds based on GDP shocks	Technology	LIMITS Database	GCAM WITCH	Loss in value of sovereign bond portfolio	Between -0.4% loss to 0.1% gain
											Underlying scenarios and geographical area have a large influence on gains and losses
Model-Based	Ralite & Thomä (2019) 2ii Report	Global (2019)	All	Stocks	Energy, Manufac- turing, Transports	Compute differences in expected NPV from financial income between BAU and decarbonisation scenario	All	Delayed-Action Scenario (Decarbonisation occurs in 2040)	NPV Valua- tion Model	Changes in asset values	-80% to +40% shock depending on sector
				Bonds							-20% to +6% shock depending on sec- tor and maturity

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Table B.2: Static stress-tests – Continued

(1) Stress-test type	(2) Authors (Year) Publication	(3) Geographical Coverage (Period)	(4) Depreciated Assets' class (Financial risk)	(5) Exposed financial sectors	(6) Assets' Sectors	(7) Methodology	(8) Transition driver	(9) Scenario(s)	(10) Underlying model(s)	(11) Metric	(12) Findings
	Ramírez (2020) 2ii Report	Colombia (2019- 2025)	All	Insurance	Top emitters in oil & gas, coal mining, power utilities, aviation, shipping, cement and steel	Explore various 2°C-compatible scenarios	Technology	2°C scenario	PACTA	Alignment of portfo- lios with climate targets	Portfolios compatible with a <1.75°C trajectory, except in power sector
	EIOPA (2020) Report	EU (2018)	All	Insurance	All	Computation of portfolio losses due to changes in sovereign bond value based scenario's GDP costs	Technology	LIMITS Database Two market con- dition hypothesis (mild, adverse) Shock in 2020-2030	GCAM, WITCH	Changes in asset values	4-5% losses at worst
	Conte & Meglioli (2021) MFSA Report	Malta (2020)	All	All	Climate- relevant sectors	Use of various asset-valuation models to compute immediate losses after the implementation of a carbon tax	Policy	Various carbon tax levels (10-200\$)	Multiple asset valuation models (one for each asset type)	Change in asset values	2-6% lossMost exposed banks suffer manageable losses
Econometrics	Grippa et al. (2020) IMF Report	Norway (2019)	Equity (Market)	Insurers, Pension funds and non- money market funds	Oil Sector	Structural VAR linking oil sector performances to stock performance	Policy	None	Dividend model	Change in asset values	-5.06

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Table B.2: Static stress-tests – Continued

(1) Stress-test type	(2) Authors (Year) Publication	(3) Geographical Coverage (Period)	(4) Depreciated Assets' class (Financial risk)	(5) Exposed financial sectors	(6) Assets' Sectors	(7) Methodology	(8) Transition driver	(9) Scenario(s)	(10) Underlying model(s)	(11) Metric	(12) Findings
World Bank (2021) World Bank Report	Colombia (2028- 2029)	All	All	All	All	Explore various 2°Compatible scenarios. Consider a two-year window along this scenario	All	Delayed – Low mit- igation	SYSMO	Increase in pro- portion of non- performing loans on different loan types	0%
								Smooth – High de- carbonisation			0.1-0.5%
								Delayed – High De- carbonisation			0.5-2%
Banco de España (2022) Report	Spain (2020- 2023)	Loans (Credit)	Banks	EU-ETS coverage	EU-ETS coverage	Compute Default probability increases on various scenarios	Policy	Higher carbon price	CATS	Increase in default probabilities	0.00%
								Extension of ETS coverage			0.00%
								Combination of above			0.01%
Ravina (2022) Working Paper	EU (2018)	Bonds (Credit/Market)	All	EU-ETS firms	EU-ETS firms	Derives a beta (risk premium) from a portfolio long on EU-ETS exposed corporate bonds and short on others. Applies a CO2 price shock on this beta for six portfolios	Policy	Three shock sizes (+20, +50 and 100 allowance price)	Irr.	Abnormal returns on portfolios	Between -0.03% and -0.33% excess returns on portfolios depending on their carbon contents

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Table B.2: Static stress-tests – Continued

(1) Stress-test type	(2) Authors (Year) Publication	(3) Geographical Coverage (Period)	(4) Depreciated Assets' class (Financial risk)	(5) Exposed financial sectors	(6) Assets' Sectors	(7) Methodology	(8) Transition driver	(9) Scenario(s)	(10) Underlying model(s)	(11) Metric	(12) Findings
	Faiella et al. (2022) <i>Banco d'Italia - Questioni di Economia e Finanza</i>	Italy (2015)	Loans (Credit)	NFCs	Irr.	Estimate losses to EBITDA due to carbon prices and computes the additional number of firms with an interest payment to EBITDA ratio superior to 50%	Policy	Four carbon prices: € 50 € 100 € 200 € 800	Irr.	Increases in the share of financially vulnerable households and NFCs	+45% - +92% vulnerable firms (Concentrated in small firms) +1.6% - +11.8% vulnerable households
	Ferentinos et al. (2023) Bank of England Working Paper	UK (2018)	Housing (Market)	Households	Irr.	Apply a diff-in-diff approach (with matching) to test the effect of the British Minimum Energy Efficiency Standard on low-efficiency house values	Policy	Irr.	Irr.	Changes in house value	Affected houses lost £5,000-9,000 in value
	Jung et al. (2021) New York Fed Staff Report	US, UK, Canada, France, Japan (2019-2020)	Equity Market)	Banks (27 large banks representing 80% of oil and gas market shares in equity holdings)	All	Derive a climate risk factor (CRISK) from a long-short portfolio and computes a beta on returns from it. Applies this beta on aggregate bank holdings and applies a six-month long 50% drop in high-carbon asset returns	Any	Irr.	Irr.	Portfolio value losses after the shock with respect to real-world counterfactual	US: US\$70-90bn (20-30% bank equity) Canadian and UK banks have similar vulnerabilities Japan and France less exposed.

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Table B.2: Static stress-tests – Continued

(1) Stress-test type	(2) Authors (Year) Publication	(3) Geographical Coverage (Period)	(4) Depreciated Assets' class (Financial risk)	(5) Exposed financial sectors	(6) Assets' Sectors	(7) Methodology	(8) Transition driver	(9) Scenario(s)	(10) Underlying model(s)	(11) Metric	(12) Findings
	Hentati-Kaffel & Ravina (2020) Working Paper	EU	Equity	All	EU-ETS firms	Derives a beta (risk premium) from a portfolio long on EU-ETS exposed equity and short on others. Applies an emission allowance shock to this beta for six portfolios. Three shock sizes (+20, +50 and +100 allowance price)	Policy	Irr.	Irr.	Abnormal returns on portfolios	Between -0.39% and -1.37% excess returns on portfolios depending on their carbon contents
	Sever & Perez-Archila (2021) IMF Working Paper	Colombia (2020)	Loans	Banks	All	Computation of default probabilities from firm financials and assessment of ripple effects to banks	Policy	Overnight implementation of a \$70 carbon tax	Irr.	Measure of banks' financial stress based on leverage and liquidity Asset shortfalls	1-4% of total assets stressed under the scenarioUp to 13% for highly exposed banks
	Ojea-Ferreiro at al. (2022) Working Paper	World (2020-2022)	Equity	All	All	Copula-based model of financial risks linking transition scenarios to changes in asset returns and then losses for financial institutions	All	Orderly, disorderly and no transition	Irr.	liquidity Asset shortfalls	Orderly scenarios yield negligible risks, while disorderly scenarios generate higher risks, notably for banks.

Note: Irr. Stands for "Irrelevant". Monetary values are in constant currency from a given date, depending on the study.* Value for which 5% of investment projects hit by the same policy shocks entail losses greater or equal to the CVaR.

Table B.3: Network stress-tests

(1) Author (Year) Publication	(2) Geographical Coverage (Period)	(3) Depreciated Assets' class (Financial risk)	(4) Exposed financial sectors	(5) Assets' Sectors	(6) Methodology	(7) Transition driver	(8) Reference Scenario(s)	(9) Underlying model(s)	(10) Findings
Battiston et al. (2017) <i>Nature Climate Change</i>	EU (2017)	Loans and Bonds (Credit & Market)	Largest Banks*	Energy and Utility	Stress-test with second-round effects - 100 % Catastrophic shock - Bottom-up with largest banks	Technology	None	None	DeutscheBank: 30% of its equity Svenska Handels- banken: 7% Second-round ef- fects can make up to 100% of the shock for some banks
					Stress-test with second-round effects - IPCC Scenario shocks - Bottom-up with largest banks and different investment strategies		LIMITS Database	WITCH & GCAM	“Green” invest- ment strategy: DeutscheBank: €300 million VaR** Svenska Handels- banken: €100 mil- lion VaR** “Brown” invest- ment strategy: DeutscheBank: €2.5 billion VaR** Svenska Handels- banken: €100 mil- lion VaR**
Bateson & Saccardi (2020) CERES Report	US (2020)	Syndicated Loans (Credit)	Banks	All	Cartography of US banks' syndicated loan exposure to climate-relevant assets Stress test includ- ing second-round effects and fire- sales	Technology	LIMITS and GREENWIN database	All IPCC Models	18% of loans ex- posed
Roncoroni et al. (2021) <i>Journal of Financial Stability</i>	Mexico (2019)	All (Credit & Market)	All	All climate- relevant sectors	Stress-test with disorderly shift to a 2°C-consistent path at several points in time	Technology	LIMITS database	WITCH & GCAM	2.5-4% of total as- sets

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Table B.3: Network stress-tests – Continued

(1) Author (Year) Publication	(2) Geographical Coverage (Period)	(3) Depreciated Assets' class (Financial risk)	(4) Exposed financial sectors	(5) Assets' Sectors	(6) Methodology	(7) Transition driver	(8) Reference Scenario(s)	(9) Underlying model(s)	(10) Findings
Semeniuk et al. (2022) PERI UMass Working Paper	Global	Equity (Market)	All	Fossil	Shock to real assets' values, computation of corresponding foregone income (dividends) and ripple-offs along ownership chains	n. a	2°C and 1.5°C	E3ME	US\$0.6 trillion of cumulated foregone income for the financial sector
Belloni et al. (2022) Working Paper	EU (2020-2025)	Loans (Credit)	Banks	All	Banking contagion model relating various carbon price scenarios to banks' vulnerability	Policy	NGFS	Model of financial contagion	Sizeable loss in case of disorderly scenarios (1.5°C low CDR and Delayed-Action), especially if firms do not abate emissions.
Emambakhsh (2022) <i>ECB Financial Stability Review</i>	EU (2022)	All (Credit & Market)	Banks	All	Stress test involving banks, insurance and pension funds computing tail losses for banks (99th percentile)	Policy	Various carbon price assumptions	Irr.	Banks: 13-40% of assets at tail losses
Gourdel & Snyder (2022) ECB Working Paper	EU (2022)	Tradable (Market)	Funds	All	Stress test involving non-banks, disaggregation of exposures across sector, computation of tail losses. Addition of a redemption shock on asset liquidity	Policy	Disinvestment shock	Irr.	Gains (1-2%) for bottom-20% carbon-intensive funds. Losses down to 8% for others. Small amplification through network effects.

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Table B.3: Network stress-tests – Continued

(1) Author (Year) Publication	(2) Geographical Coverage (Period)	(3) Depreciated Assets' class (Financial risk)	(4) Exposed financial sectors	(5) Assets' Sectors	(6) Methodology	(7) Transition driver	(8) Reference Scenario(s)	(9) Underlying model(s)	(10) Findings
Li et al. (2022) <i>Environmental Science and Pollution Research</i>	China	Loans (Credit)	Banks	All	Stress-test with second-round ef- fects based on car- bon price shocks	Policy	n. a	None	Exponential rela- tionship between carbon tax & asset losses. Threshold effect. Important regional variations.

Note: Monetary values are in constant currency from a given date, depending on the study. Studies selected through regularly repeated queries on Scopus, Google Scholar and Web of Science.

*Only the results for the most and least vulnerable entities are mentioned.

**Defined as the loss prevailing on the top-5% transition shocks in terms of magnitude.

Table B.4: Dynamic stress tests

(1) Author (Year) Publication	(2) Geographical Coverage (Period)	(3) Depreciated Assets' class (Financial risk)	(4) Exposed financial sectors	(5) Assets' Sectors	(6) Methodology	(7) Reference Scenario(s)	(8) Underlying model(s)	(9) Findings
Vermeulen et al. (2018; 2021) DNB Report	Netherlands (2017-2022)	All (Credit & Market)	Banks, pension funds & insurance companies	Mining & Petrochemical Utilities Basic Industry Transport	Use of a macroeconomic model, then apply structural change + macro shock results to balance sheet data 5-year horizon	Policy shock (Increase in worldwide carbon price by US\$100)	Shock to total asset value	Banks: - 2%
						Technology shock (Doubling of the share of low-carbon energy in final energy demand)		Insurers: -8%
						Policy + Technology shock		Pension Funds: -7%
						Confidence shock (Lower consumption and investment, increase of risk premium by one basis point)		Banks: - 1%
ESRB (2020) Report	EU (2020-2024)	All (Credit & Market)	Banks, pension funds & insurance companies	Mining & Petrochemical Utilities Basic Industry Transport	Use of a macroeconomic model, then apply structural change + macro shock results to balance sheet data 5-year horizon Includes retro-feedback from financial sector to the macroeconomy	Policy shock (Increase in worldwide carbon price by US\$100)	Shock to total asset value	Banks: - 1.8%
						Technology shock (Doubling low-carbon energy share in final energy demand)		Insurers: -2.2%
						Policy + Technology shock		Pension Funds: -10%
						Confidence shock (Lower consumption and investment, increase of risk premium by one basis point)		Banks: - 2.5%
								Banks: - 0.45%
								Insurers: -1%
								Banks: -0.3%
								Insurers: -0.8%

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Table B.4: Dynamic stress tests – Continued

(1) Author (Year) Publication	(2) Geographical Coverage (Period)	(3) Depreciated Assets' class (Financial risk)	(4) Exposed financial sectors	(5) Assets' Sectors	(6) Methodology	(7) Reference Scenario(s)	(8) Underlying model(s)	(9) Findings
Guth et al. (2021) OeNB Report	Austria (2019-2025)	Credit	Banks	17 CPRS	Coupling of an input-output model with a simple macro framework then linked to a financial risk module	Orderly	Corporate default	+0-3% depending on the sector
							Corporate bond and equity	-€200 million losses in valuation
							Banks' CET ratio	-0.7 points
						Disorderly	Corporate default	+0-10% depending on the sector
							Corporate bond and equity	-€540 million losses in valuation
							Banks' market capitalisation	-2.7 points
Carlin et al. (2022) UNEP-FI Report	World	Credit and Market	All	All	Macroeconomic model (NIESR) with some finance-relevant outputs	Sharp increase in carbon price in 2025 (US\$130-700 depending on the country). Current policy baseline. Regional disaggregation	House prices	-0.75 to -2.3% compared to baseline
							Equity prices	-15% to -35% compared to baseline
							Long real rates	+0.6% to +1.2%

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Table B.4: Dynamic stress tests – Continued

(1) Author (Year) Publication	(2) Geographical Coverage (Period)	(3) Depreciated Assets' class (Financial risk)	(4) Exposed financial sectors	(5) Assets' Sectors	(6) Methodology	(7) Reference Scenario(s)	(8) Underlying model(s)	(9) Findings
ECB-ESRB (2022) Report	EU (2021-2026)	All (Credit & Market)	Banks, Insurance, Investment Funds	All	Use of a contagion model over a five-year horizon, constant balance sheet	Substantial increase in carbon prices corresponding to the five most adverse NGFS scenarios	Credit and market losses	Banks: 0.7% in 2026 Insurers: 3% in 2026 Investment funds: 25% in 2026
Várgedő (2022) <i>Financial and Economic Review</i>	Hungary (2021-2023)	Credit	All	Banks	Macroeconomic model (Polaris) with sectoral block and financial module for the computation of default probabilities	Carbon price shock (US\$150) in 2021	Bank loss ratio	+6% loss at most

Note: Monetary values are in constant currency from a given date, depending on the study. Studies selected through regularly repeated queries on Scopus, Google Scholar and Web of Science.

*Only the results for the most and least vulnerable entities are mentioned.

**Defined as the loss prevailing on the top-5% transition shocks in terms of magnitude.

Table B.5: Long-run Portfolio Assessments

(1) Authors (Year) Publication	(2) Geographical coverage	(3) Depreciated Assets' class	(4) Metric	(5) Exposed financial sectors	(6) Assets' Sectors	(7) Methodology	(8) Reference Scenario(s)	(9) Underlying model(s)	(10) Findings
Mercer (2015) Report	Global	Expected yearly returns decreases over 35 years (to 2050)	Changes in returns	All	Energy sector equities Real estate Timber Agriculture	4-scenario approaches with 4 risk types (resources/ policy/ technology/resource)	2°C, 3°C and 4°C scenarios	Homemade investment model	Around 1% loss in returns for Oil-Gas-utilities
HSBC (2018) Report	Global	Equity	Change in value	All	All sectors	Use of IAM to derive macro and structural impacts onto equity price through a CAPM model	Homemade, based on IPCC	TIAM-UCL	2% loss on average across sectors, with significant variance
Mercer (2019) Report	Global	Expected yearly returns decreases over 35 years (to 2050)	Change in value	Asset managers (Various portfolios)	Energy sector equities Real estate Timber Agriculture	4-scenario approaches with 2 risk types (Transition & Physical) Stress-test component	2°C, 3°C and 4°C scenarios	E3ME	Small losses/gains (+0,1; -0,4) depending on the portfolio at stake. Potentially much higher with unanticipated policy shocks (factor 10)
UNEP-FI (2019) Report	Global	Equity	Climate VaR*	Asset managers (Various portfolios)	All	Link between carbon price trajectories and portfolio losses 15 years horizon for portfolios	IPCC (SSP)	REMIND/GCAM +Carbon Delta Model	Immediate: \$4.3trillion Delayed: \$5.4 trillion
Bongiorno et al. (2022) Report	UK/Global	All	Changes in returns	Asset managers	All relevant + Real Estate & several asset classes	Homemade financial model, macro picture based on E3ME	Orderly Transition (2020, smoothed pricing behaviour)	Homemade (ClimateMAPS) + E3ME	Small losses in return over manageable time spans, mostly on equity Sudden transition leads to one-off 15% return losses in 2025

Note: Monetary values are in constant currency from a given date, depending on the study. Studies selected through regularly repeated queries on Scopus, Google Scholar and Web of Science.

Table B.6: NGFS-based stress tests

(1) Author (Year) Publication	(2) Geographical Coverage (Period)	(3) Assets' Sector	(4) Methodology	(5) Reference scenario(s)	(6) Underlying model(s)	(7) Key hypotheses	(8) Market risk	(9) Credit risk
Allen et al. (2020) Banque de France Report	France (2020-2050)	All	Scenario runs compared to baseline for various outcomes of interest	Orderly Transition (Baseline): Smooth introduction of a carbon tax in 2020	IAMs NiGEM Banque de France Sectoral Model (Devulder and Lisack 2020)	Adaptive Expectations		n. a
				Delayed Transition: Introduction of a carbon tax in 2030, consistent with existing IPCC scenarios	Banque de France Financial Model		-2 to -10% shock to stock prices in exposed sectors	Default probability in exposed sectors increases by 0- 400% in exposed sectors
				Sudden Transition: Introduction of a 1.5°C-consistent carbon tax in 2025, long-run productivity shock due to technological unreadiness			-5 to -22% shock to stock prices in exposed sectors	Default probability in exposed sectors increases by 0- 500% in exposed sectors
UNEP-FI (2021) Report	World (2020-2040)	Oil & Gas Transportation Utilities	Outcomes of NGFS scenarios fed into modules computing default probabilities for various sectors	Orderly (Climate Action in 2030)	Remind-MagPIE	Perfect Foresight	n. a	Manageable in- crease in default probabilities for all sectors under study.
								Small increased in default probabilities (possibly outside of the horizon of analysis)

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(1) Author (Year) Publication	(2) Geographical Coverage (Period)	(3) Assets' Sector	(4) Methodology	(5) Reference scenario(s)	(6) Underlying model(s)	(7) Key hypotheses	(8) Market risk	(9) Credit risk
Clerc et al. (2021) ACPR Report	France (2020-2050)	All	Regulatory exercise mobilising main financial actors, asking them for their risk exposures along transition scenarios	Disorderly	Irr.	Static Balance Sheet 2019 - 2025 Dynamic Balance sheet 2025-2050	n. a	Cost of risk increases from 12 to 15.8 basis point between 2019-2050
				Delayed Transition			€80 million loss in 2050 (Mostly from sovereigns)	Cost of risk increases from 12 to 16.5 basis point between 2019-2050
				Sudden Transition Scenario			€160 million in 2050 (Mostly from sovereigns)	Cost of risk increases from 12 to 17.1 basis point between 2019-2050

Note: Monetary values are in constant currency from a given date, depending on the study. Studies selected through regularly repeated queries on Scopus, Google Scholar and Web of Science.

5.4 C. Financial econometrics

Table C.1: Carbon Alpha Studies

(1) Author (Year) Publication	(2) Asset type	(3) Assets' Sector	(4) Geographical coverage (Period)	(5) Analysis type	(6) Methodology	(7) Measure of transition risk	(8) Results
Liesen et al. (2017) <i>Journal of Business Finance and Accounting</i>	Stocks	All	Europe	Portfolio Sorting	Three portfolios based on GHG performances and disclosures Carhart four-factor model	Hand-collected data based on corporate reports on GHG emissions and disclosure	Positive annualised alphas on low-emission (+3%), top-disclosing (+5%) firms, negative alphas on high-emissions (-1%), bottom-disclosing firms (-8%)
In et al. (2017) Working Paper	Stocks	All	US	Portfolio Sorting	Green-minus-brown portfolios	Sum of all emission scopes	3-5-5.4% abnormal returns on portfolios long on carbon-efficient firms
Cheema-Fox et al. (2019) Working Paper	Stocks	All	US (2010-2016)	Asset- Pricing	Computation of returns from several portfolios consisting in various strategies	Sum of all emission scopes	Significant decarbonisation alphas detected. Attributed to investors' lack of reaction
Gostlow (2019) Working Paper	Stocks	All	North America Europe Japan	Portfolio Sorting	Several portfolios including measures of physical and transition risks. Penalisation of over-specification	Carbon intensity	Transition risk indicators cannot explain returns on portfolio
Monasterolo & de Angelis (2020) <i>Ecological Economics</i>	Stocks	Energy and fossil	EU & US (1999-2018, depends on the stock index)	Portfolio sorting	Fama-French model applied on several stock indices with a dummy before/after the Paris Agreement	Classification based on sectoral indices	After the Paris Agreement, companies have started revaluing green companies, but not brown companies
Rusmita et al. (2020) <i>International Journal of Innovation, Creativity and Change</i>	Stocks	All	Indonesia (2017-2018)	Asset- Pricing	Cross-sectional analysis on stock prices (OLS)	Carbon Disclosure	No reaction to carbon disclosure performance

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Table C.1: Carbon Alpha Studies – Continued

(1) Author (Year) Publication	(2) Asset type	(3) Assets' Sector	(4) Geographical coverage (Period)	(5) Analysis type	(6) Methodology	(7) Measure of transition risk	(8) Results
Bernardini et al. (2021) Journal of Sustainable Finance	Stocks	Utilities	Europe (2008-2016)	Portfolio Sorting	Three portfolios (Green, Green-minus-brown, Brown)	Emission intensity of production (Scopes 1 and 2)	Green portfolio performs better than brown minus green which performs better than brown portfolios
				Asset- Pricing	Estimation of carbon alphas and estimation of a corresponding risk premium		Significant carbon alphas, linked to lower perceived risk on the low-carbon market
Antoniuk (2022) Sustainable Development	Stocks	All	Norway (2010-2020)	Portfolio sorting	Low-minus-high portfolios based on quality of disclosure	Quality of disclosure	Penalisation of low-score portfolios Outperformance of high-score portfolios if energy sector excluded Presence of green alpha
Bauer et al. (2023) Working Paper	Stocks	All	United States	Portfolio sorting	Brown-minus-green portfolio	Reported emissions	Outperformance of green assets (Except in Italy)
Duan et al. (2023) Journal of Financial and Quantitative Analysis	Corporate bonds	All	Global (2005-2017)	Asset- Pricing	Building of quintile portfolios, regression analysis	Carbon intensity of revenue (Scope 1)	Presence of significant carbon alphas, attributed to investor's underreaction

Note: Studies selected through regularly repeated queries on Scopus, Google Scholar and Web of Science.

Table C.2: Carbon Premium – Bottom-up Studies

(1) Author (Year) Publication	(2) Asset Type	(3) Assets' Sector	(4) Geographical Coverage (Period)	(5) Methodology	(6) Measure of climate risk	(7) Results
Aggarwal & Dow (2012) <i>The European Journal of Finance</i>	Stocks	All (500 largest US firms)	US (2009)	Cross-Section linking emission management with financial performances	Governance in favour of emission reduction	Negative short-run effects on financials Positive long-run effects
Nandy & Lodh (2012) <i>International Review of Financial Analysis</i>	Loans	All	US (1991-2006)	Panel regression with fixed effects	Environmental score	Negative relationship between cost of loan and environmental score
Fujii et al. (2013) <i>Business strategy and the environmental business strategy</i>	Stocks	Industry	Japan (2006-2008)	OLS relating financial performances to management of environmental issues	CO2 emissions	Positive relationship between environmental performance and financial performance
He et al. (2013) <i>China Journal of Accounting Studies</i>	All	All	US (S&P 500) (2009-2010)	Simultaneous-equation model with cost of capital, carbon disclosure and carbon performances as endogenous variables (3SLS)	Carbon disclosure and carbon performances	Carbon disclosure negatively associated with cost of capital Carbon disclosure negatively associated with carbon performances
Chava (2014) <i>Management Science</i>	Stock & Loans	All	Global (1992-2007)	Regression of environment-related metrics onto cost of capital (returns, loans)	Synthetic indicators of environmental performances and concerns, including carbon emissions	Higher returns required and higher credit spread for firms with higher emissions/environmental hazards- Even by controlling for key variables
Matsumura et al. (2014) <i>The Accounting Revue</i>	Stocks	All	US (S&P 500) (2006-2008)	Link between firm value and emissions (Scope 1) Logit model of disclosure decision	Scope 1 emissions	Firms with higher Scope 1 emissions have a lower market value
Clarkson et al. (2015) <i>European Accounting Review</i>	Stocks	EU-ETS industries	EU (2006-2009)	Link between firm value and - Emissions in excess of allowances - Pass-through capacity - Emissions outside of the EU-ETS	Emissions covered by the EU-ETS	Higher excess emissions associated with lower market capitalisation (75\$/t) Higher pass-through capacities increase valuation Emissions outside of EU-ETS less valued

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Table C.2: Carbon Premium – Bottom-up Studies – Continued

(1) Author (Year) Publication	(2) Asset Type	(3) Assets' Sector	(4) Geographical Coverage (Period)	(5) Methodology	(6) Measure of climate risk	(7) Results
Delmas et al. (2015) <i>Organization and Environment</i>	Stocks	All	US (2004-2008)	Panel model linking emission reductions to financial performances	Scope 1-3 emissions	Short-run financial performances decrease, Tobin's Q, more long-term, increases
Gallego-Álvarez et al. (2015) <i>Journal of Cleaner Production</i>	Stocks	All	World (2006-2009)	Pooled OLS linking emission reduction to financial performance	Scope 1-3 GHG emissions	Positive impact of carbon emission reduction on firm performance
Kim et al. (2015) <i>Journal of Cleaner Production</i>	Stocks	All	Korea (2007-2011)	Link between cost of equity and carbon intensity, disclosure and emission ranking	Carbon intensity (Sales, Scope unclear)	Higher cost of equity associated with higher carbon intensity (.08 elasticity) Disclosure unimportant Higher emitters face lesser hikes in cost of equity
Lee et al. (2015) <i>International Journal of Production Economics</i>	Stocks	All	World (2003-2010)	Panel model linking Tobin's Q to environmental performance and green R&D	Scope 1-3 emissions	Carbon emissions negatively linked with Tobin's Q. Environmental performances comparatively less relevant
Misani & Pogutz (2015) <i>Ecological Economics</i>	Stocks	All	World (2007-2013)	Link between Tobin's Q and measure of carbon performance (non-linear)	Emission intensity of sales (Scope 1 and 2)	Inverted U-shape relationship between Tobin's Q and environmental performance
Tian et al. (2016) <i>Journal of Cleaner Production</i>	Stocks	Electricity	EU (2006-2011)	Link between emission allowances on EU-ETS and stock returns/volatility	Carbon intensity	Greener companies experienced a positive relationship between allowance and stock prices. The opposite for carbon-intensive companies
Lewandowski (2017) <i>Business Strategy and the Environment</i>	Stocks	All	World (2003-2015)	Panel regression	Emission reduction	Negative relationship between emission reduction and Tobin's Q, notably for firms with inferior carbon performances
El Ghoul et al. (2018) <i>Journal of Business Ethics</i>	Stocks	All	World (2002-2011)	Panel regression	Metric of environmental friendliness	Negative link between cost of equity and environmental friendliness everywhere in the world

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Table C.2: Carbon Premium – Bottom-up Studies – Continued

(1) Author (Year) Publication	(2) Asset Type	(3) Assets' Sector	(4) Geographical Coverage (Period)	(5) Methodology	(6) Measure of climate risk	(7) Results
Jung et al. (2018) Working Paper	Loans and bonds	All	Australia (2009-2013)	Regression analysis of carbon risk (emission intensity) and carbon awareness (reporting or not carbon intensity)	Scope 1 emissions	Higher cost of capital for carbon-intensive risks. Higher costs negated by disclosing their carbon intensities
Atanasova & Schwartz (2019) Working Paper	Stocks	Fossil firms	US & Canada -2010	Regression	Time series analysis with undeveloped proven reserves as regressors	Investment in undeveloped proven reserves has a negative effect on firm value
Delis et al. (2019) Working Paper	Syndicated bank loans	All	Global (2007-2016)	Panel regressions with more and more controls and fixed effects	Measure of climate policy exposure thanks to existing climate policy index interacted with fossil-industry dummy	Increased spreads after 2015 (Paris Agreement), mainly due to climate policy
Bui et al. (2020) <i>Accounting & Finance</i>	All	All	44 countries (2010-2015)	Panel of 44 countries Regression of carbon intensity, carbon disclosure and interaction between the two on cost of capital (debt & equity)	Carbon intensity (Sales, Scope 1 & 2)	Carbon intensity entails higher cost of capital Moderated by higher disclosure
Palea & Drogo (2020) Working Paper	Loans and bonds	All	Eurozone (2010-2018)	Panel model: regression of cost of debt metric on carbon intensity, before-after Paris Agreement dummy and controls	Scope 1 and 2 emissions over revenue	Positive relationship between carbon intensity and cost of debt for high emitters before Paris, insignificant afterwards, reverse patterns for low emitters
Bätae et al. (2021) <i>Journal of Cleaner Production</i>	Stocks	Banks	Europe (2010-2019)	Panel regression	Emission reduction	No link between cost of capital (Tobin's Q) and emission reduction effort. Positive effect on the financial performances of the bank
Carbone et al. (2021) Working Papers	Loans	All	European Union and United States (2010-2019)	Regression of credit risks on carbon emissions and controls	Scope 1, 2 and 3	Firms more exposed to transition risks have lower credit ratings than similar firms that are less exposed, notably after the Paris Agreement
Choi & Luo (2021) <i>The British Accounting Review</i>	Stocks	500 largest global firms	World (2008-2015)	Panel regression linking market value to environmental disclosure and performances	Emissions	Negative relationship between GHG emissions and market value
Ehlers et al. (2021) <i>Journal of Banking and Finance</i>	Syndicated Loans	All	31 countries (2005-2018)	Panel data: regression of risk premia on loan characteristics, carbon content and other controls	Scope 1, 2 and 3 emissions	Scope 1 emissions are priced in, others not. Paris Agreement had an effect. Risk premia are very low (7 basis points)

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Table C.2: Carbon Premium – Bottom-up Studies – Continued

(1) Author (Year) Publication	(2) Asset Type	(3) Assets' Sector	(4) Geographical Coverage (Period)	(5) Methodology	(6) Measure of climate risk	(7) Results
Garzón-Jimenez & Zorio-Grima (2021) <i>Sustainability</i>	Stocks	All	30 emerging countries (2014-2019)	Application of a Price-Earnings model to the cost of equity (dividend payments)	Voluntarily disclosed Scope 1 and 2 emissions	Negative relationship between emissions and cost of equity
Gerged et al. (2021) <i>Business Strategy and the Environment</i>	Stocks	All	United Kingdom (2011-2016)	Panel Quantile Regression linking emissions to cost of equity	Total disclosed GHG emissions	U-shaped relationship between emissions and cost of equity and emission disclosure
Kempa et al. (2021) <i>Nature Energy</i>	Loans	Energy	OECD	OLS regression of cost of debt on various controls and renewables/non-renewable dummy	Renewable/Non-renewable projects	Lower risk premium on renewables, (.15-.4 basis points)
Kleimeier & Viehs (2021) <i>Economics Letters</i>	Loans	All	Global (2009-2016)	Regression of loan spreads on carbon disclosure and emission indicators	Scope 1 and 2 emissions Disclosure dummy	Disclosure associated with lower spreads Emissions associated with higher spreads
Siddique et al. (2021) <i>International Review of Financial Analysis</i>	Stocks	All	World (2011-2015)	Panel model linking carbon performances, carbon disclosure et financial performance	Measure of carbon performance	Negative effect of carbon performance on Tobin's Q in the short run, positive in the long run
Yang et al. (2021) <i>Research Square</i>	Loans	All	China (2007-2016)	Panel regression linking cost of debt to carbon disclosure	Measure of carbon disclosure	Disclosure reduces cost of debt
Beauchamp & Cormier (2022) <i>Managerial Finance</i>	Stocks	Fossil firms	U.S and Canada (2015-2017)	Two-step methodology linking probability to disclose emissions	Proven reserves and embedded emissions	Positive relationship between proven reserves and firm value Negative effect between embedded emissions and firm value
Ho & Wong (2022) <i>Emerging Market Review</i>	Loans	All	Emerging economies (2010-2021)	Panel model linking emission intensity with loan spread – adjusted for banks' attitude towards greenness	Scope 1 and 2 emissions (intensity)	Pricing of Scope 1 emissions since the Pris agreement

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Table C.2: Carbon Premium – Bottom-up Studies – Continued

(1) Author (Year) Publication	(2) Asset Type	(3) Assets' Sector	(4) Geographical Coverage (Period)	(5) Methodology	(6) Measure of climate risk	(7) Results
Seltzer et al. (2022) Working Paper	Corporate Bonds	Non-financial companies	US (State disaggregation)	Panel model estimating credit rating and spreads on corporate bonds	Sustainalytics Environmental Score Total carbon emissions Carbon intensity	0.6-20 basis points increase in spreads (depending on metric), overall small effects Rating notches decrease by .5 notches with emissions and intensity
Vozian (2022) Working Paper	CDS	All	Europe (2010-2021)	Panel regressing implied CDS spreads on transition risk exposure	Scope 1 emissions (absolute and intensity)	Higher emissions associate with higher spreads
Zhu & Zhao (2022) <i>Technological Forecasting and Social Change</i>	Loans	All	China (2009-2019)	Panel regression linking cost of debt to carbon intensity	Carbon intensity (sales)	Emissions increase cost of debt, especially if firms fall under the “Green Credit Guidance” implemented by the Chinese government

Note: Studies selected through regularly repeated queries on Scopus, Google Scholar and Web of Science.

Table C.3: Carbon Premium – Top-down studies

(1) Author (Year) Publication	(2) Asset Type	(3) Assets' Sector	(4) Geographical coverage/Period	(5) Analysis Type	(6) Methodology	(7) Measure of climate risk	(8) Results
Oestreich & Tsiakas (2015) <i>Journal of Cleaner Production</i>	Stocks	EU-ETS (Only German Firms)	EU (2009-2014)	Portfolio sorting	Building of a carbon factor based on the abnormal returns of a “Dirty” portfolio, composed of firms that received free allowances in Phases 1 and 2 of EU-ETS. A “clean” portfolio is composed of firms that did not receive free allowances	Alpha on a dirty-minus-clean portfolio	Carbon factor significant only in Phases 1 and 2 of EU-ETS
				Asset-Pricing	Use of asset-pricing model to measure the presence of a carbon premium	Detection of a carbon premium during Phase 1 and 2	
Choi et al. (2018) Working Paper	Stock Market	All	US (1976-2016)	Regression	Cross-section on returns	US National emissions	Negative premium on carbon-intensive firms
Zhang et al. (2018) <i>Theoretical Economics Letters</i>	Stocks	Chinese Pilot ETS	China (2013-2015)	Portfolio Analysis	Three portfolios: clean, dirty, dirty-minus-clean	Firms receiving free carbon allowances	Negative abnormal returns on dirty portfolios
Bolton & Kacperczyk (2020) Working Paper	Stocks	All	Global with disaggregation (2005-2017)	Panel Asset Pricing	Panel analysis of returns with many controls Regression of climate-risk coefficient on traditional risk metrics Regional disaggregation Tests with asset-pricing models to detect premia	Scope 1,2 and 3 emissions Growth rate of Scope 1,2 and 3 emissions Emission intensity (Scope 1,2,3)	Small regional differences in carbon premiums

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Table C.3: Carbon Premium – Top-down studies – Continued

(1) Author (Year) Publication	(2) Asset Type	(3) Assets' Sector	(4) Geographical coverage/Period	(5) Analysis Type	(6) Methodology	(7) Measure of climate risk	(8) Results
Görge et al. (2020) Working Paper	Stocks	All	Global (2010-2018)	Portfolio Sorting	Three portfolios, including a Green-minus-Brown one to disentangle low-carbon premium	Aggregate "greenness" indicator based on ESG metrics	Low-carbon portfolios outperform high-carbon one, especially in the extreme
				Asset Pricing	Panel regressions with increasing controls and fixed-effects. Estimate a "carbon beta" based on an aggregate factor		Aggregate factor makes for many usual risk measures but does not measure a carbon risk. Attributed to unpriced fundamental changes
Ravina & Kaffel (2020) Working Paper	Stocks	All	EU (2008-2018)	Portfolio Sorting	Six portfolios with different degrees of greenness valued with a Fama-French 2-factor model augmented with a measure of returns associated with compliance to EU-ETS	"Green minus brown" factor: difference between weekly value-weight carbon portfolio returns from the weekly value-weight green bond portfolio returns from the beginning of Phase II	Significant coefficients on the "Green minus brown" factor, interpreted as a positive green premium
RaboResearch (2020) RaboResearch Report	Stocks	All	Eurozone (2009-2019)	Asset Pricing	Fama-French five-factor model incorporating emission scopes, intensity and EU-ETS compliance Fama-McBeth detection of risk factor	Scope 1, 2,3 Compliance with EU-ETS Scope 1 & 2 intensity (Sales)	Emission scopes not priced in, except for firms under EU-ETS No detection of carbon risk factors
				Portfolio Sorting	Three portfolios sorted by carbon efficiency		Higher cumulative returns on clean portfolios

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Table C.3: Carbon Premium – Top-down studies – Continued

(1) Author (Year) Publication	(2) Asset Type	(3) Assets' Sector	(4) Geographical coverage/Period	(5) Analysis Type	(6) Methodology	(7) Measure of climate risk	(8) Results
Roncalli et al. (2020) Working paper	Stocks	All	Global	Asset-Pricing	Application of an asset-pricing mode augmented with a time-varying version of Gorgen et al.'s risk factor	Time-varying version of Gorgen et al. (2019)	Carbon risk price in the stock market
Bolton & Kacperczyk (2021) <i>Journal of Financial Economics</i>	Stocks	All	Global (2005-2017)	Panel Asset pricing	Panel analysis of returns with many controls Regression of climate-risk coefficient on traditional risk metrics Tests with asset-pricing models to detect premia	Scope 1,2 and 3 emissions Growth rate of Scope 1,2 and 3 emissions Emission intensity (Scope 1,2,3)	Significant carbon premium on absolute emissions (not carbon intensity) not explained by traditional measures
Bua et al. (2022) ECB Working Paper	Stocks	All	Europe (2005-2021)	Asset pricing Portfolio sorting	Five-factor Fama-French model Building of low-minus-high transition risk portfolios	Text-based analysis of transition-risk related publications (press, research)	Around 7% premium on transition risks Outperformance of low-minus-high transition risk portfolio
Kennett et al. (2021) <i>Journal of Sustainable Finance and Investment</i>	Stocks	All	New-Zealand NZX50 Index 2010-2018	Asset Pricing	Carhart Four-Factor model including returns on carbon allowances on New Zealand's carbon market and their daily volatility	Returns on carbon allowances and volatility	Transition risks not priced in (except strong surges). Due to low carbon prices overall

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Table C.3: Carbon Premium – Top-down studies – Continued

(1) Author (Year) Publication	(2) Asset Type	(3) Assets' Sector	(4) Geographical coverage/Period	(5) Analysis Type	(6) Methodology	(7) Measure of climate risk	(8) Results
Witkoswki et al. (2021) <i>Energies</i>	Stocks	EU-ETS	Eurozone (2003-2019)	Portfolio Sorting	Dirty portfolio made of companies with high exposures, clean with low. Comparison of the alphas on both portfolios	Portfolio sorting criterion: Spread between emission and free allocation divided by total assets	No real outperformance on the part of green portfolios
				Asset pricing	CAPM model with study divided into different periods	Carbon beta: spread of alphas between the Dirty and Clean Portfolios	2003-2012: Positive carbon premium 2013-2015: Negative carbon premium 2016-2019: No carbon premium
Bauer et al. (2022) Working Paper	Stocks	All	US, Canada, France, Germany, Italy, Japan, UK (2010-2021)	Regression	Panel model	Total reported emissions (Scope 1 and 2)	Lower returns on brown assets (Except in Italy)
Bingler (2022) Working Paper	Sovereign Bonds	All	29 countries (2008-2021)	Panel	Panel model relating sovereign rates to energy transition performance	GermanWatch CCPI (Burck, Uhlich, and Bals 2022)	For high-rate countries, decreasing relationship between decarbonisation effort and sovereign rate

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Table C.3: Carbon Premium – Top-down studies – Continued

(1) Author (Year) Publication	(2) Asset Type	(3) Assets' Sector	(4) Geographical coverage/Period	(5) Analysis Type	(6) Methodology	(7) Measure of climate risk	(8) Results
Enders (2022) Working Paper	Stocks	All	All	Portfolio sorting	Brown-minus-green portfolios with different emission quintiles	Sorting along carbon emissions (Scope 1 & 2)	Green portfolios outperform greatly brown portfolios
				Asset-pricing model	Measure of a carbon beta based on portfolio sorting		Significant factor related to ranking along disclosed emission. Betas are detected and differ across sectors and countries
Hsu et al. (2023) <i>Journal of Finance</i>	Stocks	All	US (1986-2014)	Portfolio Sorting	Five Portfolios with different degrees of greenness	Firm's polluting releases (Local pollution)	Higher emissions imply higher returns (lower asset prices). Significant pollution premium untampered by common measures of systematic risks.
				Asset pricing			Cross-section on returns with controls. Lower emissions reduce profitability. Sensitivity to policy shifts

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Table C.3: Carbon Premium – Top-down studies – Continued

(1) Author (Year) Publication	(2) Asset Type	(3) Assets' Sector	(4) Geographical coverage/Period	(5) Analysis Type	(6) Methodology	(7) Measure of climate risk	(8) Results
Ravina (2022) <i>The Energy Journal</i>	Bonds	All	EU (2008-2018)	Portfolio Sorting	Six portfolios with different degrees of greenness valued with a Fama-French 2-factor model augmented with a measure of returns associated with compliance to EU-ETS	"Green minus brown" factor: difference between weekly value-weight carbon portfolio returns from the weekly value-weight green bond portfolio returns from the beginning of Phase II	Significant coefficients on the "Green minus brown" factor, interpreted as a positive green premium
Aswani et al. (2023) <i>Review of Finance</i>	Stocks	All	Global (2005-2019)	Panel	Panel model relating emissions with stock returns	Scope 1,2 and 3 emissions Emission intensity (Scope 1,2,3)	No link between stock returns and the log-level of disclosed emissions, positive correlation between third-party estimated emissions and stock returns. Authors' interpretation is that estimated emissions are a proxy for firms' performances
Collender et al. (2023) <i>Global Finance Journal</i>	Sovereign Bonds	n. a	37 countries (2000-2019)	Panel	Panel model relating emissions to sovereign bond yields and spreads with US bonds	National emissions (CO2)	Significant link between CO2 emissions and bond yields/spreads

Note: Studies selected through regularly repeated queries on Scopus, Google Scholar and Web of Science.

Table C.4: Climate Sentiment Studies

(1) Author (Year) Publication	(2) Methodology	(3) Measure of investor attention	(4) Results
Ardia et al. (2020) Working paper	Asset-pricing model with climate concern as additional variable	Climate concern index based on news screening allowing to derive unexpected news	Green firms outperform brown firms when climate concern is high
Choi et al. (2020) Working Paper	Panel model relating returns to climate news	Google search volume on abnormal temperature increases	Green firms outperform brown firms when local temperature is higher
Engle et al. (2020) <i>The Review of Financial Studies</i>	Building of portfolios hedging climate news	Text analysis of newspapers	Possibility to hedge exposures to climate risks with surges and withdrawals in investor attention
Apel et al. (2021) Working Paper	Building of a time-varying index approximating changes in transition risks. Application of an asset-pricing model to detect a carbon factor	Text analysis from news with text-tonality analysis to identify good or bad news and labelling by hand of climate events	Green firms outperform brown firms when climate concern is high
Brière & Ramelli (2021) Working Paper	Study of financial flows through exchange trading funds and of associated pricing	News analysis (Borrowed from Engle et al. (2020) and Choi et al. (2020))	Green firms outperform brown firms when climate concern is high
Santi (2023) Working Paper	VAR and VECM models of returns on an Emission-minus-carbon portfolio	Textual analysis of Twitter feeds on climate-related news	Green firms outperform brown firms when climate concern is high
Santi & Moretti (2021) Working Paper	Asset-pricing model with climate concern as additional variable	Indicator of climate and energy disruption "worryness"	Carbon risk premium tends to disappear in areas where climate concerns are low
Tran (2021) PhD Thesis	Asset-pricing model with climate concern as additional variable	Measure of climate uncertainty and disagreement	Climate uncertainty and disagreement associated with higher trading volumes and higher volatility. Disagreement associated with lower abnormal returns, uncertainty with higher abnormal returns
Huynh & Xia (2021) <i>Journal of Financial and Quantitative Analysis</i>	Asset-pricing model with climate concern as additional variable	News index developed by Engle et al. (2020)	Investors ready to pay more for bonds issued by environmentally friendly firms

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Table C.4: Climate Sentiment Studies – Continued

(1) Author (Year) Publication	(2) Methodology	(3) Measure of investor attention	(4) Results
Faccini et al. (2023) <i>Journal of Banking and Finance</i>	Portfolio sorting analysis - Estimation of climate risks and excess returns with asset-pricing models (Fama-French three-factor, Carhart & Fama-French five factors)	Textual analysis of climate news: shares of press articles covering climate topics in total press releases. Four topics are tested: short-run US climate policy, international climate policy, natural disasters and global warming	Positive alphas for portfolio long on high climate policy risks and short on high climate policy risks. Suggests hedging in favour of firms with low transition risks (climate betas) due to climate policy rollback. Other climate-related factors not priced in. Bottom line: only short-term domestic transition risks are priced in, mostly after 2012
	Fama-McBeth regressions (Robustness check)		
	Portfolio-sorting analysis - Estimation of climate risks and excess returns with asset-pricing model	Narrative indicator of cli- mate policy news: 3500 ar- ticles on US climate policy published between 2000 and 2018 are marked 1 if climate policy is tightening and -1 otherwise	

Note: Studies selected through regularly repeated queries on Scopus, Google Scholar and Web of Science.

Table C.5: Event studies and Difference-in-Differences Approaches

(1) Author (Year) Publication	(2) Study Type	(3) Asset Type /Sector	(4) Geographical Coverage (Period)	(5) Event	(6) Results
Lee et al. (2015) <i>Corporate Social Responsibility and Environmental Management</i>	Event study	All	Korea (2007-2009)	Carbon-Disclosure Events (Firm-specific)	Stock prices negatively affected by carbon disclosure events, less so if they are frequent
Ramiah et al. (2015) <i>Applied Economics</i>	Event study	All	US (2005-2008)	Ratification of Kyoto Protocol Election of Barack Obama	Negative abnormal returns for biggest polluters in both events
Griffin et al. (2015) <i>Energy Economics</i>	Event study	Stocks/ Oil Producers	US (2009-2013)	Test for "unburnable carbon" news	1.5-2% loss in asset price for 63 biggest oil-gas companies in the US
Byrd & Cooperman (2018) <i>Journal of Sustainable Finance & Investment</i>	Event study	Stocks/ Coal producers	North America (2011-2015)	CCS-related events (technological breakthroughs, setbacks)	Investors have priced stranded assets in, as they do not react much to CCS setbacks but seem to be still hoping for CCS breakthroughs, as they react positively to positive announces
Mukanjari & Stern (2018) Working Paper	Event study	Stocks/ Energy sector	International (2015-2016)	Paris Agreement and Ratifications Trump's election	Moderate effects Authors suggest that unexpectedness and strongness are both required for strong effects
Barnett (2019) PhD Thesis	Event study	Stocks & Commodity/ Oil	North America (1996-2017)	Test for several climate-policy events (Paris Agreement, Trump's election)	Tighter climate policy associated with lower abnormal returns on oil prices and oil producer stocks. Larger and more significant coefficients associated with recent years
Donadelli (2019) Latvia Central Bank Report	Event study	Stocks/ All	Europe (2010-2018)	Series of many climate events, effects averaged out	Abnormal losses (-1%) after 20 days
Ilhan et al. (2021) Working Paper	Event study	Stocks/ All	US (2016)	Trump Election (Associated with climate policy rollback)	Trump election's decreases downward risk
Pham et al. (2019) <i>Applied Economics</i>	Event Study	Stocks/All	Germany (2015)	Paris Agreement	Negative abnormal returns for some polluting firms

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Table C.5: Event studies and Difference-in-Differences Approaches – Continued

(1) Author (Year) Publication	(2) Study Type	(3) Asset Type /Sector	(4) Geographical Coverage (Period)	(5) Event	(6) Results
Alsaifi et al. (2020) <i>Journal of Cleaner Production</i>	Event study	Stocks/ All	UK (FTSE350) (2009-2015)	Carbon-Disclosure Events (Firm-specific)	Negative reaction to carbon disclosure
Hansen & Pollin (2020) <i>Review of Social Economy</i>	Event study	Stocks/ Fossil Firms	Global (2011-2018)	Analysis of the effect of divestment on fossil fuel share prices	Very limited effects on fossil firm share prices
Kruse et al. (2020) Working Paper	Event study	Stocks/ All	US (2015)	Paris Agreement	Green firms outperform others in the weeks following the Paris Agreement. No strong effect on brown assets
Nguyen et al. (2020) Working Paper	Difference-in- differences	Stocks & Loans	Australia (2007)	Reaction to the Australian ratification of the Kyoto protocol	Higher cost of capital for emitting firms after the ratification of the Kyoto Protocol
Nguyen & Phan (2020) <i>Journal of Corporate Finance</i>	Event study	Stocks/ All	Australia (2007)	Kyoto Protocol Ratification	Lower abnormal returns for emitters' stocks within 3 to 5 days before and after ratification due to higher distress risk
Seltzer et al. (2022) Working Paper	Difference-in- differences	Corporate Bonds (Ratings & Spread)	US (2015)	Effect of Paris Agreement on US Corporate Bonds (NFCs)	Ratings: Higher ranks in emission intensity distribution associated with higher notches (0.47-0.64) after Paris. Spreads: 23-42 basis points after Paris Agreement
Sen & Von Schickfus (2020) <i>Journal of Environmental Economics and Management</i>	Event study	Stocks/ Utilities	Germany (2015)	Decommissioning of lignite plants	Investors account for stranded assets but expect a compensation
Wen et al. (2020) <i>Energy Economics</i>	Difference-in- differences	Stocks	China (2013-2018)	Effect of the implementation of the pilot Chinese ETS	No significant difference in stock returns at the implementation of the Shenzen Pilot

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Table C.5: Event studies and Difference-in-Differences Approaches – Continued

(1) Author (Year) Publication	(2) Study Type	(3) Asset Type /Sector	(4) Geographical Coverage (Period)	(5) Event	(6) Results
Antoniuk & Leirvik (2021) <i>Journal of Sustainable Investments</i>	Event Study	Stocks/Transition- relevant sectors	Global (2009-2016)	Four events: - Climategate - Fukushima Disaster - Paris Agreement -Trump Election	Climategate: Negative shock to all sectors (Temporary) Fukushima: Negative shock to all sectors (Temporary) Paris Agreement: Decrease in returns for transition-exposed sectors Trump elecion: Negative shock to returns
Birindelli & Chiappini (2021) <i>Corporate Social Responsibility and Environmental Management</i>	Event Study	Stocks/All	Europe (2013-2018)	Series of climate policy announce- ments/shocks in Europe	All events induced negative abnormal returns for highest emitters
Carbone et al. (2021) Working Paper	Difference-in- differences	Loans/All	Europe and United-States (2010-2019)	Paris Agreement	Paris Agreement had a negative impact on high emitters' ratings
Ramelli et al. (2021) <i>The Review of Corporate Finance Studies</i>	Event study	Stocks/All	US (2016)	Study of Donald Trump's election on carbon-intensive stock prices	Investors saw Trump's term as parenthesis and hedged against future climate policy tightening by buying less carbon-intensive stocks
Ramelli et al. (2021) <i>Journal of Corporate Finance</i>	Event study	Stocks/All	Europe (2019)	Climate strike	Persistent loss in market valuation for carbon-intensive firms
Müller et al. (2022) Working Paper	Difference-in- differences	Loans	United States (2016)	Trump election	Banks with low climate commitment reduce high-carbon loan securitisation when climate policies loosens. Overall, banks tend to securitise more high-carbon loans to mitigate risks
Vozian (2022) Working Paper	Difference-in- differences	CDS	Europe (2010-2021)	Paris Agreement	After the Paris Agreement, higher emitters receive higher CDS spreads

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Table C.5: Event studies and Difference-in-Differences Approaches – Continued

(1) Author (Year) Publication	(2) Study Type	(3) Asset Type /Sector	(4) Geographical Coverage (Period)	(5) Event	(6) Results
Wu et al. (2022) <i>Environmental Science and Pollution Research</i>	Event study	Stocks	China (2009-2019)	Stock price reaction to performance announcements, textual analysis of announcements to detect climate risk-related keywords	Climate risks negatively reacted to price reaction to corporate announcements. Climate risks seem to increase trading activity, investor attention, and triggers negative media coverage

Studies selected through regularly repeated queries on Scopus, Google Scholar and Web of Science.

Chapter 2

A Climate stress-test for transition risks with a stock-flow consistent model – Introducing FASM-ID

Abstract

This chapter proposes a novel approach to climate stress tests based on the stock-flow consistent approach. It analyses how financial instability can emerge due to technological displacement and asset stranding along mitigation pathways limiting global warming to 1.5°C or 2°C. It develops a model for studying transition risks with an embedded financial system with bank and non-bank agents. It also features asset stranding as the decommissioning of excess high-carbon capital. The framework simulates decarbonisation pathways and carbon price paths embedded in scenarios provided by the Network for Greening the Financial System (NGFS). It cashes in on the different scenario variants featured in the NGFS scenario suite to explore related uncertainties. The model shows that more climate-ambitious and more constrained scenarios yield higher transition risks, both in the long and short run. However, it qualifies the threats associated with delayed-action transition scenarios compared to climate-ambitious ones. The latter can give rise to “green bubble” patterns, whereby financial disturbances emerge from the deployment of low-carbon technologies. It further shows that different financial institution types would not suffer equally from transition risks. For instance, banks are overall less affected than non-bank institutions, which can suffer from significant tensions. The model also illustrates the importance of accounting for the reaction of the financial sector along decarbonisation scenarios. Finally, by studying decarbonisation pathways from various integrated assessment frameworks, the model shows the necessity to consider many scenarios generated by different models. It finally suggests that ambitious stabilisation policies are necessary to ensure a safe transition.

Keywords: Climate Stress test, Transition risk, Asset Stranding, Stock-Flow Consistent Modelling

Acknowledgements

The author warmly thanks the attendants of the Doctorissimes 2022, ESEE Pisa 2022 and FMM 2022 conferences for useful feedback, as well as Emanuele Campiglio, Céline Guivarch, Antoine Godin, Edwin Le Héron, Severin Reissl, Antoine Mandel and Emilien Ravigné for guidance and comments. He also thanks the attendants to the Chaire Energie et Prospérité Seminar Series, the public of the macroeconomic seminar series at EIEE and the audience of the macroeconomic and finance seminars at Sant’Anna Pisa, especially Luca Fierro and Francesco Lamperti, for their feedback. All possible remaining errors are mine.

Introduction

The irruption of climate-related risks in the agenda of financial regulators and central bankers called for a renewal of methods to assess best micro- and macro-prudential risks related to climate change and the low-carbon transition (Baudino and Svoronos 2021; Daumas 2023, Chapter 1). Notably, building on traditional “stress tests” that have become increasingly popular since the Great Financial Crash, the “climate stress test” method emerged as one of the workhouses of climate-related risk assessments.

Stress tests traditionally use pre-determined scenarios based on a given narrative applied to a general modelling framework able to generate outcomes of interest. In macro-prudential regulation, these models are usually large-scale macroeconomic models with more or less emphasis on the financial sector (Borio, Drehmann, and Tsatsaronis 2014). Climate stress tests flow directly from their macroeconomic counterparts (Cartellier 2022) and have been applied to study transition risks associated with the shift to a low-carbon economy and physical risks linked to climate damage. Early climate stress tests used to rely on *ad hoc* scenarios, mostly depicting disruptive and sudden transitions (Battiston, Mandel, et al. 2017; Vermeulen et al. 2018). Since then, the climate stress test literature has increasingly organised around the general framework proposed by the Network for Greening the Financial System (NGFS 2020a) for studying climate-related risks. This framework builds on long-run decarbonisation scenarios generated by technology-rich, process-based integrated assessment models (IAMs) usually mobilised by the Intergovernmental Panel on Climate Change (IPCC). The NGFS framework intends to complement IPCC assessments on the issue of financial stability, which is typically not accounted for in process-based IAMs (Keppo et al. 2021). The most recent stress tests are high-dimension, multi-model exercises with a high data resolution that tackle transition and physical risks together. Earlier applications, by contrast, tended to focus on one of the two risks (Vermeulen et al. 2021; T. Allen et al. 2020). The models used for these exercises are well-established frameworks (NIESR 2016) based on standard assumptions (Devulder and Lisack 2020).

Yet, calls for broadening the modelling method portfolio to tackle climate-related issues have emerged in the literature (Hafner et al. 2020), including the NGFS (NGFS 2020b). Notably, agent-based (Caiani, Godin, Caverzasi, et al. 2016) and stock-flow consistent (Godley and Lavoie 2007) approaches have been considered a valuable complement to more standard frameworks. Agent-based models typically represent a highly disaggregated economy, with interacting individual agents that give rise to emerging properties. Stock-flow consistent approaches start from a more aggregated representation of the economy as a series of interrelated balance sheets linked by financial flows, with a strong emphasis put on the financial sector. This latter approach gives much importance to the financial sector through a rigorous representation of credit relationships. It also focuses on the interaction of financial stocks and flows in driving the economic dynamic. Beyond climate risks, central bankers have regarded stock-flow consistent models as a promising avenue for studying financial dynamics and balances (Burgess, Burrows, and Kinsella 2016). These features have naturally made them good candidates for the study of financial climate-related risks (Sanders et al. 2022).

Agent-based approaches (Ponta et al. 2018; Lamperti, Dosi, et al. 2018) and stock-flow consistent (T. Jackson and Victor 2015; Sers and Victor 2018) models have long tackled climate change and related risks. Lamperti, Bosetti, et al. (2019) used an agent-based model with climate damage scenarios and offered a similar exercise to a stress test focused on physical risks. On the stock-flow consistent side, Dafermos, Nikolaidi, and Galanis (2018) and Monasterolo and Raberto (2018) provide an aggregate view of the effect of climate and financial policies on the dynamic of the transition, including instability potentials (see also (Gourdel, Monasterolo, Dunz, et al. 2022)). Some other contributions explore the transboundary impacts of climate damage (Gourdel, Monasterolo, and Gallagher 2023) and climate policy (Carnevali, Deleidi, et al. 2021). Yet, so far, no stock-flow consistent model has performed a definite stress test that would simulate a fully-fledged scenario involving a transition to a low-carbon economy.

The goal of this paper is thus to offer a first step in bridging this gap by providing a stylized stress test powered by a stock-flow consistent model. It develops a stock-flow consistent model at the world level, FASM-ID (Financial Asset Stranding Model - Investment and Decarbonisation), amenable to the simulation of transition pathways and the study of real-financial dynamics along transition paths. In this paper, FASM-ID is used as a simulation platform for several scenarios and scenario variants which exist in the literature but do not incorporate finance-related outcomes. Thus, it combines outcomes from various models into an integrated framework meant to complement already existing scenario outcomes with metrics relevant to the study of low-carbon financial risks. Furthermore, as a simulation platform, it allows for meaningful comparisons across scenarios and scenario variants.

FASM-ID features a compact representation of transition dynamics to compare scenarios and their variants from different IAMs. It provides metrics of the impact of transition risks on financial and non-financial companies. This feature allows FASM-ID to represent how the financial sector will reorganise around a transition pathway. The model also proposes a disaggregated view of the financial sector modelling non-bank institutions and their interactions with banking institutions. This feature allows me to generate relevant outcomes to financial instability by clearly separating market finance from households, which typically assume it in SFC models (Dafermos, Nikolaidi, and Galanis 2017). It also calls out to usual stress test exercises, which leave aside these interactions as well. FASM-ID proposes an additional innovation by accounting for asset stranding, represented as the premature decommissioning of high-carbon assets and modelling its relationship to financial instability channels. Indeed, such an explicit link between decommissioned capital and financial instability channels is absent from model-based studies on transition risks (Jacquetin 2021), including those tackling stranded assets explicitly (A. Jackson 2018). Finally, the model prolongs existing proposals in the SFC literature by focusing on transition risks along reference mitigation pathways and carbon price schedules.

The model emulates several scenarios proposed by the NGFS (2021b; 2022) to provide

metrics relevant to transition risks. Because the impact of physical risks is already relatively well-mapped and to avoid the uncertainties linked to assumptions on climate damage functions, this stress test builds on T. Allen et al. (2020) in focusing on transition risks only. For this purpose, FASM-ID is made consistent with the emission and carbon price schedules provided by the NGFS reference scenarios. Unlike other exercises based on SFC models applying NGFS scenarios (Gourdel, Monasterolo, Dunz, et al. 2022), I force the model to match the decarbonisation trajectory of each projection. Likewise, I enforce an exogenous carbon tax to mimic climate policy. I then consider several outcomes of interest. I first focus on results measuring the realisation of transition risks (loan defaults, asset price decreases) and then examine their actual impact on financial institutions' viability. I also take advantage of the many scenario variants and vintages proposed by the NGFS to explore related uncertainties.

Results notably show that the banking sector resists transition risks. However, significant tensions can emerge on non-bank financial institutions due to the revaluation of financial assets linked to high-carbon activities. These tensions can arise in the short and long run. It suggests that the transition can hardly be thought of as a series of short-run adjustments. Instead, unsustainable dynamics can emerge in the longer run. Furthermore, this article documents significant differences across scenario variants, which differ in decarbonisation pace and carbon price assumptions. In particular, the direst scenarios are those featuring a relatively low efficiency of climate policy with stringent carbon price levels to achieve a given emission level. Results also show, in some variants, a course of events close to a "green bubble" (Nikolaïdi 2017), with some financial disturbances emerging from the development of low-carbon technologies. More precisely, the slowdown in green investment while the transition draws to an end can create tensions in the long run by decreasing the profitability of low-carbon investments. Overall, these results call for a more careful study of uncertainties around scenario variants. They also call for taking into account a larger span of possible scenario variants.

The remainder of this paper is organised as follows. Section 1 reviews the literature on climate-related risk modelling and provides further motivation. Section 2 provides a simplified depiction of the model. Section 3 describes the paper’s simulation approach and use of scenarios. Section 4 provides some calibration elements before Section 5 discusses the paper’s main takeaways. The article closes with a conclusion and a discussion of limits and future research.

1 Literature review and motivation

The issue of climate-related risks has given rise to various modelling efforts to explore potential effects on the financial system, which will be reviewed hereafter. Although this paper focuses on transition risks, some works related to physical risks will also be surveyed when they provide valuable methodological insights (see Cartellier (2022), Monasterolo, Nieto, and Schets (2023) and Daumas (2023) (Chapter 1) for exhaustive overviews and discussions).

1.1 Climate-related risks within equilibrium frameworks

A strand of research has used equilibrium models of neoclassical or neo-Keynesian inspirations.

On the one hand, a lengthy literature has provided various estimates of the asset value losses (or “stranded assets”) linked to the decarbonisation of the economy, with a focus on energy utilities and fossil fuel reserves (Saygin et al. 2019; J. Grant and Coffin 2020). Most of these models suggest that value losses would be significant, hinting at instability potentials (Daumas 2023, Chapter 1). Yet, these models typically do not feature a financial sector *per se*. As a result, they hardly bridge the gap between asset value losses in the real economy and potential disturbances.

Another strand of research, furthered mainly by regulatory authorities, has intended to measure the macroeconomic (Ens and Johnston 2020) and financial instability (T. Allen et al. 2020) implications of transition pathways, both in the short (Vermeulen

et al. 2021) and long run (Alogoskoufis et al. 2021). Building on the NGFS approach (NGFS 2022), this research has been notably interested in comparing the effects of a late and sudden (“disorderly”) low-carbon transition to the physical impacts of climate change in the case of inaction. Thanks to a data-intensive and disaggregated depiction of economic sectors, these models can map exposures and vulnerability to climate-related risks at a company level across sectors (T. Allen et al. 2020) and regions (Alogoskoufis et al. 2021). All in all, this literature points to relatively mild transition risks, even in the case of disorderly transition, which do not compare to the potentially massive impacts of climate change in the case of inaction. However, these exercises, typically using several coupled frameworks, do not embed the financial system within the economy. Usually, an external module produces financial metrics that do not feed back onto macroeconomic dynamics (see ESRB (2020) for an exception). Similarly, because they do not represent the financial sector, most of these models do not capture the reorganisation of the financial system around a transition path – except for sudden revaluation effects in the case of disorderly transition. Hence, they usually build on static balance sheet approaches (Baudino and Svoronos 2021) whereby the exposures of financial agents do not change over time. This hypothesis effectively evacuates two crucial dynamics. This feature waives the possibility for the financial system to redistribute exposures, which could result in more resilience. It also cannot explore the contrary, whereby the reshuffling of vulnerabilities would result in a greater financial sector fragility along a transition pathway due to the transfer of the high-carbon burden to less regulated and more fragile institutions. It follows that such approaches cannot capture potential contagion effects arising from the interconnectedness of financial agents of different types (Battiston, Mandel, et al. 2017). Furthermore, such work does not capture potential imbalances that may build up through time along a transition path, while such phenomena have proven crucial in furthering financial instability (Godley 2012).

Finally, these exercises typically do not represent asset stranding dynamics in the real economy, focusing only on the financial sector, while the two are likely interrelated

(Jacquetin 2021).

Beyond these modelling limitations, T. Allen et al. (2020) also point out crucial issue linked to equilibrium models. These frameworks, being relatively resilient to shocks (Borio, Drehmann, and Tsatsaronis 2014), require the application of significant macroeconomic shock (or strong monetary policy reaction (Vermeulen et al. 2018)) to allow for the emergence of substantial effects on macro-prudential variables. It raises identification issues. Indeed, it is unsure whether the measured effects are those of the low-carbon transition itself or those of broader scenario or behavioural assumptions (Daumas 2023, Chapter 1).

To bridge these gaps, the literature that has studied climate-related risks through the lens of non-equilibrium models provides valuable inspiration.

1.2 Climate-related risks in non-equilibrium models

Such models typically build on Keynesian (Mercure, Pollitt, N. R. Edwards, et al. 2018), post-Keynesian (Monasterolo and Raberto 2016; Dafermos, Nikolaidi, and Galanis 2017), or Schumpeterian (Lamperti, Dosi, et al. 2018) approaches to macroeconomics and structural change.

Some (post-)Keynesian models, like the E3ME framework (Mercure, Pollitt, N. R. Edwards, et al. 2018), have been used as an alternative to equilibrium models in studying transition risks and stranded assets. Due to their Keynesian underpinnings, these models can give rise to multiplier effects. Due to higher investment expenditures needed for the transition, shifting to a low-carbon economy can have positive macroeconomic effects. These avoid the representation of the transition as a negative macroeconomic shock, potentially large. Fazekas et al. (2021) reports that the low-carbon transition, either delayed or immediate, can bear positive macroeconomic effects due to investment expenses. Unfortunately, these models do not feature an explicit financial sector and require external modules to compute valuation effects and their effects on the financial industry.¹

¹See Semieniuk, Holden, et al. (2022) for a mapping between the devaluation of fossil fuel reserves and equity

Yet, other models have been proposed based on a fully-fledged stock-flow consistent (SFC) approach. By representing the economy first and foremost from the standpoint of financial flows – indeed, as a network of imbricated balance sheets – this methodology typically embeds a built-in financial sector that interacts directly with the real economy by providing credit and equity finance (Godley and Lavoie 2007). Early ecological SFC (E-SFC) have tackled the question of the growth imperative supposedly embedded in a credit economy (T. Jackson and Victor 2015; Cahen-Fourot and Lavoie 2016) or questions related to low-carbon innovation (Naqvi and Stockhammer 2018) or the energy-economy nexus (M. Berg, Hartley, and Richters 2015).

In the realm of climate-related risks, a broad array of frameworks have been proposed, notably pioneered by the works of Tim Jackson and Peter Victor. In their research (Sers and Victor 2018; A. Jackson and T. Jackson 2021, among others), these authors and their teams have intended to capture the macro-financial implications of energy transitions. P. Jacques et al. (2023) adopt a similar approach. This strand of the E-SFC literature has focused on issues related to large-scale changes in energy systems, notably the introduction of renewable energy sources, characterised by lesser reliability and lower Energy Returns on Energy Invested (EROI). Further, unlike climate stress tests, these frameworks rely on synthetic or homemade transition pathways, typically applied exogenously, sometimes without climate policy. They also focus more on macroeconomic impacts than on the financial sector itself. However, in the realm of physical risks, some reduced-form SFC models have also studied the effects of climate change on the viability of a debt-based economy (Bovari, Giraud, and McIsaac 2018; Bovari, Giraud, and McIsaac 2020).

Two other well-established ecological stock-flow consistent models applied to climate-related risks are DEFINE (Dafermos, Nikolaidi, and Galanis 2017) and EIRIN (Monasterolo and Raberto 2018). DEFINE aims to provide a general and open-source framework for studying climate risks and monetary, financial and fiscal policies in combating climate change (Dafermos and Nikolaidi 2021; Dafermos,

losses for financial agents and ultimate owners.

Monserand, and Nikolaidi 2022). It, therefore, includes a well-furnished depiction of the financial sector and allows for studying financial instability. It also features a representation of biophysical exchanges between natural and economic systems. However, DEFINE has neither been used to simulate explicit decarbonisation paths nor been applied to study transition risks linked to the ecological shift yet.

Conceptually close, the EIRIN model, while not representing the biosphere, allows for greater disaggregation of financial and real-economy agents. In particular, it models an explicit energy and mining sector and a separation between investment and final-good producers. It also includes a trading module and several types of tradable assets (bonds and shares). Further, EIRIN has been mobilised for various research questions on climate-related risks, both theoretical (Monasterolo and Raberto 2019) and applied (Gourdel, Monasterolo, and Gallagher 2023). Notably, recent works on EIRIN have put great emphasis on the issue of agents' expectations in the face of climate policy, both from a theoretical standpoint, with synthetic policy scenarios (Dunz, Naqvi, and Monasterolo 2019), but also with a more applied perspective, though the use of already existing scenarios. Gourdel, Monasterolo, Dunz, et al. (2022) thus builds on the NGFS suite of scenarios to study the "double materiality" of climate risks. According to this notion, climate risks will affect the economy and the financial sector, while the behaviour of economic agents will also affect the climate risk profile they will face. The authors confirm the relevance of a smooth and orderly transition, notably if agents are farsighted and believe in climate policies. However, they only focus on the climate policy side of scenarios without trying to simulate fully-fledged decarbonisation paths. In particular, they only reach a 20% reduction in emissions by 2050, which is inconsistent with net-zero targets. Although understandable due to their research question, this feature invites caution in interpreting the relatively mild transition risks they detect in their simulations.

Further, while tackling financial instability, the SFC approach has mainly focused on the role of banks and credit institutions, along the lines of Minsky (1986), highlighting the importance of leverage ratios, unsustainable credit dynamics (Godley

2012) and liquidity mismatches (Le Heron and Mouakil 2008). The role of market finance institutions and the interactions across financial agents have comparatively been understudied (Michell and Toporowski 2012), while they represent relevant units of analysis in studying financial instability (Burgess, Burrows, and Kinsella 2016; Caverzasi, Botta, and Capelli 2019). Further, it is a liability compared to other kinds of stress tests, which have been able to explore asset losses for agents beyond the banking sector (Vermeulen et al. 2021; Gourdel and Sydow 2022).

Finally, several agent-based models of various inspirations have also been designed to tackle the ecological transition (Ponta et al. 2018) and the issue of climate-related risks (Lamperti, Bosetti, et al. 2019). They notably allow for a finer-grain representation of the economy and the interconnection of financial agents. Lamperti, Bosetti, et al. (2019) notably studied the financial instability costs of the physical impact of climate change, which takes the form of the bailout bill incurred by the State to save banks from failure. Regarding transition risks, Safarzyńska and van den Bergh (2017) studied the financial instability implication of developing renewable energy sources leading to lower bank connectivity, subsequently reducing the financial system's resilience. Botte et al. (2021) developed a large-scale agent-based SFC model allowing for asset stranding – defined as the eviction of a producing agent. These works suggest that low-carbon transition risks emerge mainly in the case of very rapid transition (less than ten years) but have not studied the effect of more realistic transition paths spanning over twenty to thirty years.

1.3 Summary and scope of the article

The short review above offers a picture of the gaps in the literature. Overall, it highlighted that the equilibrium approach could be enriched in three ways:

1. A more systematic link between real asset stranding and financial instability would be desirable, requiring proper accounting and explicit connections between asset value losses on the books and the financial fragility of related companies.

2. A more directly embedded financial sector that would interact with the real economy. Furthermore, allowing for minimal heterogeneity would make for a more dynamic picture of financial instability properties.
3. Regarding transition risks, the dependence on large macroeconomic shocks should be bypassed to measure the net effects of structural change and avoid identification issues.

Many of these gaps can be bridged with non-equilibrium models, notably of (post-)Keynesian inspirations, which open valuable methodological avenues for studying transition risks. However, current approaches to transition risks in this field remain limited in several respects:

1. When they model transition scenarios, these models emphasise the energy sector alone. While unmistakably a decisive element of the transition, the decarbonisation of other sectors must also be accounted for. They also insist relatively little on financial instability or focus only on banks (P. Jacques et al. 2023), while other financial agents are worth considering.
2. Because they rely on a limited number of scenarios, they do not make for the significant uncertainties around transition dynamics acknowledged by the climate stress-test literature, which tends to use several scenarios (NGFS 2021b). Furthermore, because these scenarios are of their own design, they may not fall within the range of conceivable transition dynamics.
3. More directly, finance-oriented models have either not been applied to transition scenarios or have only considered one aspect of these scenarios. Hence, transition dynamics are not fully represented.
4. Agent-based scenarios have mainly focused on short-term, very intense transition scenarios that may represent unfeasible decarbonisation efforts, while low-carbon transition risks also belong to the longer run (Daumas 2023, Chapter 1).

In sum, non-equilibrium approaches feature desirable properties to study low-carbon transition risks. However, they are yet to be fully matched with the climate stress test methodology, particularly in their use of scenarios.

The remainder of this article will, therefore, mostly aim at bridging this gap by proposing a model, the Financial Asset Stranding Model – Investment and Decarbonisation (FASM-ID). This framework is amenable to running fully-fledged decarbonisation scenarios with a stock-flow consistent methodology. It can also explore financial instability potentials along those paths. By doing so, this article intends to provide an SFC-based climate stress test along two lines.

First, this paper will analyse transition risks along a series of reference transition paths. FASM-ID will be applied to these scenarios and provide a measure of transition risk in the real economy. Because it models the financial sector, FASM-ID can also offer some insights into the evolution of the financial fragility of financial agents. It allows me to gauge how transition risks in the real economy may translate into financial fragility for the financial sector. Besides, the model captures the dynamic effects of portfolio readjustments and realised default on loans as the transition unravels. This stress test thus goes further than T. Allen et al. (2020), which only focused on non-financial companies. It also goes further than more recent climate stress tests (Alogoskoufis et al. 2021) in modelling the reorganisation of the financial sector *along* transition pathways.

Second, this paper takes advantage of the diversity of modelling frameworks used to generate transition pathways (IPCC 2022a, see Section 3) by using FASM-ID as a comparison platform. The goal is to explore variation across modelling frameworks, a well-documented source of uncertainty in the IAM literature (Kriegler, Petermann, et al. 2015). Most stress test exercises have been performed with few scenarios, preventing the exploration of related uncertainties.

FASM-ID expands both the equilibrium and non-equilibrium literature in various directions. In methodological terms, it uses the stock-flow consistent method as a comparison platform for studying the transition risk content of already existing scenarios. For this purpose, it explicitly models transitions brought to an end to gauge what it would take to achieve climate ambitions. Finally, because it simulates pre-existing scenarios, it studies conceivable transition and carbon profiles without

applying possibly arbitrary transition paces or climate policies. In modelling terms, it includes a greater disaggregation of the financial sector than usual SFC models and studies the interactions between the banking sector and asset managers. It also includes a representation of asset stranding as asset decommissioning and models explicitly possible links from asset stranding to financial instability. These features will be described in more detail in the next section.

2 Introducing FASM-ID

This section depicts the modelling strategy deployed to build the FASM-ID model and provides an overview of key relationships between variables and model blocks. An exhaustive description of the model is given in Appendix B.

2.1 General description

The model is at a world scale. It features a non-financial and a financial sector, a representative household, a government and a central bank. The economy is structurally operating below full capacity (Palley 2021). As usual in SFC frameworks (Nikiforos and Zezza 2017), output is demand-determined, with the utilisation rate of capital moving with aggregate demand. Non-financial companies comprise two consumption good branches and an investment goods sector. Financial companies include banks and non-bank financial institutions. Expectations are adaptive or trend-following, depending on the variable.²

The model depicts the transition to a low-carbon economy a transition to a low-carbon economy whereby an Incumbent sector (IN), possessing the high-carbon capital (HC) stock, is progressively replaced by a Challenger (CH), investing low-carbon (LC), non-emitting alternative. In the process, emissions in the economy will

²Although this assumption is strong regarding financial variables, it is usual in stock-flow consistent models (Nikiforos and Zezza 2017; Dafermos, Nikolaidi, and Galanis 2017; see Dunz, Naqvi, and Monasterolo 2019, for first steps in integrating forward-looking expectations). Further, the assumption of adaptive expectations may be a way to figure the difficulties of pricing transition risks documented by the empirical literature (Daumas 2023, Chapter 1).

decrease, and the Incumbent sector will generate stranded assets (see below). Incumbent and Challenger firms produce the same consumption good with the same Leontief technology and buy their capital from an independent investment good (*IG*) sector, which only employs labour. Consumption good produces service in a monopolistic-competition market. Prices are a markup on top of labour costs, with some degree of passthrough of a potential carbon tax. Markups move with utilisation to figure inflationary pressures like Rowthorn (1977), whereby firms can charge higher markups when competition is lower due to higher demand. Nominal wages are determined based on expected inflation and output growth, while productivity in all sectors grows with total value-added in a Kaldor-Verdoorn fashion (Lavoie 2014).

Investments are funded in three ways: accumulated funds, bank loans, on which firms pay interest and principal and equity emissions, on which NFCs pay dividends.³

A representative Non-Bank Financial Institution (NBFI) purchases equities, collects household savings and pays households a financial income based on collected dividends. The NBFI sector holds a liquid asset in bank deposits and can leverage its position on short-term debt to generate higher capital gains. This feature differs from usual SFC models, which usually consolidate this sector with households, possibly a specific rentier class (e.g. Monasterolo and Raberto 2018), on the ground that the final owners of financial assets are households and the ultimate bearer of asset losses. This model departs from this practice on several grounds.

First, it is due to its focus on financial instability. Modelling a separated NBFI sector allows for studying market finance as an extra channel of financial instability while retaining analytical clarity concerning households. Indeed, the latter instead fuel financial instability through their housing assets not represented in the model (see Caverzasi and Godin (2015)). Furthermore, allocating market finance, or a part of it thereof, to households would reduce asset price losses to a distributional consideration, while it has direct financial instability implications.

Further, allowing for heterogeneous financial agents enables us to model possible in-

³“Equity” should be understood here as a catchall category for any kind of market finance instrument emitted firms.

teractions and contagions. In the model, banks and non-banks interact through the leverage of the NBFIs and the equity exposure of banks, which can amplify financial disturbances. Finally, the model follows Burgess, Burrows, and Kinsella (2016) and Caverzasi, Botta, and Capelli (2019) in arguing that representing market-finance agents allows for a better representation of a financialised economy, in which the role of market finance providers cannot be ignored.⁴ Hence, the model's structure should ideally separate across different kinds of market finance providers, such as pension funds, investment funds and other financial intermediaries. However, I assume, for simplicity, a single NBFIs agent.

A representative Bank (B) extends loans and performs price and quantity rationing. Interest rates rise with observed firms' leverage and decrease with market shares to mimic the fact that Challenger firms will be riskier at the start of the transition. At the same time, the high-carbon Incumbent will be perceived as riskier in the late periods of the transition. Quantity rationing depends positively on firms' debt-service ratio, a defined portion of profits dedicated to paying interests and principals (Dafermos, Nikolaidi, and Galanis 2017). I also allow for loan vintages to better represent the dynamics of principal repayments and interest changes. The bank also diversifies its portfolio by providing some equity finance to firms, like Dunz, Naqvi, and Monasterolo (2021) and Gourdel, Monasterolo, Dunz, et al. (2022), and buying government bonds. This feature allows the model to capture banks' exposure to asset price shocks beyond loans alone.

Further, in each period, a fraction φ_t of loans will default (see Subsection 2.4), effectively representing a loss in the value of the bank's loan portfolio. Banks also purchase government bonds and are asked to hold high-powered money. Finally, Banks attract the deposits of households, consumption goods firms and the NBFIs sector.

Both for Banks and NBFIs, equity investment is ruled by a portfolio choice model *à la* Tobin, whereby agents invest a structural share of their wealth in a given asset,

⁴See Gabor (2020) for the importance of asset managers in contemporary capitalism.

while the final share depends on relative returns. In the model, this framework is amended in two ways (Godley and Lavoie 2007). First, our structural shares for the Incumbent and Challenger equity depend on each sector's market share to symbolise the reshuffling of portfolios as the transition goes on. Second, I augment the standard framework with a risk premium based on a book-to-market ratio, a common risk factor in portfolio choice models (Fama and French 1993). This addition allows portfolio choices to be determined by the extent of physical asset stranding, which may induce a transitory mismatch between the book value of physical assets and market valuation, inviting investors to reorient investments away from overvalued companies and into undervalued companies.

The government G consumes part of the final good production, collects taxes (including a carbon tax, which is recycled in full to households), provides transfers and targets a constant deficit. The central bank CB applies a constant base rate, provides advances to close banks' balance sheets if needed and buys the residual of government bonds if necessary (Lavoie 2014; Dafermos, Nikolaidi, and Galanis 2017)

Finally, households (HH) collect wages from their labour work and are paid financial income by NBFIs they possess Units of. Households own Banks through their funds and Investment Good firms and collect the profits of these two sectors. Households consume and hold three financial assets: deposits, high-powered money and NBFIs Units.

Figure 1 provides a diagram representation of the model. Stock-flow tables are displayed in Appendix A.

2.2 Decarbonisation process

Consumption good producers (Incumbents and Challengers) conduct decarbonisation through two channels. First, in the spirit of Caiani, Godin, and Lucarelli (2012), a newcomer, Challenger sector emerges and competes with the Incumbent, which possesses the high-carbon capital stock at the start of the transition. The Challenger only invests in low-carbon capital and will snatch market shares from the Incumbent. In

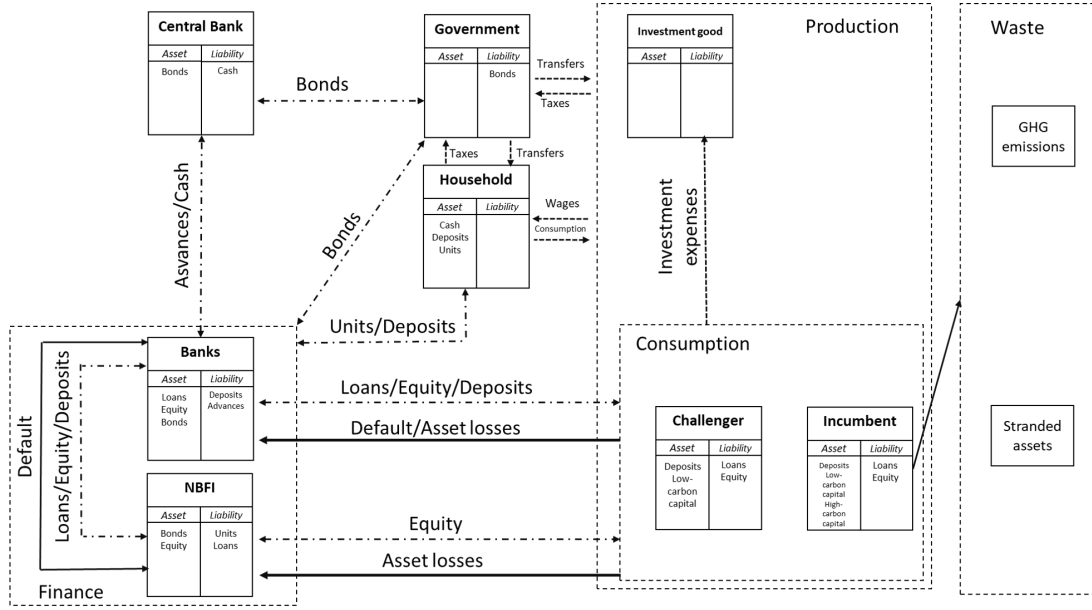


Figure 1: Diagram representation of the model. Dashed line represent transactions and financial flows. Solid lines highlight transition risk exposures.

parallel, the Incumbent sector will try to adapt its production process by retrofitting part of its high-carbon capital stock into a low-carbon alternative⁵. I also assume that Incumbents benefit from externalities⁶ as the economy decarbonises, lowering the carbon intensity of high-carbon capital. The pace and stringency of the transition depend on an exogenous decarbonisation target.

The model will target a share of low-carbon capital to be achieved at the next model stage to be consistent with the assumed decarbonisation target ($S_{LC,t}^T$). This target is imposed exogenously or solved for to match a predetermined schedule. By contrapose, Incumbents determine the desired share of high-carbon capital ($S_{HC,t}^T = 1 - S_{LC,t}^T$). If there is excess capital, they anticipate an amount of real stranding corresponding to this excess capital. To hedge against conversion, companies will convert a fraction of their capital stock by equating the investment cost of converting with the expected

⁵I assume that the high-carbon sector only retrofits its current stock and does not invest directly in a low-carbon alternative. Alternative investment behaviors were tested and showed similar results.

⁶This includes benefitting from greener transportation systems, greener energy sources and related infrastructures (Sovacool, J. Kim, and M. Yang 2021), agglomeration effects due to more compact cities (Meng and S.-C. Xu 2022), or technological and knowledge transfers as the economy decarbonises overall (Skoczkowski et al. 2020).

balance sheet loss due to stranding. Once conversion demand is determined, the Challenger sector invests in the residual desired low-carbon capital stock to match the target. Figure 2 summarises the decarbonisation process.

The choice of a Challenger-Incumbent structure to depict decarbonisation is motivated by the desire to represent that the low-carbon transition will entail a large-scale transformation of our economies, with important amounts of stranded assets [Daumas (2023) ; Chapter 1]. It is justified further by the important cross-sectoral interactions between high and low emitters (Cahen-Fourot, Campiglio, Godin, et al. 2021; Godin and Hadji-Lazaro 2022), which calls for considering a whole high-carbon production system instead of sole sectors. It finally allows me to picture a losing sector that can only adapt to the low-carbon transition at a cost and explicitly represent winners.

2.3 Asset stranding

The model also features a representation of physical asset stranding through decommissioning capital vintages. Throughout the transition, Incumbents will face excess capital compared to decarbonisation goals. To avoid large losses on their balance sheet, they will convert a fraction of this expected excess capital into low-carbon capital. The residual is sheer stranding, whose nominal value will represent a shock to Incumbents' balance sheets. Appendix B.1.3.2 describes our accounting method for stranded assets.

2.4 Paths to financial fragility

This model intends to study financial instability potentials along whole transition paths. Although I do not model crisis dynamics *per se*, the model features various channels through which economic agents become more financially fragile.

For the Incumbent and Challenger and the NBFIs sectors, the main metric of financial fragility in the model is the default probability on loans. Following Dafermos, Nikolaidi, and Galanis (2017), the default probability $\varphi_{NPL,\ell,t}$ of each agent

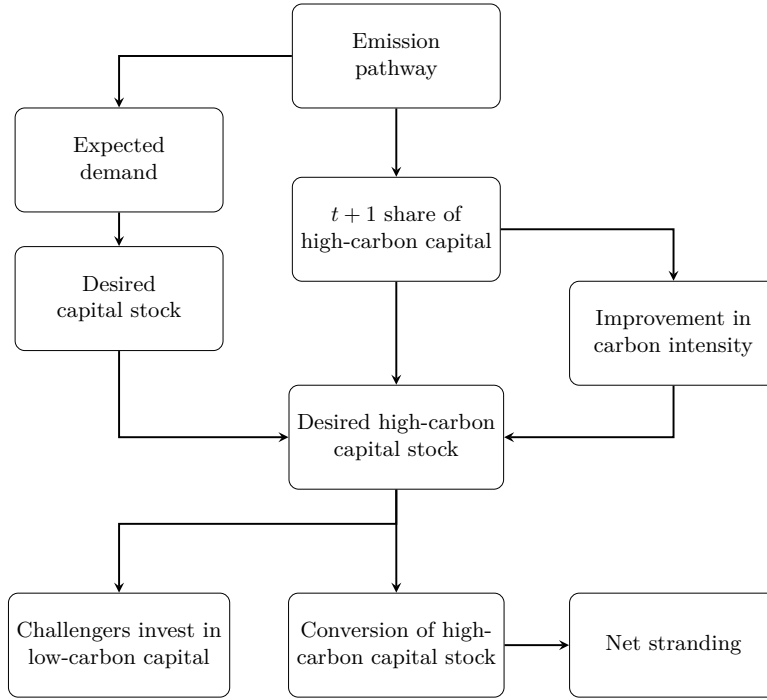


Figure 2: Representation of the transition process in FASM-ID

($\ell \in IN, CH, NBFI$) is a logistic function of their liquidity ratio $\iota_{\ell,t}$, defined as the ratio between total cash outflows to total cash inflows adjusted for change in their deposit assets:⁷

$$\varphi_{NPL,\ell,t} = \frac{1}{1 + \varphi_0 e^{\varphi_1 - \varphi_2 \iota_{\ell,t}}}, \quad (2.1)$$

where NPL stands for “Non-Performing Loans”, and with φ_0 , φ_1 ⁸ and φ_2 are calibrated parameters. Based on this equation, an increase in financial outflows (like a carbon tax) or a decrease in inflows (lower proceeds, credit rationing, negative changes in liquid assets) will result in higher default probabilities.

The model also provides a measure of banks’ financial fragility through their capital

⁷This definition strays from the initial formulation by Dafermos, Nikolaidi, and Galanis (2017) and is further justified in Appendix B.

⁸Note that the φ_1 parameter for the NBFI sector is rescaled to compensate for the the different definition of ι_{NBFI} .

adequacy ratio, defined as the ratio of their own funds to the asset size of their portfolio:

$$CAR_t = \frac{OF_t}{\omega_1 L_t + \omega_2 Eq_{B,HC,t} + \omega_3 Eq_{B,LC,t} + \omega_4 GB_{B,t}}, \quad (2.2)$$

where L_t is the banks' total loan portfolio, $Eq_{B,HC,t}$ the value of their Incumbent equity holdings, $Eq_{B,LC,t}$ that of their Challenger equity holding and $GB_{B,t}$ their government bond holdings and $\omega_{1,2,3,4}$ are risk weights⁹. The capital adequacy ratio is affected by the transition in two ways. At the numerator, the value of the banks' own funds will decrease in the case of non-performing loans (Dafermos, Nikolaidi, and Galanis 2017). Second, at the denominator, any increase in bank investment more than proportional to the increase in own funds would decrease the capital adequacy ratio, effectively corresponding to an implicit increase in bank leverage.

Financial agents are also affected by capital losses in financial markets. I adopt a simplified financial market structure whereby the price of financial assets is determined by the ratio of the nominal demand for equity and the number of shares outstanding, as is standard in SFC models (Godley and Lavoie 2007; Burgess, Burrows, and Kinsella 2016; see Dunz, Naqvi, and Monasterolo 2019, for a more sophisticated trading module):

$$p_{A,\ell,t} = \frac{A_{\ell,t}^{NBFI} + A_{\ell,t}^B}{a_{\ell,t}}. \quad (2.3)$$

Revaluation is defined as:

$$CG_{\ell,t} = (p_{\ell,t}^A - p_{\ell,t-1}^A) a_{\ell,t-1}. \quad (2.4)$$

Capital gains and losses are split across asset holders based on the fraction of the nominal value they hold.¹⁰ For banks, I assume similarly to non-performing loans

⁹In our calibration, we set $\omega_1 = \omega_2 = \omega_3 = 1$ and $\omega_4 = 0$, following Dafermos, Nikolaidi, and Galanis (2017).

¹⁰Since all assets are traded at the same price, this is equivalent to the fraction of shares outstanding, which would be more exact.

that capital losses are attributed to own funds. For the NBFIs sector, capital losses are absorbed by deposits, which serve as a buffer stock, feeding into default probability. Finally, as sketched above, financial agents are exposed to each other through the equity and loan-taking channels.

The transition process will fuel these shocks through several channels.

The transition will first affect the Incumbent sector by diminishing its market shares, leading to lower equity demand and lower proceeds, increasing default probability. The carbon tax that will be applied will also dent into Incumbents' proceeds, with the same effects. All these will also affect the Incumbent's dividend payments, which will directly affect banks and the NBFIs sector. Incumbents will also face higher credit rationing due to lower profits. They will also face higher interest rates due to losses in market shares. Finally, asset stranding will affect Incumbents in two ways. It will increase their leverage and, therefore, raise interest rates further. Second, it will induce an overvaluation in financial markets, leading to decreased equity demand.

On its side, because it will have to carry out very large investments, the Challenger sector may also face higher credit rationing and interest rates if its leverage and debt service ratio increase in a "green bubble" fashion (Nauman 2021; Semieniuk, Campiglio, et al. 2021). Figure 3 summarises our causality channels.

3 Simulation approach

The model will be used in the following to emulate pre-existing scenarios. For this exercise, I will rely on the scenarios proposed by the Network for Greening the Financial System (NGFS), which has already been used with SFC models (Dunz, Naqvi, and Monasterolo 2019; Gourdel, Monasterolo, Dunz, et al. 2022).

3.1 The NGFS climate risk narrative and scenarios

For the study of climate-related risks, the NGFS designed a reference conceptual framework based on the trade-off between transition and climate damage (physical

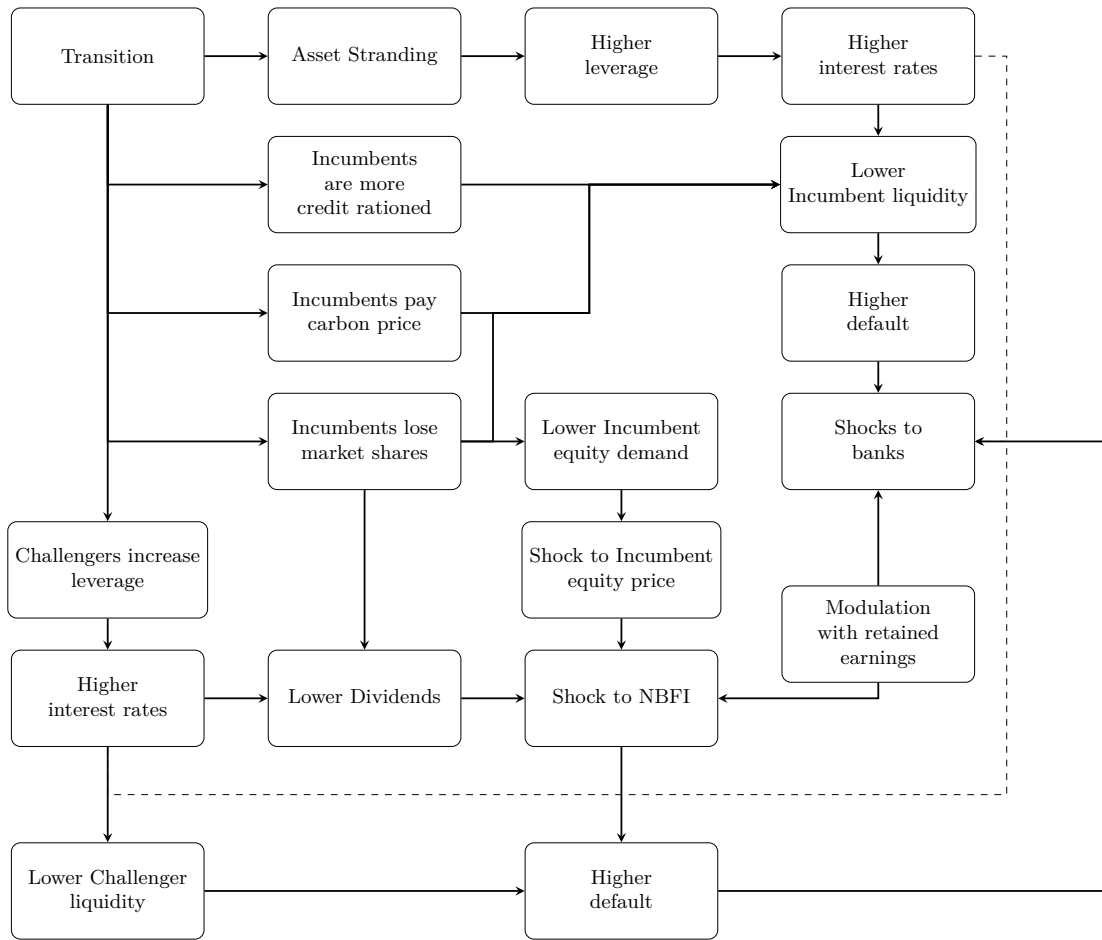


Figure 3: Causality channels to financial instability

risks) highlighted by Mark Carney (2016). Waiting for too long before transitioning would imply high climate change impacts, which could entail systemic risks for the financial system (ECB 2021). On the other hand, the low-carbon transition will entail a massive reallocation of resources throughout the economy. If carried out disruptively, it could trigger downward asset revaluations in some sectors, with adverse financial instability consequences (van der Ploeg and Rezai 2020a). By contrast, a smooth low-carbon transition would limit financial instability, thanks to gradually phased-in climate policies, anchored expectations and progressive technical change.

This narrative led the NGFS to propose six scenarios,¹¹ summarised in Figure 4.

¹¹These scenarios are drawn from the 2021 and 2022 vintage of NGFS scenarios. The original scenario set,

This matrix organises scenarios based on their climate risk content.

On the right-hand side, “Hot House World” scenarios are of two kinds. “Current Policy” scenarios are long-run projections of current policy and technological trends. “Nationally Determined Contributions” (NDCs) scenarios suppose that Nation-States abide by their NDCs. They feature insufficient transition efforts, leading the world beyond the 2°C Paris limit. They are thus characterised *ex-ante* by low transition risk and high physical risk.

The left-hand column of the matrix comprises fully-fledged transition scenarios with various degrees of ambition and assumptions on climate policy, international coordination and technological penetration. These scenarios are further separated into two kinds:

- Orderly scenarios depict the smooth transition process characterised by Mark Carney (2016). Due to early action, bearable technological penetration, and smooth climate policy. The “Below 2°C” scenario is assumed to bear less transition risks due to lower climate ambition.
- Disorderly scenarios are more disruptive, either because the transition begins in 2030 instead of 2020 (Delayed-Action scenarios) or due to uncoordinated policy action at the international level, calling for much more disruptive climate policies overall.

These scenarios were simulated by well-established Integrated Assessment Models (IAMs): MESSAGEix-GLOBIOM (Krey et al. 2016), GCAM (JGCRI 2019) and REMIND-MagPIE (Luderer et al. 2015), boiling down to a total of 18 variants (three models times six scenarios). Variants of the same scenarios feature the same global narrative on climate policy implementation, technology penetration and climate ambition. However, they are simulated by the three models above, which differ in terms of structures and core assumptions. Hence, for a given narrative, results from different variants can be non-trivially different, as Figure 5 illustrates. Although these projections run until 2100, this paper follows the climate-related risk literature in

published in 2020 (Bertram, Jérôme Hilaire, et al. 2020), comprised eight scenarios organised along a different narrative. Results from this vintage will be discussed in the result section, but their presentation is postponed to Appendix E for the sake of brevity.

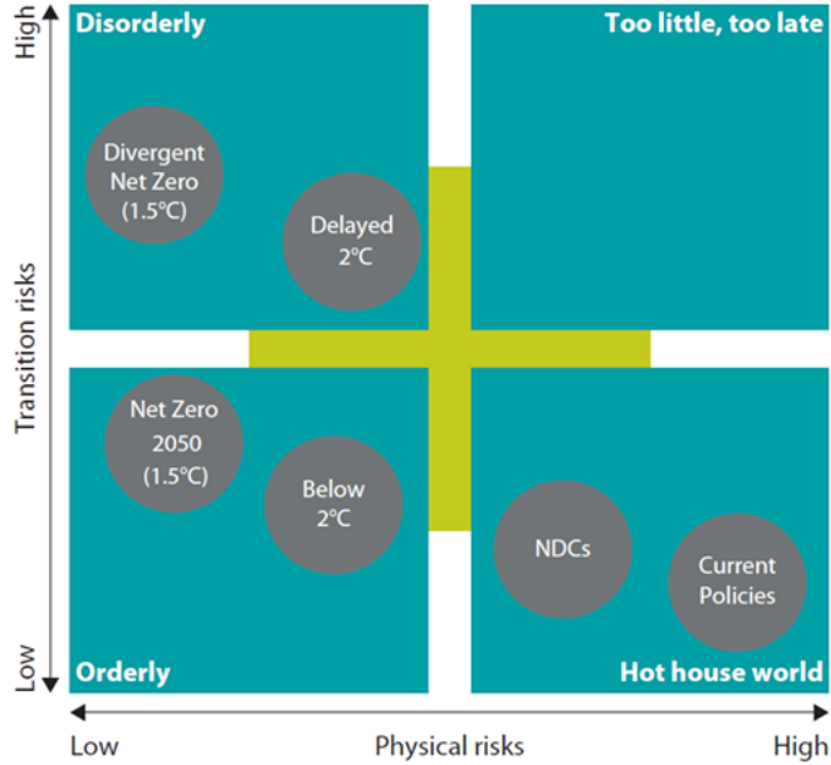


Figure 4: The NGFS scenario matrix, borrowed from NGFS (2022)

focusing on the 2020-2050 period, which is supposed to gather most transition risks (T. Allen et al. 2020).

3.2 Bringing the scenarios to the model

Such IAMs are large-scale tools with a detailed depiction of mitigation options and a rich set of outcomes. FASM-ID adopts a simpler representation of climate mitigation. Hence, to reproduce NGFS scenarios, I reduce them to an emission schedule and a carbon price path.

For each scenario, FASM-ID targets an exogenous emission schedule through slower or faster low-carbon technology penetration through the variable S_{LC}^T (see Section 2). The emission intensity of high-carbon capital at the beginning of the transition is calibrated by dividing the 2020 emissions given by the scenario under consideration by total real output. The model is solved for the sequence $\{S_{LC,t}^T\}_{t \in [2020-2050]}$ by

minimising the distance between the reference emission schedule and the model's emission pathways with a gradient descent method. It, therefore, captures the financial transition risks involved in a fully realised transition.¹²

Unlike some climate stress test exercises (T. Allen et al. 2020), I do not constrain the rate of economic growth to match that of the reference scenario, except in the baseline (see Section 4). This choice is consistent with ECB's climate stress tests, which leaves economic growth free (Alogoskoufis et al. 2021). It is further motivated by the will to allow for Keynesian multipliers in the model in a bid to bypass the identification issues raised by T. Allen et al. (2020) in the study of transition risks. Leaving growth free is also necessary to fully capture the interactions between the financial sector and the real economy along a transition path, which may have macroeconomic consequences. Furthermore, the simulations show that, in the long run, our growth trend reverts to a value relatively close to the baseline benchmark. Finally, imposing a growth path as a scenario assumption implies strong assumptions about the relationships between growth and the low-carbon transition. These being uncertain, this paper opted to tackle this issue in the sensitivity analysis developed in Appendix D.

Also, FASM-ID features two shortcomings. First, it does not incorporate explicit carbon dioxide removal (CDR) technologies, while all scenarios imply net negative emissions. However, these shortcomings are tempered by how FASM-ID is applied to scenarios. Regarding CDR technologies, in most scenarios, net negative emissions appear mostly after 2050, outside the period concentrating most transition risks. Therefore, I assume that low-carbon technology penetration and carbon intensity improvements include implicitly negative emission technologies and set post-2050 net negative emissions to zero in the schedule targeted by the model. Steeper carbon prices and decarbonisation schedules encapsulate the lack of CDR technologies. Second, being calibrated at a world level, FASM-ID also waives any consideration on

¹²This feature forces me to limit the extent of the possible brakes the financial sector could put on transition dynamics, like credit rationing or transition adverse expectations (Battiston, Monasterolo, Riahi, et al. 2020). More precisely, because I am not interested in failed transition, the model's behavioural equations are written in sso that the financial sector does not limit investment to such an extent that it prevents the transition from happening. In that sense, the model does not explore the "double materiality" of transition risks, whereby the behaviour of the financial sector also impacts decarbonisation dynamics (Gourdel, Monasterolo, Dunz, et al. 2022).

policy coordination. However, the steepness of carbon price schedules also proxy for this since a bad coordination of climate policy usually implies less optimal and, therefore, higher carbon prices. Hence, while I fully acknowledge these liabilities, they are partially addressed by the paper's methodology.

Finally, in the vein of T. Allen et al. (2020) and the IPCC methodology (IPCC 2022b), this exercise focuses on transition risks only and does not feature the climate damage hypotheses retained by the NGFS (2022). This choice is also motivated by the large uncertainties surrounding damage functions (Pindyck 2013) and the will to isolate the net effect of transition risks on the financial sector.

3.3 Scenario variants

As sketched above, this paper cashes in on the diversity of modelling frameworks used by the NGFS to run all 18 provided variants. Figures 5 display the corresponding emission paths and carbon price schedules.

As can be seen, scenarios differ mostly in carbon price schedules, with REMIND exhibiting lower overall carbon taxes and MESSAGE generally showing more stringent climate policies, except in some scenarios, where GCAM is more stringent. However, the emission trajectories can also show non-trivial differences in terms of shape and pace. Notably, MESSAGE exhibits more convex paths, with more decarbonisation effort in the short run, while GCAM tends to accelerate and go further than the other models in the longer run. REMIND generally adopts a middle-range position, with relatively steeper paths in the medium run. These differences across models in generating scenarios could have implications on projected transition risk profiles.

Finally, in a similar way, the NGFS has so far published two other vintages of scenarios in 2020 and 2021. While the 2022 and 2021 vintages have the same narrative and differ only in quantitative hypotheses, the 2020 series adopted a slightly different standpoint to determine scenarios. It will, therefore, also be worth examining how the changes in narratives and underlying hypotheses could impact transition risk measurement.

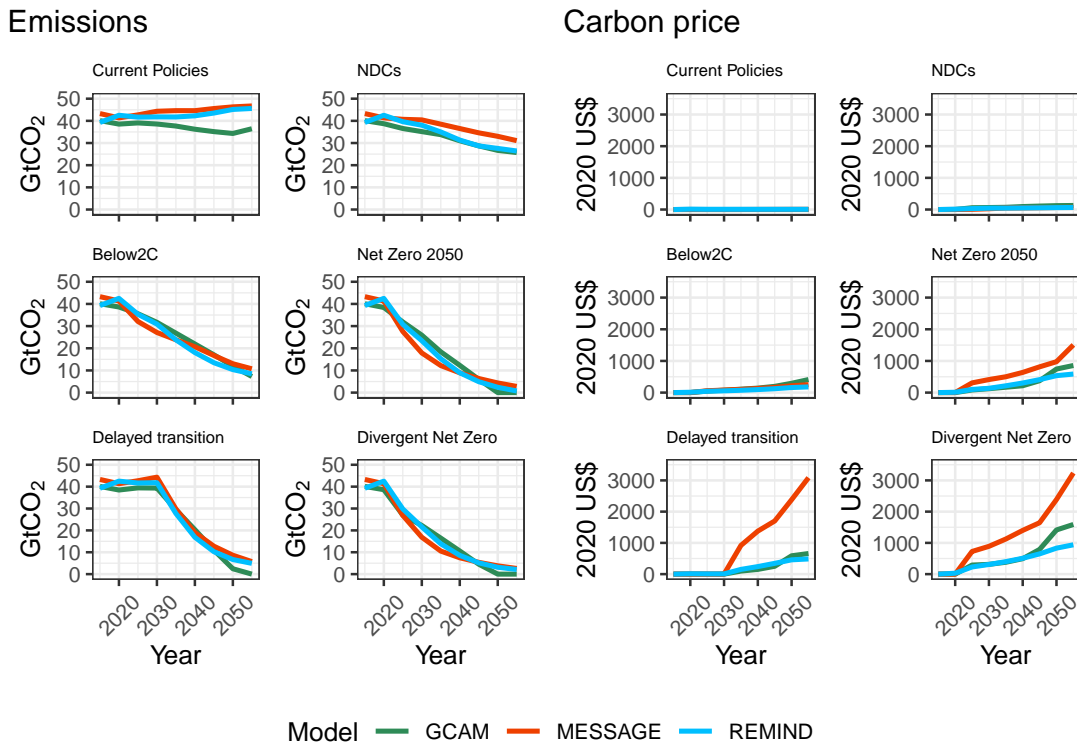


Figure 5: NGFS Scenarios (2022 Vintage) – Emission trajectories and carbon price schedules. Each line is a scenario variant. Panels (a) and (b) display emissions and carbon prices respectively.

As can be seen, scenarios differ mostly in carbon price schedules, with REMIND exhibiting lower overall carbon taxes and MESSAGE generally showing more stringent climate policies, except in some scenarios, where GCAM is more stringent. However, the emission trajectories can also show non-trivial differences in terms of shape and pace. Notably, MESSAGE exhibits more convex paths, with more decarbonisation effort in the short run, while GCAM tends to accelerate and go further than the other models in the longer run. REMIND generally adopts a middle-range position, with relatively steeper paths in the medium run. These differences across models in generating scenarios could have implications for studying transition risks.¹³

¹³In this respect, this work comes very close to a recent proposal by Gasparini, Baer, and Ives (2022), who also run a microeconomic stress test with multiple scenarios. This work can be seen as a complementary exercise offering a view of financial transition risks at the macroeconomic level.

4 Calibration

Before moving to the result, this section describes the calibration strategy of the paper, which goes in two steps. Appendix C. provides a detailed presentation of all parameter values and calibration targets, while providing more details on the calibration method.

4.1 Empirical parameters and steady-state

The model first builds on a series of empirically grounded parameters all detailed in Appendix C. They are all drawn from various sources in the literature. Some parameters were set instrumentally or after other similar modelling efforts. The model is first solved at an artificial “year zero” and forced to match a series of key ratios (wage share, capital adequacy ratios, leverage...), while respecting stock-flow norms. It is then brought to a non-oscillatory, stable, steady-state conditional on a vector of empirically grounded parameters. This steady-state is reached after around 40 iterations and is prolonged during around 20 iterations to ensure the convergence of key variables and reach satisfactory starting values for relevant indicators.

Macroeconomic variables (Nominal GDP, inflation, value of the capital stock, wage share, government deficit) and related parameters are calibrated on the year 2019 and drawn from WIOD (Timmer et al. 2015) and the World Bank (2022). Data on credit rationing is driven from the empirical literature (Beyhaghi et al. 2020; Aristei and Angori 2022) to reach a value of around 10%, while values on default probabilities for NFCs (2.8%) are drawn from the World Bank (2022). For NBFI, it was set at around 2.4% based on European Banking Authority (2019). Target leverage ratios were taken from the literature (Ferrari and Antonicchia 2018; Graham, Leary, and M. Roberts 2015) but adjusted downwards by around 30%, as I do not take either corporate bonds or short-term debt into account (McKinsey & Company 2018; FRED 2023b). The loan-to-investment ratio was taken from Al-Eyd et al. (2015) and equals 80%, as an average across developed countries. The structural share of government

bonds in NBFIs portfolio was set such that the ownership of NBFIs is around 15% after Andritzky (2012). Finally, the target share of units in household wealth was calibrated to ensure a share of currency and deposits in total wealth of around 20%, consistent with data on advanced economies (OECD 2022).

Because our transition simulation starts in 2020, values for the year 2019 are targeted.

Finally, to allow for the presence of some low-carbon capital before the transition start, and avoid too sharp an emergence for the Challenger sector, the model is calibrated to yield a non-zero market share for this sector. Unfortunately, data on “low-carbon” or “green” firms is scarce and full of uncertainties. I nonetheless use as a proxy the share of US and EU reporting green investment, which amount to 5 and 13% respectively in 2021 according to Faivre et al. (2023). With a different strategy, Kruse, Mohnen, and Sato (2020) identify a 5% share of US firms reporting at least some “green” revenue, with best-in class representing 2 to 3% of the sample. This amounts to a “green firm” market share of 8 to 9% by averaging across the EU and the US. Finally, Georgeson and Maslin (2019) estimate that the “green” economy overall represented close to 7% of US GDP in 2016 and 10% of Chinese GDP. They also report that the “green” economy of non China, non-US G20 countries amounted to around 10% of GDP. Given all these evidence, to adopt a middle-ground and to remain conservative *vis à vis* non-G20 country, I set this parameter to 8%.¹⁴

As shown in the sensitivity analysis (see Appendix D.), steady-states exist for a wide range of free parameters. I nonetheless fix some key partial-adjustment parameters to ensure the absence of oscillation for all retained steady-states.

4.2 Baseline calibration

This steady-state will not be the baseline for our analysis, as it would mean taking a no-policy scenario as a point of comparison. Rather, our baseline will apply the decarbonisation and carbon price schedules of the NGFS’s “Current Policy” scenario variants. This choice is motivated by the effective implementation of current policies

¹⁴Sensitivity tests with starting shares between 5 and 15% did not show strong changes in qualitative results.

as of now and their likely continuation in the future. It, however, departs from most stress test exercises, which consider “orderly” transitions as their benchmark. While choosing an “orderly” scenario for a baseline is useful in contrasting orderly and disorderly transitions, it does not allow us to assess the potentially disruptive effects of supposedly “orderly” transitions.

The baseline scenario is calibrated based on the steady state, adjusting the starting iteration if needed to adjust 2019 nominal GDP and other values. It further targets some dynamic behaviour, notably the average growth rate over the run, which is set at around 2.54% per year on average after the NGFS scenarios, average inflation, and the average default rate across sectors. I also target a share of NBFIs loans in total portfolio of 10-15% (Franceschi et al. 2023) and a share of equity held by banks of around 10-15% (Von Beschwitz and Foos 2018; ECB 2020b). Carbon intensity at the start of the run is adjusted for the emission scenario since, as shown in Figure 5, all projections do not start at the same inflation level.

For indicators usually not displayed by IAMs but present in the model, like inflation, I keep the macroeconomic assumptions used to calibrate the model for 2019. The passthrough rate at the macroeconomic level is 20% based on Känzig (2023). In contrast, absent firm empirical evidence, the carbon intensity improvement rate was set instrumentally but will be subjected to sensitivity analysis. Since several variants of the same scenarios are simulated, one baseline by variant is generated to retain comparability.

Finally, the base rate, the interest on government bonds and the interest rate on deposits are constant for simplicity and because of the long-run aspect of the exercise. Furthermore, the role of changes in the base rate and government bond rates in triggering transition risks on fixed-income assets is well-established (ESRB 2020; Vermeulen et al. 2021). Because these effects usually follow a policy reaction – notably to inflationary pressures due to the transition – the model simplifies the assumption that the central bank accommodates the low-carbon transition. This feature allows me to focus on other financial instability channels. The two parameters will be

subjected to a sensitivity analysis, whose results are displayed in Appendix D.

5 Results

5.1 Outcomes of interest

I consider five outcomes of interest related to financial instability. Since no noteworthy patterns emerged during our simulation for the Challenger sector the analysis will focus on the Incumbent sector, symbolising the “sunset” (Semieniuk, Campiglio, et al. 2021) industries directly affected by the transition. I also provide insights on banks and NBFIs. As sketched above, results will be displayed for the period 2020-2050, extended to 2055 for readability. Table 1 summarises our metrics of interest.

Default probability and equity prices are usual metrics in NGFS-based exercises (T. Allen et al. 2020; Dunz, Naqvi, and Monasterolo 2019). Default probabilities show the extent to which banks could be made more fragile along a transition path. On the other hand, equity prices measure the extent of asset losses in stock exchanges. These variables measure realisations of transition risks, respectively, of firm and market risks.

Once these realisations are measured, their actual effect on financial institutions’ financial health remains to be gauged. The capital adequacy ratio measures the actual vulnerability of banks to transition shocks (credit risk), while changes to NBFIs default probability measure that of NBFIs (financial counterparty risk). I also present the dynamics of capital gains and losses to measure potential increases in volatility due to the transition.

5.2 Main results for REMIND-MagPIE

First, I focus on the results emerging from the emulation of the scenario variant generated by REMIND-MagPie, which is usually the reference model in most similar exercises (T. Allen et al. 2020; Gourdel, Monasterolo, Dunz, et al. 2022). I first

Table 1: Outcomes of interest

Outcome	Description	Symbol	Underlying risk
Default probability of Incumbent firms	Default probability increasing with sector's illiquidity	$\varphi_{IN,t}$	Firm Risk
Equity price - Incumbent	Ratio of nominal demand for equity to the real number of securities	$p_{A,IN,t}$	Market risk
Capital Adequacy Ratio	Ratio of own funds to loan exposure	CAR_t	Credit Risk
Default probability of NBFI	Default probability increasing with sector's illiquidity	$\varphi_{NBFI,t}$	Counterparty Risk - Financial Markets
Capital gains/losses	Revaluation of held assets	CG_t	Volatility

present metrics showing the realisation of transition risks. I then examine variables measuring how banks and institutions bear the losses associated with the first two variables.

5.2.1 Transition risk realisations

Figure 6 displays transition risk realisations. Panel (a) shows the default probability of the Incumbent, and Panel (b) features the price dynamics of its equity asset. Panel (c) complements Panel (b) by showing related capital gains and losses. The dashed black line displays the “Current Policy” baseline results to ease comparison. Finally, the shaded red area draws the 95% sensitivity range.

The Incumbent’s default probability in the baseline increases somewhat due to the implementation of climate policy, which generates a tax burden, and the slow development of the Challenger sector, to reach a near-plateau slightly below 4%. It roughly corresponds to the world average between 2000 and 2015, overlooking financial crises. Hence, such figures are realistic, considering the tensions that would emerge anyways under the continuation of current policies. The NDC scenarios stand very close, with slightly higher rates in the short and medium-to-long run.

On the other hand, immediate-action transition scenarios exhibit right from the out-

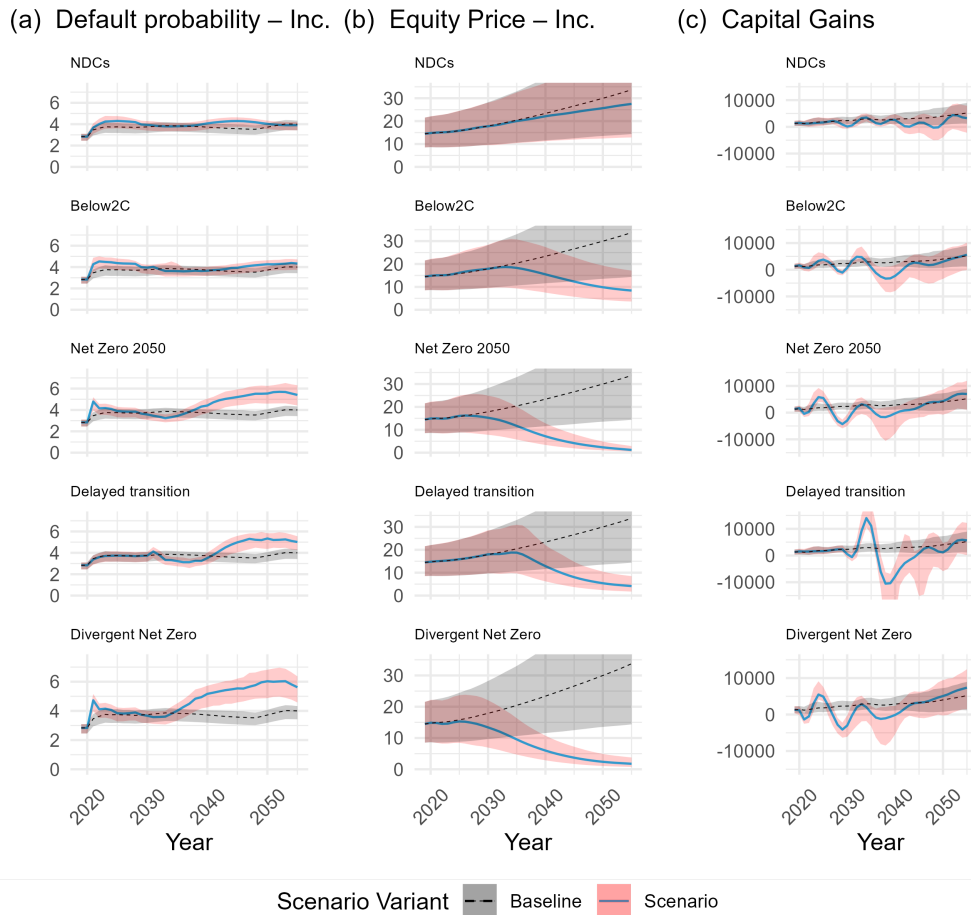


Figure 6: Transition risk realisations – REMIND MagPie variant (2022 vintage). The shaded areas are the 95% sensitivity range, in red for the main outcome and grey for the baseline. Panel (a) shows the default probability of Incumbents. Panel (b) displays the equity price of the Incumbent. Panel (c) expounds capital gains.

set higher default probability rates, which quickly reach 4-5%, then decrease to relatively low values, and then slowly increase until 6.5-7% before going slightly down. This non-linear path is due partly to our Keynesian approach: since the transition positively affects growth in the medium run, Incumbents can partly grow away from financial fragility. This feature explains why default probabilities are lower than the baseline in the medium run. However, these agents become increasingly fragile once the Challenger has taken over. Hence, this effect is only transitory. As expected, the highest values are reached fastest for disorderly transitions. These numbers are

high both compared to baseline and by historical standards. It suggests that the low-carbon transition, under any kind of scenario, would put high-carbon activities under significant stress in the immediate aftermath of the introduction of climate policy and in the longer run. Default probability rates tend to increase in the long run, suggesting that transition risks may extend far beyond sudden, short-run adjustments (Batten, Sowerbutts, and Tanaka 2016) despite relative improvements in the medium run.

The Delayed-action scenario exhibits higher default probability in the short to medium run after the start of the transition than in the orderly “Below 2°C” scenario. However, it shows overall less sharp adjustments than more climate-ambitious scenarios, like Net-Zero 2050. This feature is first attributable to multiplier effects in the short run, which are relatively stronger because of the need to catch up on the lag accumulated during the 2020s. It can also be explained by the fact that the Delayed-Action Scenario assumes the Current Policy scenario until 2030 (Section 3). This feature entails a degree of low-carbon capital penetration and conversion in the Current Policy scenarios over the 2020s. Because Incumbents convert their capital stock before the late introduction of climate policy, they can absorb policy shocks occurring in the 2030s. Higher growth due to the necessarily rapid penetration of low-carbon capital results in higher proceeds. It allows firms to grow away from financial difficulties. By contrast, immediate-action scenarios with high climate ambitions feature no or lesser conversion and do not allow Incumbents to bear at least part of the shock, resulting in higher default. Inflationary pressures are also overall higher in such scenarios. It weighs on aggregate demand and counterbalances partly the multiplier effects of low-carbon investment.

Equity prices for the Incumbent follow an upward path in no-transition scenarios, consistently with historical trends (Hagenbjörk 2020). The NDC scenario is broadly similar, showing slower dynamics. In immediate-action scenarios, Incumbent’s equity prices are characterised by a small degree of volatility in the short run, with a slow-down and then a transitory dip, which is more pronounced in disorderly scenarios.

The initial transition shock generates proceeds for the Incumbent through multiplier effects. These proceeds allow it to grow away from its loss in market shares, profits start to decrease, and dividends with them. They get temporarily stabilised through markup inflation (due to passthrough and higher utilisation rates) but inevitably go down as the Challenger sector develops and market shares are lost. By the end of the 2030s at the latest, the equity price of the Incumbent decreases quasi-monotonously, especially in more climate-ambitious scenarios. It suggests that early-action scenarios exhibit “erosion risks” in the long run (Giese, Nagy, and L.-E. Lee 2021) as the Incumbent sector loses market shares. The delayed-action scenario follows the same pattern but shifted by ten years. However, adjustments are sharper: as shown in Panel (c), after a period of high capital gains due to the multiplier effect induced by the transition (see above), sharp decreases in Incumbent equity prices trigger very large capital losses in the medium run after the start of the transition.

5.2.2 Impact on the financial sector

How do these transition realisations translate into vulnerability for financial institutions? Figure 7 displays related results, with Panel (a) showing banks’ capital adequacy ratio (CAR) and Panel (b) the default probability of the NBFi sector. Are also displayed counterfactual runs without NBFi leverage to highlight amplification effects arising from within-financial sector interactions.

Regarding Banks, results show that the transition barely affects their CAR beyond short-run adjustments. This is due to higher default rates in the Incumbent sector and a significant credit expansion for the Challenger sector. However, banks are quickly able to absorb these losses. Capital losses for banks on their equity portfolio are also relatively limited in absolute due to their minor contribution to the equity market. Note nonetheless that these transitory shocks represent 5 to 15% of the distance between the base CAR of 18% and Basel III’s prudential ratio of 8%, which, for the most stringent scenarios, is significant.

Disorderly scenarios generate, as expected, more significant shocks, which remain

small (2-point shock maximum). In both cases, this pattern is attributable to the fact that banks benefit significantly from the emergence of the Challenger sector, which, developing very fast, exhibits default propensities. Diversifying banks' portfolios as the transition unravels gives them more resilience, limiting the impact of the transition on their CAR.

The picture, however, is more dire for the NBFIs sector. As Panel (b) in Figure 7 shows, the NDC and Below 2°C scenarios feature relatively contained default probabilities – although they are relatively high by historical standards (European Banking Authority 2019). Immediate-action scenarios feature a significant shock right after the beginning of the transition, especially the Divergent Net Zero scenario, which peaks at around a 10% default rate. NBFIs default rates in the Delayed-Action scenario also approach 10% in the medium run after climate policy implementation. These sharp adjustments are all attributable to capital losses and dividend diminutions, which significantly reduce the liquidity of NBFIs, which increases their default probability (see Section 2.4). More importantly, the scenarios exhibit waves of higher default probabilities, which follow the waves of capital losses shown in Figure 6 Panel (c). It suggests that transition risks for NBFIs extend beyond the short run and that medium to long-run risks should be carefully monitored. Further, these high default rates feed back onto banks, which face lower CAR and more protracted fragility than in a scenario without NBFIs. Banks seem to navigate medium-run surges in NBFIs default probabilities, thanks to diversification into the Challenger sector.

Finally, the model shows viable sensitivity ranges, adding confidence to our qualitative insights. For our selected calibration (see Appendix D), results are relatively similar, both quantitatively and qualitatively, although our main calibration stands as relatively conservative.¹⁵ An exception is the Delayed-Action scenario, which exhibits a much higher dependence on parameters and a greater variability in results.

This result suggests that the viability of a delayed-action transition may more signif-

¹⁵Due to our sampling process, the sensitivity range cannot be exactly centered around the main calibration. This also explains why, for some scenarios and outcomes, the main calibration stands at the limit of the sensitivity range.

icantly hinge on macroeconomic conditions than other scenarios.

5.3 Results for the whole NGFS model suite: A comparison across models

The results above hold for one scenario variant, which implies a specific decarbonisation pathway and climate policy assumptions. Yet, as sketched in Section 3, the other variants in the NGFS scenario set can include non-trivially different assumptions regarding decarbonisation dynamics and climate policy intensity. This feature may have non-trivial implications on transition risk profiles. The goal of this subsection is, therefore, to bank on FASM-ID's ability to simulate scenarios generated by several models and compare the outcomes of the three models of NGFS's suite. The following will thus compare the results obtained in REMIND-generated scenarios to those yielded by the projections provided by MESSAGE and GCAM.

Figure 8 displays results for all scenario variants (three per scenario) on a sample of outcomes (CAR, NBFI default Probability and Incumbent Default Probability) in the worst-case scenarios provided by the NGFS, i.e, Below 2°C, Delayed Action, Net-Zero and Divergent Net-Zero.

Overall, in all model variants, projections behave as expected, with the most disorderly scenarios yielding the highest transition risk projections. An exception is NBFI default probability for GCAM in the medium run, which exhibits higher values than other projections and higher Incumbent default probability in some periods. This feature is due to the profile of GCAM's Current Policy is more stringent than those generated by the two other models. As shown in Figure 5, GCAM's Current Policy scenario implies a decrease in emissions compared to the two others, accelerating the Challenger sector's development in the medium run. Therefore, it creates some tensions in the long run, which remain modest. It highlights crucial differences in baselines' definition, which stress testers must be aware of.

Looking more closely, outcomes show small but non-trivial differences across simulations. Qualitatively, notably for NBFI default, scenarios exhibit differences in the

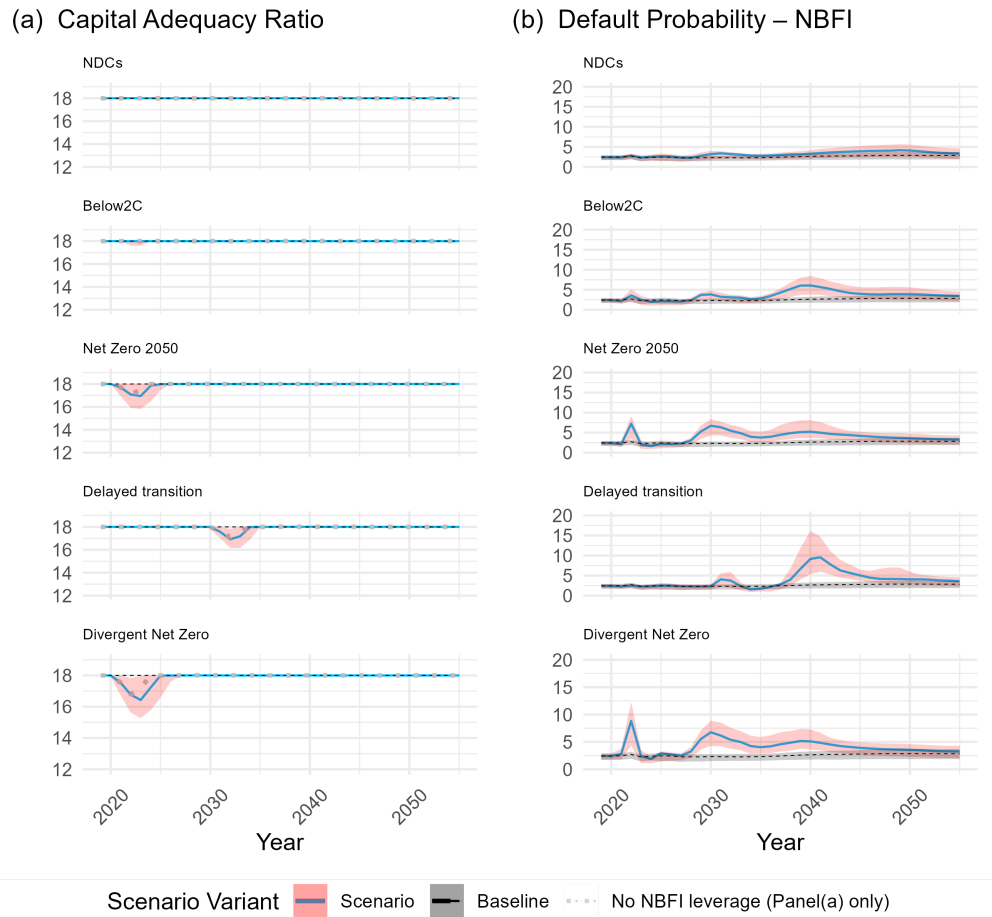


Figure 7: Transition risk vulnerabilities – REMIND MagPie variant (2022 Vintage). The shaded areas are the 95% sensitivity range, in red for the main outcome and grey for the baseline. The grey line is a counterfactual without NBF1 leverage. Panel (a) displays the capital adequacy ratio, while Panel (b) shows NBF1 default probability. Values are in percentage points.

precise unravelling of financial disturbances, especially in immediate-action systems. The delayed-action scenario variants are globally in line. This difference lies in the fact that immediate-action scenarios are more uncertain than delayed-action scenarios in terms of decarbonisation dynamics, the latter assuming very similar concave shapes in the short run and only diverging in terms of long-run climate ambition (see Figure 5). In most scenarios, except in delayed action, REMIND stands halfway between the two other models, consistently with its intermediate position: low carbon prices but relatively stringent decarbonisation dynamics. It can thus be safely taken

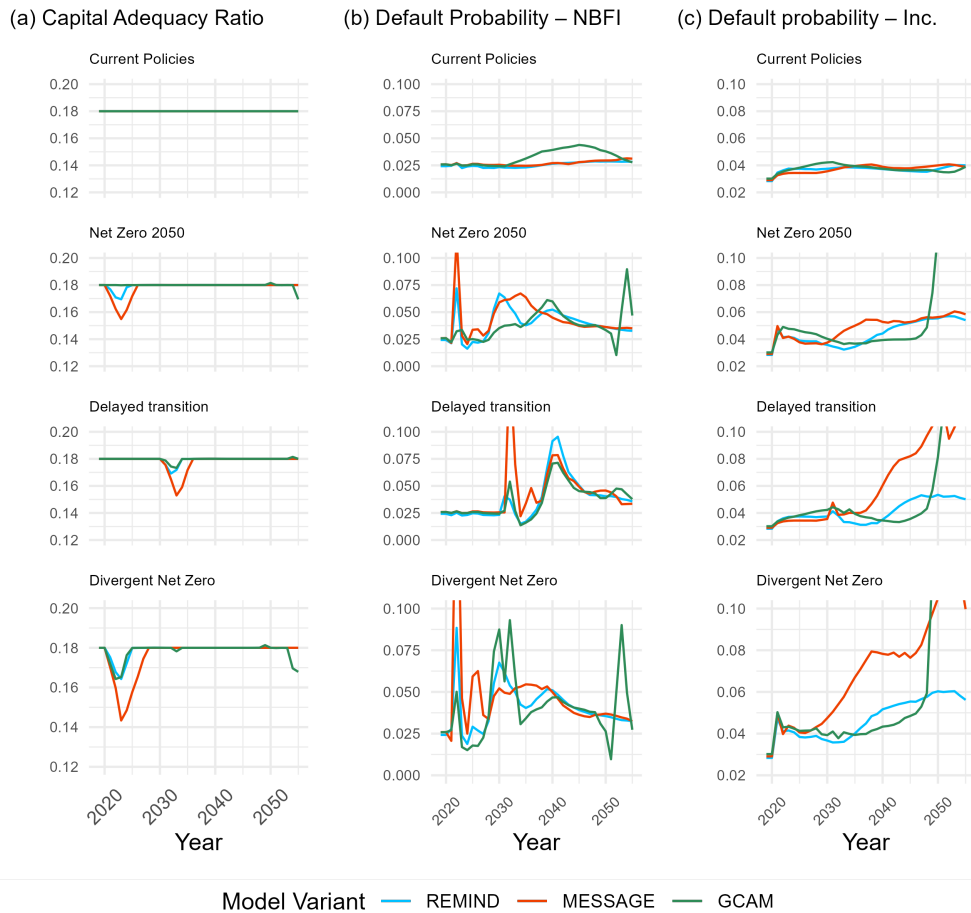


Figure 8: Macroeprudential risks – Worst-case NGFS scenarios (2022 Vintage). Each line represents a model variants. Note that, for readability purposes, some axes have been cut. Panel (a) shows the capital adequacy ratio. Panel (b) shows the default probability of NBF1. Panel (c) shows the default probability of Incumbents.

as a benchmark.

Quantitatively, MESSAGE’s variant exhibits the highest transition risks in the short and medium run, with the biggest shock to CAR and the highest default probabilities. It is attributable to two elements (see Figure 5). First, the MESSAGE variants exhibit the sharpest decarbonisation dynamics in the short to medium run, which implies a quick loss in market share and profitability for the Incumbent sector. Second, MESSAGE exhibits the highest carbon price schedule in the long run for most scenarios. It weighs on the Incumbent’s repayment abilities, which brings their default

probabilities to very high values in late periods and exacerbates amplification mechanisms in the short run. Further, MESSAGE qualifies the usual distinction between orderly and disorderly scenarios put forward by the NGFS (2022): due to significant short-term adjustments in the Net-Zero 2050 scenario (orderly), this scenario exhibits a higher short-term risk profile than the Delayed action scenario (disorderly).

GCAM exhibits a similar long-run behaviour but less because of carbon prices than due to more drastic decarbonisation dynamics. Indeed, GCAM implies 0 emissions around 2050 (see Figure 5), which entails the near-total exit of the Incumbent sector. It first translates into a sharp rise in default probability of the Incumbent, whose market shares are reduced to almost zero. Second, when this happens, a slump occurs due to the slowdown in Challenger investment since there are no more high-carbon production capacities to replace. It feeds back onto the profitability of the Challenger sector, whose return on assets diminishes transitorily, leading to some financial disturbances. This behaviour comes close to a long-run green bubble narrative (Nikolaïdi 2017) whereby investment in low-carbon technology can create financial troubles in the medium to long run, which are due here to the necessary slowdown of transition dynamics. This discussion shows that the precise shape and pace of decarbonisation dynamics and carbon price assumptions can significantly drive results. Given the high degree of uncertainty related to these two aspects (IPCC 2022a), it invites us to consider scenario variants with attention.

5.4 Variation across vintages (2021)

How do these results hold for earlier vintages of the NGFS scenarios? I close the result section with a brief comparison of the 2021 and 2022 vintages. Results for the 2020 vintage are postponed to Appendices for brevity. Results for the 2021 vintage are displayed in Figure 9.

Overall, there are strong similarities across scenario vintages. This is expected, given that they build on the same narratives (NGFS 2022). Yet, some differences arise. First, Current Policy scenarios exhibit much closer behaviours across models. Then,

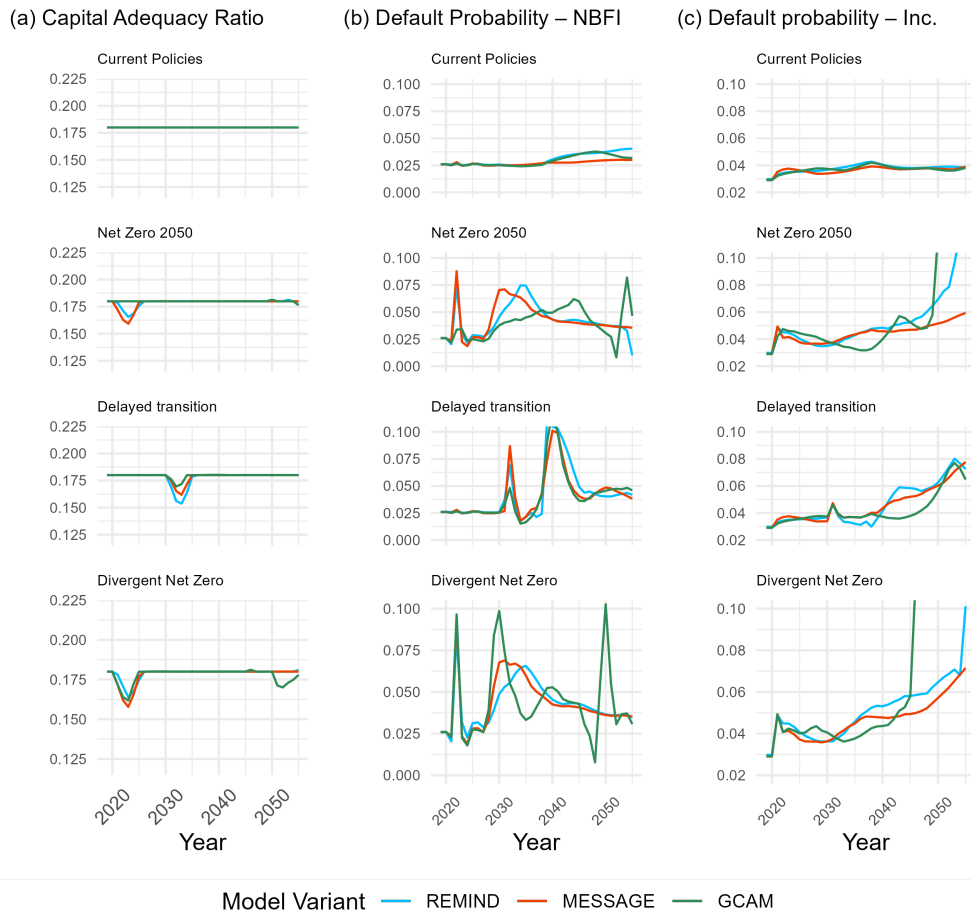


Figure 9: Macroeprudential risks – Worst-case NGFS scenarios (2021). Each line represents a model variants. Note that, for readability purposes, some axes have been cut. Panel (a) shows the capital adequacy ratio. Panel (b) shows the default probability of NBF1. Panel (c) shows the default probability of Incumbents.

the 2021 delayed-action scenario seems more severe than its 2020 counterpart, with the REMIND variant showing the largest shock. Results for the Divergent Net Zero model are much more in line across models, with MESSAGE showing less strong adjustments overall. Finally, GCAM exhibits stronger short-term and long-term adjustments, which suggests a change in the pace of its decarbonisation dynamics between 2021 and 2022.

6 Conclusion and discussion

6.1 Main takeaways

The results show that transition risks can be sizeable for the losing sectors but not across all financial risks. Firm and market risks can be sizeable for the losing sectors. Firm risk increases over time for the Incumbent, with significant short-term adjustments in climate-ambitious scenarios. The same goes for market risks: past some short-term adjustments, which can trigger substantial capital losses, asset prices dwindle in the medium to long run, giving rise to erosion risk, consistently with the intuition of Giese, Nagy, and L.-E. Lee (2021). Although these decreases are monotonous, they can also give rise to substantial capital losses in the medium to long run. As a result, while FASM-ID clearly shows the existence of short-term adjustments for transition pathways, it also points out the possible building up of long-run transition risks in the real economy. Such risks, however, need not translate one to one to the financial sector, which may be able to absorb part of the losses incurred on its exposures. It is notably the case for banks, which face almost only short-term losses and seem able to navigate further disturbances as the transition unravels. In other words, the low-carbon transition creates a secure loan outlet for banks, which can reap high profits at low risks. This view suggests that the low-carbon transition may have relatively beneficial outcomes in terms of financial stability through the wealth and outlets created by the emergence of low-carbon activities (Linnenluecke, Han, et al. 2019; Monasterolo 2020b). Credit risks are therefore limited within FASM-ID. However, the picture of financial counterparty risk shows greater risks. FASM-ID shows acute increases in NBF1 default probability along the transition path. In the short run, it significantly amplifies the shocks onto banks. This aspect leads to two conclusions. First, from a theoretical standpoint, it highlights the importance of accounting for possible amplification mechanisms and vindicates the model's disaggregation of the financial sector. Then, from a modelling perspective, it underscores the need to model the financial sector's reaction to the transition as it goes.

Scenario-wise, our results globally behave as expected, with the measured transition risk content of scenarios increasing with their climate ambition, the pace of green capital development, and climate policy disruptiveness. However, compared to common wisdom (Batten, Sowerbutts, and Tanaka 2016; Kalkuhl, Steckel, and Edenhofer 2020), the delayed-action scenario only features a little less risk than climate-ambitious scenarios. This feature is consistent with previous evidence on credit risk and its impact on banks (Alogoskoufis et al. 2021). Furthermore, the Delayed-Action scenario features a relative diversification of banks' portfolio loans before introducing climate policy. Hence, when the transition starts in 2030, their portfolio is already relatively balanced, limiting disruptions. Thus, in this framework, the primary determinant of transition risks is more climate ambition and the intensity of climate policy than the timing of action. Also, the results show that the usual distinction between "orderly" and "disorderly" scenarios may not necessarily hold for all scenario variants and all types of risk and may depend on the horizon of analysis. Results finally point to significant variations across scenarios regarding transition risk content and profiles. In particular, the intensity of climate policy necessary to achieve a given climate target and the precise pace and shape of the decarbonisation schedule drive significant variation in results. Quantitatively, the MESSAGE scenario variants tend to exhibit the direst transition risk profiles, primarily because of their high carbon price assumptions and sharp short-term decarbonisation dynamics.

Conversely, the GCAM variant exhibits significant risks in the longer run. Notably, "deep-decarbonisation" scenarios show something close to a green bubble. REMIND usually stands in between the two others. While it vindicates the choice of this model as a reference (Gourdel, Monasterolo, Dunz, et al. 2022), it also invites caution in considering a broader array of variants to map model uncertainty (Kriegler, Petermann, et al. 2015) better. FASM-ID shows minor but non-trivial differences between the 2021 and 2022 NGFS scenario vintages.

6.2 Limitations and future research

The model features simplifying assumptions that could drive these results to a certain extent. These limitations also invite considering the model's quantitative estimates with some caution.

This general transition risk picture is conservative due to the positive macroeconomic effects exhibited by the model. Compared to similar models, assumptions of slack, no capacity constraint in the investment sector, constant returns to scale, and a positive relationship between growth and productivity lower the private costs of the low-carbon transition. Capital conversion is straightforward due to the absence of increasing prices, allowing Incumbent firms to diversify their production process more efficiently than expected. Also, the way the model figures decarbonisation is crude, with a readily available non-polluting capital, which amounts to a silver bullet. Diversifying portfolios or coming up as a fully decarbonised sector is easier. It also drives the growth effects of the model: because a readily viable alternative is available, decarbonising through production curtailments is useless. It may overestimate multipliers.

The model also seems optimistic regarding the development of the Challenger sector, which does not entail financial disturbances or “green bubble” dynamics, except in some scenarios. It could be due to symmetric risk default propensity assumptions, while newcomers may carry greater intrinsic risk. Conversely, a shrinking sector could be growingly sensitive to illiquidity and carry more risk as its market share decreases. Further, as is usual with post-Keynesian SFC models, expectations are backwards-looking. Such structures mechanically restrict the hedging behaviour of agents, which may need to diversify their activities sufficiently to avoid the carbon tax. For instance, firms may incur high losses in non-stringent scenarios because they do not smooth their carbon tax bill over time. Relatedly, the model lacks a meaningful asset pricing theory like in most SFC frameworks, including tradable assets (Godley and Lavoie 2007; Burgess, Burrows, and Kinsella 2016). Asset prices are defined passively as the ratio between nominal demand for equity and the real amount of outstand-

ing equity, with only a very loose relationship to firms' financials and especially no forward-looking pricing process (see Gourdel, Monasterolo, Dunz, et al. (2022) for the inclusion of a proper trading module in an SFC model and Dafermos, Nikolaidi, and Galanis (2017) for the representation of a primary and a secondary markets for bonds). Finally, the model's financial sector is short-sighted and only reacts to developments in the real economy, while capital reallocation could occur autonomously based on decarbonisation expectations (Battiston, Monasterolo, Riahi, et al. 2020). Because the model only features aggregated banking and NBFIs sectors, it implicitly assumes that all agents populating these aggregates are equally exposed to transition risks and that they move their exposures harmoniously. It could explain the relative innocuity of transition scenarios for banks since they all simultaneously reshuffle their loan portfolios harmoniously. Yet, the literature documents a very skewed distribution of exposures, with some prominent players concentrating on the most significant vulnerabilities (Baer 2021; Battiston, Monasterolo, Riahi, et al. 2020). Furthermore, FASM-ID's NBFIs sector gathers a considerable heterogeneity of agents with various business models and risk management approaches. This shortcoming calls for a more disaggregated picture of the financial sector. Applying an agent-based framework to our financial system (see Botta et al. 2021) with more types of financial agents (Caverzasi, Botta, and Capelli 2019) could bridge this gap. Another dimension of disaggregation that the model currently needs to capture is geographical. For instance, stranded assets are very unequally distributed between countries (Daumas 2023, Chapter 1) and could, therefore, bear very different consequences on financial instability across countries. Further, the low-carbon transition may pose acute transboundary risks (Volz et al. 2021; Magacho et al. 2021; Gourdel, Monasterolo, Dunz, et al. 2022) that may create additional financial instability channels currently not captured by FASM-ID. A direct extension could be to build a North-South version of FASM-ID along the line of Carnevali, Deleidi, et al. (2021) to capture better financial account dynamics linked to the low-carbon transition.

Although further model refinements are needed, this framework is easy enough to

modulate and accommodate different carbon price paths while linking them to emission targets. Hence, it could be a valuable tool to explore a broad ensemble of scenarios generated by a large set of models and compare outcomes linked to financial instability. Applications of robust decision-making or scenario discovery methods (Lempert 2019) could represent sound applications of this framework. This may help complement traditional scenarios with an easy-to-implement financial-instability view.

6.3 Policy Implications

With these caveats in mind, the results from this climate stress test nonetheless have some policy implications.

First, market risks are likely more acute than credit risks, which have received more attention in the literature (Basel Committee 2021b). Asset devaluations can be very sharp and give rise to potentially high tensions in financial markets. Since, in parallel, banks can stand most of the transition, it invites policymakers to monitor market risk as a priority. Further, our results ask us to envisage a “soft-landing” for low-carbon activities to defuse possible “green bubble” courses of events in the long run. Finally, FASM-ID suggests that a critical driver of transition risks is the relative efficiency of climate policy. Scenario variants in which a given climate target can only be achieved through very stringent climate policy – notably the MESSAGE variants – trigger the highest transition risks. It also invites considering alternative climate policies that may help Incumbents and financial institutions navigate the transition better.

I further insist that the risks highlighted in this paper are no reason for delaying climate policy or reducing climate ambition. As repeatedly emphasised by previous stress tests (Alogoskoufis et al. 2021; ECB/ESRB Project Team on climate risk monitoring 2022), the risks associated with climate change impacts are incomparably higher than those that an ambitious and decisive transition to a low-carbon economy could trigger. Since decarbonisation is not an option, this paper highlights the need for complementary macroprudential policies to reduce the (macro-) financial stress

associated with the low-carbon transition.

Finally, on the use of scenarios by policymakers, results clearly show that significant differences can emerge across scenario variants and vintages. It calls for a careful study of model and scenario uncertainty in studying transition risks. A possible step in that direction could be an increase in the number of projections and model variants to map the range of potential uncertainties better.

The next chapter of this dissertation will precisely embark on this endeavour. Indeed, this proof-of-concept exercise aimed at introducing our modelling framework and drawing some teachings for the study of transition risks. However, the number of studied scenarios and scenario profiles was limited. It invites caution in drawing general conclusions about the transition risk content of the low-carbon shift. Indeed, the Energy-Economy-Environment literature has provided a very wide array of possible transition paths and narratives provided by over the past twenty years (de Haan et al. 2016; IPCC 2022a). While relying on a reduced number of scenarios within a well-defined conceptual framework has the advantage of clarity and simplicity and is certainly useful for regulated institutions it also diminishes the range of transition paths that agents admit as possible. Said otherwise, neither all possible transition dynamics (pace of carbon emission reductions, climate ambition) nor all possible climate policy intensities, nor, consequently, all possible decarbonisation-climate policy combinations are explored and examined. It potentially leaves aside some configurations whose transition risk content is, as a consequence, unknown. The next chapter precisely tackles this issue by expanding the range of potential scenarios and scenario profiles in a bid to better assess what kind of low-carbon transitions are riskiest for the financial system.

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Appendices

A. Stock-Flow Tables

Table A.2: Balance-Sheet Matrix

	Asset	Households	Incumbents	Challengers	In. good Banks	NBFIs	Government	Central Bank	Sum
Balance sheet	High-carbon capital		$+\Omega_{IN}^H$						$+\Omega_{IN}^H$
	Low-carbon capital		$+\Omega_{IN}^L$	$+\Omega_{CH}^L$					$+\Omega_{IN}^L + \Omega_{CH}^L$
	High-Powered Money	$+H_H$			$+H_B$			$-H$	0
	Units	$+U$				$-U$			0
	Deposits	$+D_H$	$+D_{IN}$	$+D_{CH}$	$-D$	$+D_{NBFI}$			0
	Loans		$-L_{IN}$	$-L_{CH}$	$+L$	$-L_{NBFI}$			0
	Bonds				$+GB_B$	$+GB_{NBFI}$	$-GB$	$+GB_{CB}$	0
	Advances				$-J_{CB}$			$+J_{CB}$	0
	Equity		$-A_{IN}$	$-A_{CH}$		$+A$			0
	Own Funds	$+OF$			$-OF$				0
Revaluation Matrix	Non-performing loans		$+NPL_{IN}$	$+NPL_{CH}$	$-NPL$	$+NPL_{NBFI}$			0
	Equity		$-a_{IN}\Delta p_{A,IN}$	$-a_{CH}\Delta p_{A,CH}$	$+a_{IN,B}\Delta p_{A,IN}$	$+a_{IN,NBFI}\Delta p_{A,IN}$			0
	Asset Stranding				$+a_{CH,B}\Delta p_{A,CH}$	$+a_{CH,NBFI}\Delta p_{A,CH}$			0
Own funds	$+\Delta OF$				$-\Delta OF$			0	
Net Worth		$-V_H$	$-V_{IN}$	$-V_{CH}$	0	0	$-V_{NBFI}$	$-V_G$	0
									$+\Omega_{IN}^H + \Omega_{IN}^L + \Omega_{CH}^L - Q$

B. Model Equations

B.1. Non-financial sector

B.1.1 Production and employment Consumption-good firms supply a homogeneous consumption good x^s with a Leontief technology:

$$x_{\ell_t}^s = \min \left(\lambda_{\ell_t} N_{\ell_t}, \kappa_{\ell} \omega_{\ell_t} \right), \quad (\text{B.1})$$

with $\ell \in \{CH, IN\}$, t the time index, and where N_{ℓ_t} and ω_{ℓ_t} are respectively employed labour and total capital stock in sector ℓ . λ_{ℓ_t} and κ_{ℓ} are respectively the labour and capital intensity in sector i . Because the Incumbent sector possesses both high- and low-carbon capital, I obtain:

$$\kappa_{IN} = \kappa^H S_{IN_t}^H + \kappa^L (1 - S_{IN_t}^H), \quad (\text{B.2})$$

where κ^j , $j \in \{H, L\}$ denotes the capital intensity for high- and low-carbon capital, respectively, and S_{IN}^H the share of high-carbon capital in the total of the Incumbent sector.

Because the Challenger sector only invests in low-carbon capital, $\kappa_{CH} = \kappa^L$. I assume that capital intensities are the same for both types of capital, such that $\kappa^H = \kappa^L = \kappa_{IN} = \kappa_{CH}$. Capital intensities are held constant.

To best represent the dynamics of asset stranding, I allow for capital vintages. The high or low-carbon capital stock of both sectors can be represented as a vector $b_{\ell_t}^j$ of capital vintages:

$$b_{\ell_t}^j = \begin{pmatrix} (1 - \delta^j)^t k_{\ell_0}^j \\ (1 - \delta^j)^{(t-1)} k_{\ell_1}^j \\ \vdots \\ k_{\ell_t}^j \end{pmatrix}, \quad (\text{B.3})$$

where δ^j , $j \in \{H, L\}$ is the natural depreciation rate of capital, which is supposed to be the same for both high- and low-carbon capital.

It is assumed that capital stocks only differ by their time of installation and, therefore, have the same productivity κ_j . As a result, I can sum to obtain the total real j -type capital stock for sector ℓ :

$$\omega_{\ell}^j = \sum_{n=0}^t ((1 - \delta^j)^{t-n}) \kappa_{\ell_n}^j. \quad (\text{B.4})$$

For the Incumbent sector, the total real capital stock ω_{IN_t} is given by $\omega_{IN_t}^H + \omega_{IN_t}^L$, and $\omega_{CH_t} = \omega_{CH_t}^L$.

The valuation of capital goods is made at historical costs, *i.e.*, at their purchase price:

$$B_{\ell_t}^j = \begin{pmatrix} (1 - \delta^j)^t \kappa_{\ell_0}^j p_0^j \\ (1 - \delta^j)^{(t-1)} \kappa_{\ell_1}^j p_1^j \\ \vdots \\ p_t^j \kappa_{\ell_t}^j \end{pmatrix}, \quad (\text{B.5})$$

with p_t^j the purchase price of the j -type of capital goods. By summing, I obtain the total value of the j -type capital stock for sector ℓ :

$$\Omega_{\ell}^j = \sum_{n=0}^t (1 - \delta^j)^{t-n} \kappa_{\ell_n}^j p_n^j. \quad (\text{B.6})$$

Like in Monasterolo and Raberto (2018), the investment goods sector only employs labour. It also uses a Leontief technology and produces two kinds of investment goods (i_t^j) , $j \in \{H, L\}$:

$$i_t^{j^s} = \lambda_{IG_t}^j N_{IG_t}^j, \quad (\text{B.7})$$

with λ_{IG}^j and L_{IG}^j respectively the labour intensity in producing the j -type of capital and the number of people employed. The investment goods sector also provides a

capital conversion service (from high- to low-carbon) o_t for the Incumbent sector, which also employs labour:

$$o_t^s = \lambda_{IG_t}^o N_{IG_t}^o. \quad (\text{B.8})$$

In all sectors, output is demand-determined, and inventories are assumed away such that the market always clears. Capital is plentiful and structurally underutilised, with the utilisation rate of capital $u_i \leq 1$. It is defined as:

$$u_{\ell_t} = \frac{x_{\ell_t}^d}{\kappa_{\ell} \omega_{\ell_t}}, \quad (\text{B.9})$$

where d denotes demand, and $x_{\ell_t}^s = x_{\ell_t}^d \forall i, t$.

Output is dispatched across sectors based on their share of capital in total:

$$x_{CH_t}^d = x_t^d \frac{\omega_{CH_t}}{\omega_{IN_t} + \omega_{CH_t}} = x_t^d S_{CH_t}, \quad (\text{B.10})$$

$$x_{IN_t}^d = x_t^d (1 - S_{CH_t}), \quad (\text{B.11})$$

where x_t^d is the total demand for the consumption good, determined as the sum of real household and government consumption:

$$x_t^d = c_t + g_t. \quad (\text{B.12})$$

Nominal values are determined by multiplying real values by their prices. I assume that the consumption good is sold at the same price p_{x_t} regardless of the producer:

$$X_{IN_t} = x_{IN_t} p_{x_t} \quad (\text{B.13})$$

$$X_{CH_t} = x_{CH_t} p_{x_t} \quad (\text{B.14})$$

I finally define u_{x_t} the aggregate sectoral utilisation rate, with x denoting the whole consumption good sector:

$$u_{x_t} = \frac{x_t^d}{\kappa_{IN}\omega_{IN_t} + \kappa_{CH}\omega_{CH_t}}. \quad (\text{B.15})$$

For the Incumbent sector, I assume that output demand is allocated between high- and low-carbon capital such that the utilisation rate is equal across the two kinds of capital.

Since there is no intermediate consumption, nominal value-added is defined as:

$$VA_{IN_t} = X_{IN_t}, \quad (\text{B.16})$$

$$VA_{CH_t} = X_{LC_t}. \quad (\text{B.17})$$

And real value-added is defined by deflating nominal value-added by the corresponding price, namely:

$$va_{IN_t} = x_{IN_t}, \quad (\text{B.18})$$

$$va_{CH_t} = x_{CH_t}. \quad (\text{B.19})$$

I assume that government and households are served equally by both sectors.

Labour¹⁶ in the consumption good sector is determined as follows:

$$N_{\ell_t} = \frac{x_{\ell_t}^d}{\lambda_{\ell_t}}. \quad (\text{B.20})$$

It is determined in the same way in the investment goods sector:

¹⁶Note that labour is expressed in working hours in the model.

$$N_{IG_t}^j = \frac{i_\ell^{j,d}}{\lambda_{IG_t}^j}, \quad (\text{B.21})$$

$$N_{IG_t}^o = \frac{o_t^d}{\lambda_{IG_t}^o}, \quad (\text{B.22})$$

Labour productivities for different activities are calibrated at the starting point. It is assumed that they are the same for consumption good sectors, such that $\lambda_{CH_t} = \lambda_{IN_t} = \lambda_{x_t}$ for all t . They are all assumed to grow with total real value-added growth:

$$\lambda_{x_t} = \lambda_{x_{t-1}} \left(1 + \nu_\lambda g_{va_{t-1}}\right), \quad \forall t, \quad (\text{B.23})$$

$$\lambda_{IG_t}^j = \lambda_{IG_{t-1}}^j \left(1 + \nu_\lambda g_{va_{t-1}}\right), \quad j \in \{H, L\}, \quad \forall t, \quad (\text{B.24})$$

$$\lambda_{IG_t}^o = \lambda_{IG_{t-1}}^o \left(1 + \nu_\lambda g_{va_{t-1}}\right), \quad \forall t, \quad (\text{B.25})$$

with:

$$g_{va_t} = \frac{va_t - va_{t-1}}{va_{t-1}}, \quad (\text{B.26})$$

and va_t total real value added, defined below, ν_λ a calibrated parameter. This simplification is meant to translate an average Kaldor-Verdoorn relationship to each sector, typically detected at the macroeconomic level (Carnevali, Godin, et al. 2020).

Finally, I assume a competitive labour market with homogenous skills, such that the nominal wage rate is the same for all activities. Its growth depends on past inflation and output growth to mimic an expectation-augmented Phillips curve:

$$w_t = w_{t-1} \left(1 + \nu_{w_1} g_{p_{x_{t-1}}} + \nu_{w_2} g_{va_{t-1}}\right), \quad (\text{B.27})$$

with:

$$g_{p_t} = \frac{p_{x_t} - p_{x_{t-1}}}{p_{x_{t-1}}}. \quad (\text{B.28})$$

B.1.2 Pollution Emissions are supposed to be embodied in production through an emission intensity ε , that is held constant. As a result, the high-carbon Incumbent emits E_t gigatons of CO_2 proportionately to its share of output produced with high carbon capital:

$$E_t = \varepsilon x_{IN_t} \frac{\omega_{IN_t}^H}{\omega_{IN_t}^H + \omega_{IN_t}^L} = \varepsilon x_{IN_t} \frac{\omega_{IN_t}^H}{\omega_{IN_t}}. \quad (\text{B.29})$$

A carbon tax is levied on these emissions given by:

$$T_C = \theta_{c_t} E_t. \quad (\text{B.30})$$

Where θ_{c_t} is the time-varying price of a gigaton of CO_2 .

B.1.3 Prices and profits

Prices are determined as a markup on top of unit costs (Lavoie 2014). Since there is no intermediate consumption, unit costs correspond to labour costs.

$$UC_{\ell_t} = \frac{w_t}{\lambda_{\ell_t}}, \quad (\text{B.31})$$

$$UC_{IG_t^j} = \frac{w_t}{\lambda_{IG_t^j}}, \quad (\text{B.32})$$

$$UC_{IG_t^o} = \frac{w_t}{\lambda_{IG_t^j}}. \quad (\text{B.33})$$

B.1.3.1 Consumption good sector I suppose that $\lambda_{IN_t} = \lambda_{CH_t} \forall t$. It follows that $UC_{CH_t} = UC_{IN_t} = UC_{x_t}$. As mentioned above, I also consider that there is no price competition between Challengers and Incumbents, such that the homogeneous consumption good x is sold at the same price whatever the seller:

$$p_{x_t} = \left(1 + \mu_{x_t} + (1 - S_{LC_t}) \omega_p \frac{\theta_c e_t}{UC_{x_t}} \right) UC_{x_t}, \quad (\text{B.34})$$

with μ_{x_t} an aggregate markup for the whole sector. It evolves as follows:

$$\mu_{x_t} = \mu_{x_{t-1}} + \eta_1 (u_{X_t} - u_X^T) - \eta_2 (\pi_{x_t}^* - \overline{\pi^N}). \quad (\text{B.35})$$

$(1 - S_{LC_t}) \omega_p \frac{\theta_c e_t}{UC_{x_t}}$ is a passthrough of the unit carbon tax cost at a rate ω_p , which depends negatively on the market share of the Challenger sector ($1 - S_{LC_t}$), to denote the fact that only the Incumbent sector pays the carbon tax, and, therefore, applies the passthrough.

Following Rowthorn (1977), firms first modulate their markup according to the distance between the utilisation rate and their desired utilisation rate u_X^T . The rationale is that in the face of higher demand, firms suffer from lesser competition pressures, allowing them to set higher markups than in time of lower demand. Then, they modulate their markup to reach an exogenous profitability target $\overline{\pi^N}$, supposed constant. Π_ℓ^N , $\ell \in \{CH, IN\}$ is defined as the net profitability of sector i , and \tilde{A}_{ℓ_t} is the principal repayment charge of sector ℓ at time t . This correction allows firms to account for all their capital costs in renewing their markups. Indeed, our accounting definition of net profitability¹⁷ only considers interest charges:

$$\Pi_{\ell_t}^N = \Pi_{\ell_t} - R_{\ell_t} - T_{\ell_t} + r_{D_{t-1}} D_{\ell_{t-1}} + \tau_{\ell_t}, \quad (\text{B.36})$$

where Π_{ℓ_t} is gross operating profits, R_{ℓ_t} is the interest charge, T_{ℓ_t} are total taxes, r_{D_t} the interest rate on deposits of the previous period, $D_{\ell_{t-1}}$ is the amount of deposits held by the firm in the previous period – on which it earns interest – and τ_{ℓ_t} are government subsidies. Gross operating profits are defined as follows:

¹⁷Note that this label is not correct with respect to usual accounting conventions, net profits being strictly defined as gross profits net of interests, taxes and dividends, and depreciation. I keep the "net profitability" label to allow for a more direct differences between gross and "net" in the model. Note further that I waive depreciation in the definition of net profits to highlight that this accounting line is typically not an expense but a provision. Depreciation, within this accounting framework, is included in the budget constraint under investment expenses.

$$\Pi_{\ell_t} = X_{\ell_t} - W_{\ell_t}, \quad (\text{B.37})$$

with $W_{\ell_t} = w_t L_{\ell_t}$, $\ell \in \{CH, IN\}$ the wage bill.

Dividends are paid out of net profits based on a constant payout ratio and are zero if net profits are negative:

$$d_{\ell_t} = \max(0, \xi_{\ell} \cdot \Pi_{\ell_t}^N). \quad (\text{B.38})$$

The residual forms retained earnings RE_{ℓ_t} , which are used to meet principal repayment and fund current investment expenses.

Dividends are dispatched across Banks and NBFIs based on the share of total equity outstanding they hold:

$$d_{\ell_t}^B = \frac{A_{\ell_t}^B}{A_{\ell_t}} d_{\ell_t}, \quad (\text{B.39})$$

$$d_{\ell_t}^{NBFI} = \frac{A_{\ell_t}^{NBFI}}{A_{\ell_t}} d_{\ell_t}, \quad (\text{B.40})$$

Where $A_{\ell_t}^B$ and $A_{\ell_t}^{NBFI}$ are the nominal equity holdings of Banks and NBFIs respectively.

B.1.3.2 Investment goods sector Prices are also composed of a markup on top of unit costs, which is supposed constant across investment and conversion services.

$$p_t^j = (1 + \mu_{IG_t}) UC_{IG_t}^j, \quad j \in \{H, L\}, \quad (\text{B.41})$$

$$p_t^o = (1 + \mu_{IG_t}) UC_{IG_t}^o. \quad (\text{B.42})$$

The markup in the investment goods sector also evolves to target a constant profitability, averaged out across investment goods and services:

$$\mu_{IG_t} = \mu_{IG_{t-1}} + \eta \left(\pi_{IG_{t-1}}^N - \overline{\pi_{IG}^N} \right), \quad (\text{B.43})$$

with π_{IG}^N constant.

Because the investment goods sector does not invest and does not face capital costs, there is no need to correct for principal repayment. Further, because the investment sector does not hold deposits, net profitability reduces to operating surplus corrected for taxes and transfers:

$$\Pi_{IG_t}^N = \Pi_{IG_t} - T_{IG_t} + \tau_{IG_t}, \quad (\text{B.44})$$

and gross operating surplus is given by:

$$\Pi_{IG_t} = p_t^H i_t^H + p_t^L i_t^L + p_t^o o_t - w_t (N_{IG}^H + N_{IG}^L + N_{IG}^o). \quad (\text{B.45})$$

All profits are paid in full to households, which are assumed to own the sector.

B.1.4. Technological development

I assume that investment is purely demand-determined. This choice is motivated by our modelling purpose: introducing a profit motive could prevent sectors from investing enough to meet decarbonisation targets. Firms, given capital intensities, will compute a target capital stock that they will try to reach to meet the demand they expect for the next period.

First, total expected demand is determined as follows:

$$x_t^e = x_t (1 + g_{x_t}) \quad (\text{B.46})$$

$$g_{x_t} = \frac{(x_t - x_{t-1})}{x_{t-1}}. \quad (\text{B.47})$$

I further assume that firms target the same utilisation rate u_x^T . Because capital stocks

have the same capital-output ratio, firms can derive an aggregate target for the real capital stock for the next period:

$$\omega_{x_t}^T = \frac{x_t^e}{u_{x,t}^T \kappa_x}. \quad (\text{B.48})$$

It is assumed that the target utilisation rate is adjusted to avoid overcapacity to a normal utilisation rate, along the lines of Lavoie (2014):

$$u_{x_t}^T = u^{T^*} - \xi_u (u_{x_t} - u^{T^*}), \quad (\text{B.49})$$

where ξ_u is constant.

Once this target is set, I can determine the target share of low and high-carbon capital $S_{LC_t}^T$. Since the model is meant to simulate existing decarbonisation trajectories, this share is determined based on an exogenous decarbonisation schedule E_t^T , and is solved for with a gradient descent.

Once $S_{LC_t}^T$ is determined, I can derive the targeted real high-carbon capital stock as follows:

$$\omega_{x_t}^{HT} = (1 - S_{LC_t}^T) \omega_{x_t}^T. \quad (\text{B.50})$$

I also suppose that technological spillovers allow the carbon intensity of high-carbon capital to improve with the penetration of low-carbon capital, taking $S_{LC_t}^T$ as a proxy:

$$e_t = \frac{e_{t-1}}{1 + \beta_e (S_{LC_t}^T - S_{LC_{t-1}}^T)}. \quad (\text{B.51})$$

This behavioural equation is meant to mimic the improvements of technologies in using polluting inputs. It implicitly encapsulates improvements in energy efficiency, the adoption of less polluting production modes, and, to a certain extent, carbon dioxide removal technologies. Note that it allows for a convex decrease in carbon intensity, implying that, although some improvements can be realised, they are bounded. This feature is meant to avoid the carbon intensity of polluting production processes con-

verging towards zero, which could imply the presence of a backstop technology, a heavily criticised feature of many climate economics models (Foster, B. Clark, and York 2009). Rather, unlimited improvements may not be feasible due to physical and technical limitations, like in the deployment of CDR technologies (McLaren 2012) or improvements to energy efficiency (Gutowski et al. 2013).

Incumbent firms will then compare this target to their total high-carbon stock ω_{H_t} :

1. If $\omega_t^{H^T} - \omega_t^H > 0$, the Incumbent firm formulates a target investment $i_t^{H^T}$ that also makes for the natural depreciation of capital Δ_{H_t} , which is the sum across all vintages of natural depreciation. In that case, target high-carbon investment is given by:

$$i_{IN_t}^{H^T} = \xi_{inv}(\omega_t^{H^T} - \omega_t^H) + \Delta_{H_t}, \quad (\text{B.52})$$

where ξ_{inv} is a partial-adjustment investment rule, as in Godley and Lavoie (2007).

1. If $\xi_{inv}(\omega_t^{H^T} - \omega_{H_t}) < 0$, then there is excess high-carbon capital, that the firm may have to scrap. I denote q_t^e the expected stranding based on the targeted high-carbon capital stock:

$$q_t^e = -\min(0, \xi_{inv}(\omega_t^{H^T} - \omega_{H_t})). \quad (\text{B.53})$$

In that case, I assumed that firms make only for total natural depreciation Δ_{H_t} , which is the sum across all vintages of natural depreciation. Target high-carbon investment writes:

$$i_{IN_t}^{H^T} = \Delta_t^H. \quad (\text{B.54})$$

In this latter case, firms anticipate a stranding q_t^e they will try to hedge against. To do so, they will try to convert a fraction χ_t^0 of their capital stock. To do so, they first compute the nominal value of the expected stranding Q_t^e . Then, they solve this equation for χ_t^0 :

$$\chi_t^0 p_t^o \omega_t^H = Q_t^e, \quad (\text{B.55})$$

and target the following conversion quantity:

$$o_t^T = \chi_t^o \omega_t^H. \quad (\text{B.56})$$

That is, firms redirect the balance sheet cost they expect to the retrofitting of their capital stock. Incumbents do not invest in low-carbon capital to make for the natural depreciation of their retrofitted machines:

$$i_{IN_t}^L = \Delta_{IN_t}^L \quad (\text{B.57})$$

Once conversion demand is formulated, the Challenger targets a low-carbon capital stock by considering expected stranding and conversion demand:

$$\omega_{CH_t}^T = \omega_{x_t}^T - (\omega_H^T - o_t^T - (q_t^e - o_t^T)) - (\omega_{CH_t}^L + o_t^T), \quad (\text{B.58})$$

$$i_{CH_t}^{LT} = \omega_{CH_t}^T - \omega_{CH_t} + \Delta_{CH_t}^L. \quad (\text{B.59})$$

It then invests based on the same rule as the Incumbent sector, with the same partial-adjustment coefficient ξ_{inv} .

Once these investment targets are determined, I can define their nominal counterparts:

$$I_{IN_t}^{HT} = p_t^H i_{IN_t}^{HT}, \quad (\text{B.60})$$

$$O_t^T = p_t^L o_t, \quad (\text{B.61})$$

$$I_{IN_t}^{LT} = p_t^L i_{IN_t}^{LT}, \quad (\text{B.62})$$

$$I_{IN_t}^T = I_{IN_t}^{HT} + O_t^T + I_{IN_t}^{LT}, \quad (\text{B.63})$$

$$I_{CH_t}^{LT} = p_t^L i_{CH_t}^{LT}. \quad (\text{B.64})$$

B.1.5. Funding and investment constraints

Investments are funded with past accumulated deposits, current retained earnings, loans and equity emissions.

I assume that firms fund a constant fraction of their planned investment expenses with bank loans:

$$NL_{\ell_t}^d = \psi_{\ell} I_{\ell_t}^T, \quad (\text{B.65})$$

with $\psi_{\ell} = \bar{\psi} \forall \ell$

Banks will only accommodate a fraction $(1 - \varpi_{\ell_t})$ of this loan demand at each point in time:

$$NL_{\ell_t} = (1 - \varpi_{\ell_t}) NL_{\ell_t}^d \quad (\text{B.66})$$

Firms will also emit equity residually to bridge the gap between already available funds and desired investment:

$$a_{\ell_t} = a_{\ell_{t-1}} + \frac{I_{\ell_t}^T - NL_{\ell_t} - (D_{\ell_{t-1}} + RE_{\ell_{t-1}}) - \Gamma_{\ell_{t-1}}}{p_{a_{\ell_t}}^e} \quad (\text{B.67})$$

Where a_{i_t} is the real amount of equity issued by the firm, A_{i_t} the nominal demand for this firm's equity from NBFIs, $p_{A_{i_t}}^e$ expected prices, and $p_{A_{i_t}}$ the actual price. Expected prices are determined through adaptive expectations:

$$p_{A_{\ell}}^e = p_{A_{\ell_{t-1}}}^e + \eta_e (p_{A_{\ell_{t-1}}}^e - p_{A_{\ell_{t-2}}}). \quad (\text{B.68})$$

As usual in SFC modelling (Godley and Lavoie 2007; Burgess, Burrows, and Kinsella 2016; Dafermos, Nikolaidi, and Galanis 2017), I assume that equity prices clear the market by balancing nominal demand for equity A_{ℓ_t} and real supply of equity a_{ℓ_t} :

$$p_{a_{\ell_t}} = \frac{A_{\ell_t}}{a_{\ell_t}}. \quad (\text{B.69})$$

Where $A_{\ell_t} = A_{\ell_t}^B + A_{\ell_t}^{NBFI}$, the sum of the nominal demand from the bank and the

NBFI sectors. Since equities are traded at the same price, I assume that outstanding shares are dispatched across banks and NBFIs proportionally to their nominal demand in the total. For $n \in B, NBFI$:

$$a_\ell^n = \frac{A_\ell^n}{A_\ell} A_\ell. \quad (\text{B.70})$$

This results in the following budget constraints:¹⁸

$$I_{CH_t}^c = RE_{CH_t} + \Delta D_{CH_t} + \Delta a_{CH_t} p_{a_{CH_t}} + NL_{CH_t} - \Gamma_{CH_t}, \quad (\text{B.72})$$

$$I_{IN_t}^c = RE_{IN_t} + \Delta D_{IN_t} + \Delta a_{IN_t} p_{a_{IN_t}} + NL_{IN_t} - \Gamma_{IN_t}. \quad (\text{B.73})$$

Where c stands for “constrained” and indicates the maximum amount of investment expenses firms can afford given available internal and external funds. Actual sectoral investments thus write:

$$I_{\ell_t} = \min(I_{\ell_t}^c, I_{\ell_t}^T), \quad \ell \in \{CH, IN\}. \quad (\text{B.74})$$

If $I_{\ell_t}^T < I_{\ell_t}^c$, firms pocket the residual as deposits. In the case of the Incumbent sector, which invests in three different items, constrained high-carbon and low-carbon investment and conversion write as follows:

$$I_{IN_t}^H = I_{IN_t}^c \frac{I_{IN_t}^{Hc}}{I_{IN_t}^T}, \quad (\text{B.75})$$

$$O_t = I_{IN_t}^c \frac{O_t^T}{I_{IN_t}^T}, \quad (\text{B.76})$$

¹⁸Because our carbon price paths can be very stringent, they can entail very high losses for Incumbent firms, that can find themselves unable to repay past loans even if they cut investment completely. To avoid major disruptions to the model’s architecture – notably how I represent defaults – I assume that firms can roll-over their debt if they face financing constraint, and that banks fully accommodate this demand:

$$*NL_i = (1 - \varpi_{i,t}) \psi_i Inv_{i,t}^d - \min(0, RE_{i,t} - Rep_{i,t}) \quad (\text{B.71})$$

Given this affects directly the liquidity available to firms, this leads us to adopting a more conservative stance with respect to default risks. Furthermore, this allows us to counterbalance our extreme interpretation of carbon price schedules as produced by IAMs. This course of event only concerns a single scenario, that could not be run otherwise due to very high carbon prices.

$$I_{IN_t}^L = I_{IN_t}^c \frac{I_{IN_t}^L}{I_{IN_t}^T}, \quad (\text{B.77})$$

Once actual nominal investment expenses are determined, real investment demand is determined by dividing by corresponding prices. Demanded capital is delivered in the next period and corresponds to an additional row in the capital vintage vector $b_{i_t}^j$. Real conversion entails a decrease in the stock of high-carbon capital and an increase in the stock of low-carbon capital of the Incumbent sector. High-carbon vintages are converted based on their share in total high-carbon capital. Finally, natural depreciation is always comprised in newly added capital vintages.

Finally, when actual conversion o_t is determined, actual asset stranding can be computed as follows:

$$q_t = q_t^e - o_t. \quad (\text{B.78})$$

I assume that asset stranding affects in priority the oldest capital vintages. The nominal value of stranded assets Q_t is removed from the balance sheet of the Incumbent sector and is modelled as a balance sheet shock.

Total investment $I_t = I_{IN_t} + I_{CH_t}$ defines nominal value added in the investment goods sector. Real value added is obtained by deflating with the corresponding price indices.

B.2. Households

In the model, households consume and save. They hold three assets: bank deposits (D_H), cash (H_H), and NBF1 units (U).

Households determine their consumption expenditures based on past consumption (C_{t-1}), expected available income (YD_t^e), and expected wealth, namely (V_{t-1}^e). I also assume that agents have different consuming propensities depending on the source of income, as usual in SFC modelling (Godley and Lavoie 2007). Defining:

$$\rho_{\pi_t} = \frac{(1 - \theta_H)(i_{D_{t-1}} D_{t-1} + F_{t-1} + F_t + \Pi_{IG_{t-1}} + \Pi_{B_{t-1}})}{YD_{t-1}}, \quad (\text{B.79})$$

with $i_{D_{t-1}}D_{t-1}$ interests on deposits, F_t financial income from non-bank financial institutions, Π_{B_t} bank profits, Π_{IG_t} investment sector profits and YD_t disposable income.

$$C_t = C_{t-1} + \gamma_C \left(\alpha_{YD} (1 - \rho_{\pi_t}) YD_t^e + \alpha_{\pi} \rho_{\pi_t} YD_t^e \beta_V V_{t-1}^e \right), \quad (\text{B.80})$$

with:

$$YD_t^e = YD_{t-1}^e - \eta (YD_{t-2}^e - YD_{t-1}^e), \quad (\text{B.81})$$

$$V_t^e = V_{t-1}^e - \eta (V_{t-2}^e - V_{t-1}^e). \quad (\text{B.82})$$

Real consumption demand is determined by deflating total expenditures by the price of the consumption good:

$$c_t = \frac{C_t}{p_{x_t}}. \quad (\text{B.83})$$

Households hold a constant fraction of their wealth as high-powered money and NBFIs units. Deposits are a buffer:

$$H_t = \alpha_{HPM} V_t^e, \quad (\text{B.84})$$

$$U_t = \alpha_{HPM} V_t^e, \quad (\text{B.85})$$

$$D_{H_t} = D_{H_{t-1}} + YD_t - C_t - (H_{H_t} - H_{H_{t-1}}) - (U_t - U_{t-1}), \quad (\text{B.86})$$

with YD_t disposable income defined as:

$$YD_t = W_t + i_{D_{t-1}} D_{H_{t-1}} + F_t + \Pi_{IG_t} + \Pi_{B_t} + \tau_{H_t} - T_{H_t}. \quad (\text{B.87})$$

W_t is the economy-wide wage bill equal to $W_{CH_t} + W_{IN_t} + W_{IG_t}$, F_t is financial income from non-bank financial institutions, Π_{B_t} bank profits, Π_{IG_t} profits from the investment goods sector, τ_{H_t} government transfers to households, and T_{H_t} household taxes.

B.3. Financial sector

B.3.1. Non-Bank Financial Institutions

The non-bank financial sector mimics funds, providing firms with market finance. They plainly are financial intermediaries that take some of household savings to invest it into equities and government bonds, greatly inspired by Burgess et al.'s (2016) treatment of insurance and pension funds. Pension funds sell fund units U_t to households at a constant price and use the collected savings to three types of financial assets: government bonds (GB_{NBFI_t}), equity from Incumbents (A_{IN_t}) and equity from Challengers (A_{CH_t}). They also hold deposits (D_{NBFI_t}) on which they earn interest. If NBFIs fall short of rolling funds, the government step in to fill the gap through a transfer E_{NBFI_t} . NBFIs collect financial income from their assets (dividends and interests on government bonds), which constitute their profits:

$$\Pi_{NBFI_t} = r_{B_{t-1}} GB_{NBFI_{t-1}} + d_{IN_t}^{NBFI} + d_{CH_t}^{NBFI} + r_{D_{t-1}} D_{NBFI_{t-1}}. \quad (\text{B.88})$$

Retained earnings are defined as:

$$RE_{NBFI_t} = (1 - \xi_{NBFI}) \Pi_{NBFI_t}. \quad (\text{B.89})$$

With this formula, nothing forbids retained earnings to be negative. In that case, NBFIs dissave from their deposits to hand out a higher financial income F_t to households:

$$F_t = \Pi_{NBFI_t} - RE_{NBFI_t}. \quad (\text{B.90})$$

Asset allocation is determined through a Tobin portfolio choice model Godley and Lavoie (2007):

$$\begin{pmatrix} GB_{NBFI_{t-1}} \\ A_{IN_t}^{NBFI} \\ A_{CH_t}^{NBFI} \end{pmatrix} = \begin{pmatrix} \lambda_{0_t^{GB}} \\ \lambda_{0_t^{IN}} \\ \lambda_{0_t^{CH}} \end{pmatrix} + \begin{pmatrix} \lambda_{11} & \lambda_{12} & \lambda_{13} \\ \lambda_{21} & \lambda_{22} & \lambda_{23} \\ \lambda_{31} & \lambda_{32} & \lambda_{33} \end{pmatrix} \begin{pmatrix} h_{GB_t}^e \\ h_{IN_t}^e \\ h_{CH_t}^e \end{pmatrix} v_t. \quad (\text{B.91})$$

Deposits are a buffer stock:

$$\begin{aligned} D_{NBFI_t} &= D_{NBFI_{t-1}} + U_t - U_{t-1} - \\ &\quad (p_{A_{IN_t}} (a_{IN_t}^{NBFI} - a_{IN_{t-1}}^{NBFI}) + p_{A_{CH_t}} \\ &\quad (a_{CH_t}^{NBFI} - a_{CH_{t-1}}^{NBFI}) + GB_{NBFI_t} - GB_{NBFI_{(t-1)}}) + \Theta_{NBFI_t}. \end{aligned} \quad (\text{B.92})$$

v_t stands for the total funds available for asset purchases.

$h_{\ell,t}^e$ ($i \in IN, CH$) are expected returns on assets, which depend on dividends and expected capital gains:

$$h_{\ell,t}^e = \frac{Div_{\ell,t}}{A_{\ell,t}} + \omega_{CG} \left(p_{A_{\ell_t}} / p_{A_{\ell_{t-1}}} - 1 \right). \quad (\text{B.93})$$

As in Caverzasi and Godin (2015), agents discount capital gains, here by a factor $(1 - \omega_{CG})$. For government bonds, the expected return is the interest rate i_{GB} .

The $\lambda_{j,k}$, $(j, k) \in [1, 3] \times [1, 3]$ are reaction parameters respecting Tobin's condition (Godley and Lavoie 2007). The basic Tobin model does not easily make for structural change through the assumption of constant equilibrium portfolio shares λ_0 . I therefore give these parameters the following law of motion:

$$\lambda_{0_t^{GB}} = \overline{\lambda_0^{GB}}, \quad (\text{B.94})$$

$$\lambda_{0_t^{IN}} = \left(1 - \overline{\lambda_0^{GB}} \right) S_{IN_t}, \quad (\text{B.95})$$

$$\lambda_{0_t^{CH}} = \left(1 - \overline{\lambda_0^{GB}} \right) S_{CH_t}. \quad (\text{B.96})$$

Fixing the structural share of government bonds, the structural share in NBFi port-

folios of the two consumption-good sub-sectors evolves with their market share.

Finally, capital gains write:

$$cCG_{NBFI_t} = A_{IN_{t-1}} \left(p_{A_{IN_t}} - p_{A_{IN_{t-1}}} \right) + a_{CH_{t-1}} \left(p_{A_{CH_t}} - p_{A_{CH_{t-1}}} \right). \quad (\text{B.97})$$

It is assumed that they are fully reinvested in each period.

Finally, the NBFIs sector can leverage its position by borrowing a constant share of its past available funding from banks. These borrowed funds add up to available funds for investment.

$$NL_{NBFI_t} = (1 - \varpi_{NBFI_t}) \nu Funds_{t-1}. \quad (\text{B.98})$$

NBFIs use short-term funding, with their loans characterised by a maturity $M_{NBFI} = 1$, to which the calculations developed in the previous sections apply. Short rates are lower than long rates by a factor two to mimic the daily US Treasury yield curve rate in 2018 to avoid the Covid crisis (Treasury 2018).

Like NFCs, NBFIs are characterised by an illiquidity ratio, defined as follows:

Finally, v_t is defined as:

$$v_t = U_t + CG_{U_{t-1}} + NL_{NBFI_t}. \quad (\text{B.99})$$

Thus, NBFIs use the funds collected through the sale of Units to fund asset purchases, leveraged funds and previous-period capital gains.

B.3.2. Banking sector

Banks collect deposits, extend loans, buy government bonds and take on central bank advances to close their balance sheets. They also collect deposits from firms, households and NBFIs. They finally fix interest rates, performing price rationing and implement quantity rationing when faced with loan demand.

B.3.2.1. Banks' portfolio investment Banks invest a sum equivalent to a constant fraction ξ_{Funds_B} of their deposit liabilities into equity, following a Tobinesque approach:

$$\begin{pmatrix} Eq_{LC}^B \\ Eq_{HC}^B \end{pmatrix} = \begin{pmatrix} \lambda_{IN_0}^B & \lambda_{IN_1}^B & \lambda_{IN_2}^B \\ \lambda_{CH_0}^B & \lambda_{CH_1}^B & \lambda_{CH_2}^B \end{pmatrix} \begin{pmatrix} 1 \\ r_{IN}^e \\ r_{LC}^e \end{pmatrix} \xi_{Dep} Dep_{t-1}, \quad (\text{B.100})$$

With:

$$\lambda_{IN_0}^B = 1 - S_{CH} \quad (\text{B.101})$$

$$\lambda_{CH_0}^B = S_{CH}, \quad (\text{B.102})$$

S_{CH} being the market share of Challenger sector $\frac{x_{HC}}{x}$

Capital gains are defined in the same way as in the NBFi sector and are attributed to the banks' own funds OF .

B.3.2.2. Interest rates, credit rationing and defaults Interest rates consist in a markup on top of the risk-free interest rate, which is fixed by the central bank as usual in SFC modelling (Caiani, Godin, and Lucarelli 2012; Dafermos, Nikolaidi, and Galanis 2017; Godley and Lavoie 2007; Lavoie and Daigle 2011):

$$r_{L_{\ell t}} = r_{cb} + \mu_{\ell t}. \quad (\text{B.103})$$

Markups are sector-specific ($\ell = \{IN, CH\}$) and are composed of three components:

$$\mu_{\ell} = \bar{\mu}_{bank} + \sigma_{\ell}(S_{\ell}) + \sigma_{NPL} \left(1 - \frac{1}{1 + (lev_{i,t-1} - lev)} \right), \quad (\text{B.104})$$

with $\bar{\mu}$ a minimum profit markup on top of the risk-free interest rate and σ_i sector-specific markups, which evolves with the market share (S_{ℓ}) of the sector to figure

the progressive mainstreaming of the Challenger (Campiglio, Spiganti, and Wiskich 2023) and the increased risks associated with dying sectors (Delis, Greiff, and Ongena 2019). σ_{lev} is a reaction to observed leverage lev_{ℓ_t} relative to a "normal" leverage \overline{lev} in each sector, defined as follows:

$$lev_{\ell_t} = \frac{L_{\ell_t}}{D_{\ell_t} + \Omega_{\ell_t}^H + \Omega_{\ell_t}^L}. \quad (\text{B.105})$$

Note that I assume that the loan markup rule is non-linear and bounded to avoid any divergence in the case of high leverage.

For the NBFIs sector, the sectoral markup is assumed constant. Plus, since NBFIs use short-term debt, I adjust the loan markup by a factor $\omega_{int} = 2$ to mimic a yield curve (see above):

$$\mu_{\ell} = \frac{1}{\omega_{int}} \left(\overline{\mu}_{bank} + \sigma_{NBFIs} \right) + \sigma_{NPL} \left(1 - \frac{1}{1 + (lev_{i,t-1} - \overline{lev})} \right). \quad (\text{B.106})$$

Credit constraint is based on the financial health of banks and the borrowing firm:

$$\varpi_{\ell_t} = \frac{1}{1 + \varpi_0 \exp(\varpi_1 - \varpi_2 dsr_{\ell_t} + \varpi_3 (CAR_{t-1} - \overline{CAR}))}. \quad (\text{B.107})$$

Where:

$$dsr_{\ell_t} = \frac{K_{cost_{\ell_t}}}{\Pi_{\ell_t}}, \quad (\text{B.108})$$

And:

$$CAR_t = \frac{OF_t}{\omega_1 L_t + \omega_2 Eq_{B,HC,t} + \omega_3 Eq_{B,LC,t} + \omega_4 GB_{B,t}}, \quad (\text{B.109})$$

with OF_t the Banks' own funds and L_{ℓ_t} the total loan stock outstanding for sector ℓ , defined below. As in Dafermos, Nikolaidi, and Galanis (2017), I assume $\omega_1 = \omega_2 = 3 = 1$ and $\omega_4 = 0$, such that:

$$CAR_t = \frac{OF_t}{L_t + Eq_{B,HC,t} + Eq_{B,LC,t}},$$

Default probabilities are defined write as:

$$\varphi_{NPL_{\ell_t}} = \frac{1}{1 + \varphi_0 \exp(\varphi_1 - \varphi_2 \iota_{\ell_t})}, \quad (\text{B.110})$$

with ι_{ℓ_t} the agent's illiquidity ratio. I augment Dafermos et al.'s (2017) formulation, which defines the illiquidity ratio as the ratio of inflows to outflows. To account for deposits, which are a source of liquidity not represented in Dafermos, Nikolaidi, and Galanis (2017), I consider changes in deposits at the denominator and the receipts from interests on deposits. For NFCs ($\ell \in CH, IN$), it writes:¹⁹

$$\iota_{\ell_t} = \frac{\hat{I}_{\ell_t} + T_{\ell_t} + d_{\ell_t} + W_{\ell_t}}{X_{\ell_t} + NL_{\ell_t} + \tau_{\ell_t} + p_{A_{\ell_t}} (a_{\ell_t} - a_{\ell_{t-1}} + i_{Dep} Dep_{\ell_{t-1}} + (Dep_{\ell_t} - Dep_{\ell_{t-1}}))}. \quad (\text{B.111})$$

Note that, like Dafermos, Nikolaidi, and Galanis (2017), I exclude investment expenses but include conversion costs, as they represent a fee paid to the investment sector.

For NBFIs, it writes:

$$\iota_{NBFI_t} = \frac{\hat{I}_{NBFI_t} + F_t + p_{A_{IN_t}} p_{A_{IN_t}} (a_{IN_t}^{NBFI} - a_{IN_{t-1}}^{NBFI}) + p_{A_{CH_t}} (a_{CH_t}^{NBFI} - a_{CH_{t-1}}^{NBFI}) + (GB_{NBFI_t} - GB_{NBFI_{t-1}})}{\Pi_{NBFI_t} + NL_{NBFI_t} + i_{Dep} Dep_{NBFI_{t-1}} + (Dep_{NBFI_t} - Dep_{NBFI_{t-1}} + (U_t - U_{t-1}))}. \quad (\text{B.112})$$

With ℓ_t total capital cost. Logistic shapes for default and credit rationing probabilities are well-established functional forms in SFC and agent-based modelling (Caiani, Godin, Caverzasi, et al. 2016). Logistic shapes (under the form of logit econometric models) also have empirical validity, as they are widely used to estimate default propensities (T. Allen et al. 2020; Cathcart et al. 2020) and credit rationing (Becchetti, Garcia, and Trovato 2011; Rahji and Fakayode 2009). To keep things simple,

¹⁹This formulation, adopted here for convenience, poses nonetheless some theoretical issues. In particular, considering (nearly) all outflows and inflows in the definition of the liquidity ratio may be erroneous, as debt is usually serviced only through cash flow circulating in the current account (profits) unless debt roll-over is allowed. Further, only considering flows may underestimate default probabilities, which depend on stocks (Cathcart et al. 2020), like liquid assets. I go for a middle-ground by including changes in deposits at the denominator. Special thanks go to Edwin Le Héron for raising these relevant issues.

I limit the number of arguments for each function to those employed in Dafermos, Nikolaidi, and Galanis (2017).

Symmetrically to capital stocks in the consumption good sectors, I model loan vintages, which allow for a realistic representation of principal repayment, capital costs, and loan maturity. Banks' loan assets on firm ℓ are represented as a vector Z_t writing:

$$Z_{\ell_t} = \begin{pmatrix} \max\left(0, l_\ell^0 - \sum_{n=1}^t \gamma_{\ell_n}^0\right) \left(1 - \varphi_{NPL_{\ell_t}}\right) \\ \max\left(0, l_\ell^1 - \sum_{n=2}^t \gamma_{\ell_n}^1\right) \left(1 - \varphi_{NPL_{\ell_t}}\right) \\ \vdots \\ l_\ell^t \end{pmatrix}, \quad (\text{B.113})$$

with l_ℓ^s , $s \in [1, t]$, the amount of the loan vintage at its time of extension to firm ℓ and $\gamma_{\ell_n}^s$ the principal repayment flow for loan vintage s to firm i paid at time $n \in [s + 1, t]$ (loans being repaid from the period following their issuance onwards). Finally, I assume that defaults $\varphi_{NPL_{\ell_t}}$ are distributed homogenously amongst past loans. When the loan principal is repaid, it is erased from the bank's books.

The total loan stock for a given sector ℓ is obtained by summing all components of the Z_{ℓ_t} vector at each time step. The total loan stock for the whole economy L_t is the sum over all sectors.

Loans of different vintages have the same maturity M . Following a well-established formula for loan repayment with a constant annuity, the annual capital cost corresponding to the vintage taken at time s by firm ℓ , $\hat{I}_{\ell_t}^s$, which includes both repayment and interest:

$$\hat{I}_{\ell_t}^s = \frac{\left(r_{L_{\ell_s}} (1 + r_{L_{\ell_s}})^M\right)}{\left(1 + r_{L_{\ell_s}}\right)^M - 1} l_\ell^s, \quad (\text{B.114})$$

with $l_\ell^s = NL_{\ell_s}$, that is the actual loan amount extended to firm ℓ at time s and $r_{L_{\ell_s}}$ the interest rate on this loan contract. The total capital cost is constant.

The interest paid on this precise vintage evolves with principal repayment and reaches zero when the loan reaches maturity. Correcting again for non-performing loans, it

writes:

$$\rho_{\ell_t}^s = r_{L_{\ell_s}} \max \left(0, (l_{\ell_t}^s - \sum_{n=s+1}^t \gamma_{\ell_n}^s) \right) (1 - \varphi_{NPL_{\ell_t}}). \quad (\text{B.115})$$

The principal repayment is the residual and writes:

$$\gamma_{\ell_t}^s = \Xi_{\ell_t}^s - \rho_{\ell_t}^s. \quad (\text{B.116})$$

Hence, the interest part of the capital cost decreases with time, while the repayment charge increases. By accounting identity, total loan stocks follow the law of motion:

$$L_{\ell_t} = L_{\ell_t} + NL_{\ell_t} - \Gamma_{\ell_t} - NPL_{\ell_t}, \quad (\text{B.117})$$

with NPL_{ℓ_t} being the sum of all default loans on all vintages for sector ℓ .

B.3.2.3. Regulatory Obligations Banks must hold a certain fraction of their deposits as high-powered money:

$$HPM_{B_t} = \eta_{B_{Dep}} D_t, \quad (\text{B.118})$$

with $D_t = D_{H_t} + D_{NBFI_t} + D_{CH_t} + D_{IN_t}$ the total amount of deposits.

Banks balance sheet is closed by demanding advances central bank J_{CB} , like in Dafermos, Nikolaidi, and Galanis (2018):

$$J_{CB}^d = J_{CB_{t-1}} + L_t - L_{t-1} - HPM_{B_t} - HPM_{B_{t-1}} - (D_t - D_{t-1}) - RE_{B_t} + GB_{B_t} - GB_{B_{t-1}}, \quad (\text{B.119})$$

where D_t is the total deposit stock at time t and GB_{B_t} the amount of government bonds held by banks.

Banks pay interests on advances.

I finally assume, like in Dafermos, Nikolaidi, and Galanis (2017), that if banks fall below a minimum capital adequacy ratio CAR_{min} , the government steps in to bail

banks out. The bailout Θ_{B_t} takes the form of a capital transfer directed to own funds.

B.3.2.3. Profits and retained earnings Bank profits are written as follows:

$$\Pi_{B_t} = R_{CH_t} + R_{IN_t} + r_{B_{t-1}}GB_{B_{t-1}} - r_{D_{t-1}}D_{t-1} - r_{CB}J_{CB_{t-1}} + d_{CH_t}^B + d_{IN_t}^B, \quad (\text{B.120})$$

where r_{CB} is the interest on central bank advances.

Dividends d_{B_t} are a constant fraction of profits:

$$d_{B_t} = \xi_B \Pi_{B_t}. \quad (\text{B.121})$$

Retained earnings write:

$$RE_{B_t} = (1 - \xi_B) \Pi_{B_t}. \quad (\text{B.122})$$

Banks use part of their retained earnings to buy make for non-performing loans that harm their own funds and target a constant capital adequacy ratio. Own funds are defined as follows:

$$OF_t = OF_{t-1} - NPL_t + \alpha_{RE_{B_t}} RE_{B_t} + \Theta_{B_t} + CG_{B_{t-1}}, \quad (\text{B.123})$$

with:

$$\alpha_{RE_{B_t}} = \min \left(1, \max \left(0, \frac{\overline{CAR} * L_t - OF_{t-1} + NPL_t}{RE_{B_t}} \right) \right), \quad (\text{B.124})$$

which is defined to target \overline{CAR} , a normal capital adequacy ratio. Retained earnings that are not used to make for non-performing loans are used to purchase government bonds to avoid accumulating dormant capital on top of a fraction of deposits:

$$GB_B^d = \alpha_D D_t + \left(1 - \alpha_{RE_{B_t}} \right) RE_{B_t}. \quad (\text{B.125})$$

With such behavioural equations, banks always reach their target capital adequacy ratio, except when retained earnings are insufficient.

B.3.3. Central Bank

The central bank fixes the interest rate and charges it on advances. It is held fixed throughout:

$$r_{CB_t} = \overline{r_{CB}}. \quad (\text{B.126})$$

The central bank provides advance on demand (which is a redundant equation, typical of SFC models (Godley and Lavoie 2007)):

$$A^s = A^d \quad (\text{B.127})$$

The central bank purchases the residual amount of government bonds if it is positive, to ensure equality between bond supply and bond demand:

$$GB_{CB_t} = GB_{CB_{t-1}} + \begin{cases} GB_{G_t}^s - GB_{G_{t-1}}^s - GB_{B_t}^d - GB_{B_{t-1}}^d - GB_{G_{NBFI_t}}^d \\ -GB_{G_{NBFI_t}}^d \text{ if } \Delta B_{G_t}^s - \Delta B_{G_{B_t}}^d - \Delta B_{G_{NBFI_t}}^d > 0 \\ 0 \text{ otherwise} \end{cases} \quad (\text{B.128})$$

Central bank profits write:

$$\Pi_{CB_t} = r_{CB_t} J_{CB_{t-1}} + i_{B_G} GB_{cb_{t-1}}. \quad (\text{B.129})$$

The central bank pays them in full to the government.

B.3.4. Government

The government spends on consumption goods, manages taxes and transfers, and rescues the banking sector through a contingent bailout. Along transition paths, the government levies a carbon tax, whose proceeds are not recycled.

I assume that the government spends a constant proportion of last-period nominal value-added:

$$G_t = \gamma_{Gov_t} VA_{t-1}. \quad (B.130)$$

Real government consumption writes:

$$g_t = \frac{G_t}{p_{x_t}}. \quad (B.131)$$

With:

$$\gamma_{Gov_t} = \gamma_{Gov_{t-1}} + \eta_{\gamma_{Gov}} \left(\frac{NLP_{Gov_{t-1}}}{VA_t} - \frac{\overline{NLP_{Gov}}}{VA} \right). \quad (B.132)$$

That is, the government targets a deficit as a fraction of GDP, denoted by $\frac{\overline{NLP_{Gov}}}{VA}$.

The government levies other taxes on household available income and the gross profits of the three non-financial firms of the model: investment goods, Challengers, and Incumbents.

$$T_{H_t} = \theta_H Y D_t, \quad (B.133)$$

$$T_{\ell_t} = \theta_\ell \Pi_{\ell_t}, \quad \ell \in \{IG, CH\}, \quad (B.134)$$

$$T_{HC_t} = \theta_{HC} \Pi_{HC_t} + \theta_{c_t} E_t. \quad (B.135)$$

Incumbents also pay a carbon tax T_C proportional to emissions E_t at a rate θ_{c_t} .

$$T_t = T_{H_t} + T_{IG_t} + T_{CH_t} + T_{IN_t} + T_{C_t}. \quad (B.136)$$

The tax receipt is split between subsidies to producers and households. I define total subsidies as:

$$\tau_t = \alpha_\tau VA_{t-1}. \quad (B.137)$$

With $\alpha_\tau = 0.1$, and:

$$\tau_{H_t} = \frac{\alpha_\tau VA_{t-1}}{2} + T_{C_t}, \quad (B.138)$$

$$\tau_{IG_t} = 0, \quad (B.139)$$

$$\tau_{IN_t} = S_{IN_t} \frac{\alpha_\tau V A_{t-1}}{2}, \quad (\text{B.140})$$

$$\tau_{CH_t} = (1 - S_{IN_t}) \frac{\alpha_\tau V A_{t-1}}{2}. \quad (\text{B.141})$$

Note the presence of the carbon tax in household transfers.

The central bank pays the government all its profits Π_{CB_t} .

Finally, if the capital adequacy ratio of banks falls below a threshold CAR_{min} , the government can optionally effectuate a capital transfer to the banking sector to avoid a financial crash, like in Dafermos, Nikolaidi, and Galanis (2017).

The government funds its deficits by emitting bonds:

$$\Delta GB_t^s = G_t + \tau_t + i_{GB} GB_{t-1}^s - T_t - \Pi_{CB} + \Theta_{NBFI_t} + \Theta_{B_t}. \quad (\text{B.142})$$

Where GB_t is the total amount outstanding of government bonds at time t . I assume, also to keep things simple, that government bonds are perpetuities, hence that there is no principal repayment. The interest rate on bonds is constant, and so is their price.

I also restrict government debt GB_t to always be positive. If $GB_t < 0$, I impose $GB_t = 0$ and assume that the government pays the excess to households as transfers.

B.3.5. Accounting

I finish by presenting key accounting identities.

B.3.5.1. Values-Added

$$\begin{aligned} VA_t &= C_t + I_t + O_t + G_t = VA_{IN_t} + VA_{CH_t} + VA_{IG_t} \\ &= WB_{IN_t} + WB_{CH_t} + WB_{IG_t} + \Pi_{IN_t} + \Pi_{CH_t} + \Pi_{IG_t}. \end{aligned} \quad (\text{B.143})$$

$$va_t = c_t + i_t + o_t + g_t = va_{IN_t} + va_{CH_t} + va_{IG_t}. \quad (\text{B.144})$$

B.3.5.2. Net-lending positions

Households

$$NLP_{H_t} = YD_t - C_t = D_{H_t} - D_{H_{t-1}} + H_{H_t} - H_{H_{t-1}} + U_t - U_{t-1}. \quad (\text{B.145})$$

Challengers

$$\begin{aligned} NLP_{CH_t} = RE_{CH_t} - I_{CH_t} &= (D_{CH_t} - D_{CH_{t-1}}) - (L_{CH_t} - L_{CH_{t-1}}) \\ &\quad - p_{ACH_t} (a_{CH_t} - a_{CH_{t-1}}). \end{aligned} \quad (\text{B.146})$$

Incumbents

$$\begin{aligned} NLP_{CH_t} = RE_{IN_t} - I_{IN_t} &= (D_{IN_t} - D_{IN_{t-1}}) - (L_{IN_t} - L_{IN_{t-1}}) \\ &\quad - p_{AIN_t} (a_{IN_t} - a_{IN_t}). \end{aligned} \quad (\text{B.147})$$

Banks

$$\begin{aligned} NLP_{B_t} &= RE_{B_t} + \Theta_B \\ &= (L_t - L_{t-1}) + (GB_{B_t} - GB_{B_{t-1}}) + (H_{B_t} - H_{B_{t-1}}) - \\ &\quad (J_{CB_t} - J_{CB_{t-1}}) - (D_t - D_{t-1}) + p_{AIN_t} (a_{IN_t}^B - a_{IN_t}^B) \\ &\quad + p_{ACH_t} (a_{CH_t}^B - a_{CH_{t-1}}^B). \end{aligned} \quad (\text{B.148})$$

NBFI

$$\begin{aligned} NLP_{NBFI_t} &= RE_{NBFI_t} + \Theta_{NBFI} = U_t - U_{t-1} - \\ &\quad \left(\begin{aligned} &D_{NBFI_t} - D_{NBFI_{t-1}} + p_{AIN_t} (a_{IN_t}^{NBFI} - a_{IN_{t-1}}^{NBFI}) \\ &+ p_{ACH_t} (a_{CH_t}^{NBFI} - a_{CH_{t-1}}^{NBFI}) + (GB_{NBFI_t} - GB_{NBFI_{t-1}}) \end{aligned} \right). \end{aligned} \quad (\text{B.149})$$

Government

$$NLP_{G_t} = T_t + \Pi_{CB_t} - G_t - \tau_t - r_{GB} GB_{t-1} - \Theta_{NBFI_t} - \Theta_{B_t} = GB_t - GB_{t-1}. \quad (\text{B.150})$$

Central Bank

$$\begin{aligned}
NLP_{CB_t} = 0 &= r_{GB}GB_{CB_{t-1}} + i_{CB}J_{CB_{t-1}} - \Pi_{CB_t} \\
&= (GB_{CB_t} - GB_{CB_{t-1}}) + (J_{CB_t} - J_{CB_{t-1}}) - (H_t - H_{t-1}).
\end{aligned} \tag{B.151}$$

By virtue of stock-flow consistencies, all net lending positions sum up to zero.

B.3.5.3. Wealth**Households**

$$V_{H_t} = D_{H_t} + H_{H_t} + U_t + OF_t = D_{H_{t-1}} + OF_t - OF_{t-1} + YD_t - C_t. \tag{B.152}$$

Incumbents

$$V_{IN_t} = D_{IN_t} + \Omega_{IN_t} - L_{IN_t} - A_{IN_t}. \tag{B.153}$$

Challengers

$$V_{CH_t} = D_{CH_t} + \Omega_{CH} - L_{CH_t} - A_{CH_t}. \tag{B.154}$$

NBFIs

$$V_{NBFI_t} = D_{NBFI_t} + A_{IN_t} + A_{CH} - U_t. \tag{B.155}$$

C. Calibration

The calibration method proceeds in three steps.

First, a series of stylised facts were chosen as targets for our baseline scenarios and for starting values based on existing projections or empirical data. The model is then solved at an artificial year zero by respecting stock-flow norms, under the constraint of some key ratios, like the wage share and the capital adequacy ratio. This year zero is “under-calibrated” to let the model converge towards acceptable values for nominal variables of interest. The model is then set to converge until reaching a stable steady-state. Relevant targets and constraints are described in Appendix C.1.

Then, a range of parameters was calibrated based on empirical data to target some and, when unavailable, sensible ranges of values. These parameters are described in Appendix C.2.

Third, I pinpointed a range of uncertain parameters that I used to generate our baseline calibrations but that could legitimately take other values and yield similar baseline calibrations. These sensitivity parameters also include some empirical parameters that are held constant in our model, while they could change through time, for instance, interests on government bonds or bank deposits. These parameters are subjected to the sensitivity analysis developed in Appendix D. Amongst these sensitivity parameters, many are held constant across scenario variants and vintages. However, three parameters had to be modulated to yield the baseline stylised facts across scenario variants and vintages. All this information is gathered in Appendix C.3.

C.1. Target Endogenous starting values and across baseline simulations

The model targets a range of stylised facts across baseline simulations. It notably includes macroeconomic variables like inflation, growth or government deficit. Because I am interested in financial dynamics, I also target some stylised facts directly related to finance, such as average default probabilities, the dispatch of financial assets across

financial agents, or banks' capital adequacy ratio. These values are summarised in Table C.1.

C.2. Fixed calibration parameters

Fixed calibration parameters are primarily drawn from empirical data or set to yield some of the stylised facts mentioned in Table C.1. It notably includes tax rates, structural shares in investment portfolios, and utilisation rates. Other parameters, mostly adjustment speeds – notably for utilisation rates and investments – are calibrated to ensure a rapid convergence to a stable, non-oscillatory steady state (ξ_{inv} , ξ_u). Finally, a residual of parameters is taken from a reasonable range of values usually encountered in the literature, such as the parameters ruling the consumption function (α_{Π} , β_B).

Table C.1: Target values for endogenous variables

Variable	Description	Target Value
Before the start of the transition (2019)		
$\frac{A^B}{A^B + ANBFI}$	Share of equity held by banks	10-15% (Von Beschwitz and Foes 2018)
$\frac{GB_{NBFI}}{GB}$	Government bond ownership of NBFIs	15% (Andritzky 2012)
CAR	Bank's Capital Adequacy Ratio	18% (ECB 2020a)
$\frac{NLP_G}{VA}$	Government deficit (% GDP)	1.8% (World Bank 2022)
S_{LC}	Market share of challenger (%)	8% (Georgeson and Maslin 2019; Kruse, Mohnen, and Sato 2020; Faivre et al. 2023)
VA	Nominal GDP	876100 (World Bank 2022)
g_{p_e}	Inflation Rate (World Bank, 2022)	2.18% (World Bank 2022)
g_{va}	Real value-added growth	2.54% (NGFS 2022)
$\lambda_i, i \in \{IN, CH, K_H, L_H\}$	Labour productivities except conversion	3 Based on (Timmer et al. 2015), set to reach target nominal values after around 60 iterations
λ_o	Labour productivity for conversion (Reasonable range of values)	1 Assumption that conversion is, at the beginning three times more expensive than normal investment
φ_{NPL}	Average default propensity	2.7% (World Bank 2022; EBA 2019)
ϖ_{IN}, ϖ_{CH}	Credit constraint across sectors	10-15% (Beyhaghi et al. 2020)
$\frac{WB}{VA}$	Wage Share	49% (Timmer et al. 2015)
ω_{HC}	Capital stock (total capital stock in 2019)	2263200 (Timmer et al. 2015)
During the transition (Average values)		
$\frac{A^B}{A^B + ANBFI}$	Share of equity held by banks	10-15% (Von Beschwitz and Foes 2018)
$\frac{GB_{NBFI}}{GB}$	Government bond ownership of NBFIs	15% (Andritzky 2012)
$\frac{LN_{BFI}}{L}$	Share of NBFI loans in total	10-15% (Franceschi et al. 2023) (Morningstar and DBRS 2022)
$\frac{NLP_G}{VA}$	Government deficit	1.8% (World Bank 2022)
g_{p_e}	Inflation Rate	2.18% (World Bank 2022)
g_{va}	Real value-added growth	2.54% (NGFS 2022)
$\frac{WB}{VA}$	Wage Share	49% (Timmer et al. 2015)
φ_{NPL}	Average default propensity	2.8% (World Bank 2022; EBA 2019)
ϖ_{IN}, ϖ_{CH}	Credit constraint	10-15% (Beyhaghi et al. 2020)

Note: In all runs, these values are reached with a tolerance inferior to 10%

Table C.2: Fixed parameters

Parameter	Description	Value	Justification/Source
α_{Π}	Specific sensitivity coefficient - Capital income	0.4	Reasonable range of value
α_{HPM}	Fraction of household wealth held in cash	1%	Reasonable range of values
α_U	Fraction of household wealth held in units	85%	Consistent with EU and US data (ECB 2020c; Deloitte 2019)
α_{τ}	Subsidies as percent of nominal GDP	10%	World Bank (2022)
α_{YD}	Specific sensitivity coefficient – Expected Non-Financial available income	0.9	Reasonable range of values
$\frac{NLP_G}{VA}$	Target government deficit	1.8%	World Bank (2022)
$\frac{NLP_G}{VA}$	Target government deficit	1.8%	World Bank (2022)
β_V	Specific sensitivity coefficient - Expected Wealth	0.01	Reasonable range of value
γ_D	Fraction of deposits held in government bonds by banks	10%	Chosen within a reasonable range of values
γ_H	Fraction of deposits held in cash by banks	5%	
δ_H	Depreciation rate – High-carbon capital	5%	Reasonable range of values
δ_L	Depreciation rate – Low-carbon capital	5%	Reasonable range of values
η	Parameter ruling adaptive expectations	0.1	Calibrated to generate baseline
η_g	Partial-Ajdustment for target deficit	0.5	Chosen to limit oscillations in steady-state
$\kappa_{IN} = \kappa_{CH} = \kappa_L = \kappa_H$	Capital intensity	1.279	Timmer et al. (2015)
$\lambda_{GB,0}$	Share of government bonds in NBF1 portfolios	5%	Andritzky (2012)
M_{NBF1}	Maturity of NBF1 loans	1	Calibrated to mimic short-term funding
ν_{λ}	Sensitivity of productivity growth to value-added growth	0.825	Calibrated based on Dafermos, Nikolaidi, and Galanis (2017) estimate
ϕ_{max}	Maximum allowed default probability	25%	From Dafermos, Nikolaidi, and Galanis (2017)
ψ	Investment-to-debt ratio	80%	Average across developed economies (Al-Eyd et al. 2015)
θ_H	Tax rate on available income	25%	Global average effective personal income tax rate (The Global Economy 2020; OECD 2023)
θ_{IG}	Tax rate on investment good profits	23.54%	lobal corporate tax rate (Bray 2021)
θ_{IN}	Tax rate on Incumbent profits	23.54%	Global corporate tax rate (Bray 2021)
θ_{LC}	Tax rate on Challenger profits	23.54%	lobal corporate tax rate (Bray 2021)
ϖ_{max}	Maximum allowed credit constraint	50%	From Dafermos, Nikolaidi, and Galanis (2017)
ξ_{inv}	Partial-Ajdustment parameter (Investment and assets stranding)	0.5	Chosen to limit oscillations in steady-state
ξ_u	Partial-Ajdustment for normal utilisation rate	0.5	Chosen to limit oscillations in steady-state
u_X^T	Target utilisation rate in the consumption good sector	75%	Botte (2019)
$\omega_{1,2,3}$	Prudential weights on loans (1) and stocks (2,3) in CAR	1	Dafermos, Nikolaidi, and Galanis (2017)
ω_4	Prudential weights on government bonds in CAR	0	Dafermos, Nikolaidi, and Galanis (2017)

C.3. Sensitivity parameters

Alongside the fixed parameters expounded above, a range of parameters were given relatively arbitrary values, with different sets possibly giving rise to similar calibrations. They will, therefore, be subjected to a sensitivity analysis in Appendix C. They include behavioural parameters without firm empirical grounds, like the sensitivity to the the inverted Tobin's Q (τ_{Tob}), or parameters ruling credit rationing ($\varpi_{1,2,3}$) and default probabilities ($\varphi_{1,2}$).

Furthermore, to generate similar baselines, some sensitivity parameters were given different values depending on the model variant and/or the scenario vintage. These three parameters are the sensitivity of consumption γ_C , the parameter ruling trend inflation ν_{w_2} and the parameters ruling minimum default probability, for non-financial companies ($\varphi_1^{CH,IN}$) and non-bank financial institutions (φ_1^{NBFI}).

Finally, labour productivities could not be calibrated from the starting point of our scenarios, since they are endogenous variables in the model. To calibrate them, I modulated the value of the starting value of labour productivity, before launching the learning period of the model. They were first calibrated before the learning period based on WIOD (Timmer et al. 2015) to get a wage share of 49% in period 0 of the model. Because they rule the general price level in our model (see Equation (B.31)-(B.33)), they were further adjusted such that target nominal values are reached after the learning period of the model. Note that they denote the productivity of labour hours, with employment from WIOD adjusted with the average number of hours worked from Dafermos, Nikolaidi, and Galanis (2017).

I first display the sensitivity parameters common to all simulations, and then differentiate across variants and vintages.

Table C.3: Sensitivity parameters

Parameter	Description	Value	Justification/Source
$\bar{\mu}$	Markup on base rate	6.5%	Calibrated to reach a weighted average on commercial rates of 8% (World Bank 2022)
\overline{lev}	Normal leverage	20%	Reasonable range of values after adjustment
β_e	Technological spillover coefficient	0.1	Reasonable range of value
$\lambda_{i,j}, i, j \in \{1, 2, 3\}$	Sensitivity to changes in expected returns	0.06/-0.03	Reasonable range of value, symmetry constraints (Godley and Lavoie 2007)
λ_{KLC}^*	Labour productivity of low-carbon capital production	3*	WIOD (Timmer et al. 2015) and Dafermos, Nikolaidi, and Galanis (2017)
λ_o^*	Labour productivity of conversion	1*	WIOD (Timmer et al. 2015) and Dafermos, Nikolaidi, and Galanis (2017)
ν	Parameter ruling NBFI leverage	0.1	Calibrated to generate baseline
ν_{w_1}	Sensitivity of nominal wage growth to past CPI inflation	0.7	Calibrated to generate baseline
ν_{w_2}	Sensitivity of nominal wage growth to past growth	1.1	Calibrated to generate baseline
ν_u	Sensitivity of markup to drift from target utilisation rate	0.04	Calibrated to generate baseline
r_D	Interest rate on deposits	0.5%	Consistent with European (ECB 2023) and US (FRED 2023a) data
ω_p	Passthrough rate	0.2	Drawn from Känzig (2023)
r_{CB}	Interest rate on central bank advances	1%	Early-2020 Fed rate (FRED 2022)
r_{GB}	Interest rate on government bonds	2%	Average on country data (World Bank 2022)
σ_{HC}	Sector loan markup - Incumbent	2.5%	Calibrated to reach a weighted average on commercial rates of 8% (World Bank 2022)
σ_{LC}	Sector loan markup - Challenger	2.5%	Calibrated to reach a weighted average on commercial rates of 8% (World Bank 2022)
σ_{NBFI}	Sector loan markup - NBFI	2.5%	Calibrated to reach a weighted average on commercial rates of 8% (World Bank 2022)
σ_{lev}	Sensitivity of interest to observed leverage	2.5%	Calibrated to reach a weighted average on commercial rates of 8% (World Bank 2022)
τ_{Tob}	Sensitivity of portfolio choice to Tobin's Q	0.5	Reasonable range of values
φ_2	Parameter ruling sensitivity of default probability to liquidity ratio	7.85	Calibrated to yield baseline calibration
ϖ_1	Parameter ruling maximum credit rationing	4.5	Calibrated to generate baseline
ϖ_2	Parameter ruling sensitivity of credit rationing to debt service ratio	1	Calibrated to generate baseline
ϖ_3	Parameter ruling sensitivity of credit rationing to deviation from target capital adequacy ratio	6	Calibrated to generate baseline
ξ_B	Dividend-payout ratio of banks	0.4	Chosen conservatively from the minimum payout ratio of EU banks since 2000 (Muñoz 2020)
ξ_{FundsB}	Fraction of deposits invested in equity by banks	10%	Calibrated to match share of banks in equity ownership (Von Beschwitz and Foos 2018)
ξ_{CH}, ξ_{IN}	Dividend-payout ratio of firms	40%	Average across world regions (Hartford Funds 2023; McCrum 2018)
Refinitiv, Factset			
ξ_{NBFI}	NBFI payout ratio	90%	Reasonable range of values
ω_{CG}	Discounting of capital gains	0.6	Chosen to ease model convergence

*Starting value before the learning period of the model

D. Global Sensitivity Analysis

Given the high number of uncertain parameters in this model, I perform a global sensitivity analysis to pinpoint possible drivers. With the empirical parameters free, the sensitivity analysis is run on 29 parameters. The procedure is in three steps. First, I used a Morris method to discriminate those parameters most susceptible to drive the model away from the steady-state. This allowed me to draw meaningful sensitivity ranges for each parameter, reported in Table D.1.

Second, based on these ranges, I sampled 100,000 vectors of 29 parameters through Latin Hypercube Sampling and ran the model without climate policy. Around 97.5% of the runs resulted in a stable steady-state, confirming that the model accommodates a wide range of calibrations. Amongst these, were selected those yielding a steady-state close to the main calibration, *i.e.*, with steady-state outcomes within a 10% range of those obtained in base runs. Then, all these calibrations were used on scenarios. Correcting for outliers, the sample comprises 505 sensitivity runs for each scenario. For brevity and due to computational constraints, the sensitivity analysis is performed only on the 2022 set of scenarios generated by the REMIND-MagPIE framework.

I further use the results with Ordinary Least Squares (OLS) to highlight the effect of parameters on some outcomes. To explore possible non-linearities, I add the squared value of parameters to the linear model. Finally, I control for each scenario with a dummy variable indicating which scenario is considered. This yields the general linear model for a given outcome Y . This process yields the following general model:

$$Y = \alpha + \beta_1\Gamma + \beta_2(\Gamma)^2 + \beta_3Scen + \varepsilon. \quad (\text{B.156})$$

Where Γ is the vector of sensitivity parameters and $(\Gamma)^2$ denotes that the values of the parameter in the vector Γ are squares. Given our basic model's manyvariables, I run a step-wise model choice based on Akaike's Information Criterion (AIC)²⁰ to yield a

²⁰The AIC was chosen over the also commonly found Bayesian Information Criterion (BIC) because the AIC

Table C.4: Vintage-specific values

Parameter	Description	REMIND	MESSAGE	GCAM
2022 Vintage				
ν_{w_2}	Sensitivity of nominal wage growth to past growth	1.1	1.1	1.1
γ_C	Sensitivity of consumption to available funds	0.073	0.0735	0.073
$\phi_1^{CH,IN}$	Parameter ruling minimum default probability (NFC)	8.1	8.05	7.975
ϕ_1^{NBFI}	Parameter ruling minimum default probability (NBFI)	8.987	8.855	8.7725
2021 Vintage				
γ_C	Sensitivity of consumption to available funds	0.0735	0.0735	0.0735
$\phi_1^{CH,IN}$	Parameter ruling minimum default probability (NFC)	8.02	8.05	8.03
ϕ_1^{NBFI}	Parameter ruling minimum default probability (NBFI)	8.822	8.855	8.833
2020 Vintage				
γ_C	Sensitivity of consumption to available funds	0.0735	0.0735	0.0735
$\phi_1^{CH,IN}$	Parameter ruling minimum default probability (NFC)	8.03	8.045	8.045
ϕ_1^{NBFI}	Parameter ruling minimum default probability (NBFI)	8.833	8.8495	8.8495

parsimonious model and improve readability. The sensitivity analysis is performed on synthetic indicators relevant to financial instability: the minimum CAR reached over the run, the average Incumbent default probability and the average NBFI default probability. Results are reported in Table D.2, which ranks each parameter by its explanatory power for each of our outcomes.

It appears first that our model explains very well the variance in our results, with (adjusted) R^2 of at least 81%. The scenario variables are all significant, with expected signs, given that the reference value is the “Current Policy” scenario. Second, our model has a relatively high level of non-linearities, as is highlighted by the high number of significant non-linear effects in the final specifications. Further, variables influence results differently depending on the outcome.

- The minimum CAR is affected positively by inflation and growth parameters. For growth, things are as expected: banks benefit from higher profits in the case of higher output. Inflation increasing overall cash flows tends to decrease default propensities – as per the results from the other outcomes, resulting in more resilient CAR. Financial parameters also act as expected. The participation of banks in financial markets increases their resilience due to higher profits and higher capital gains. However, a greater market volatility (λ_λ) affect their resilience negatively through a non-linear effect. Interest rates on deposits decrease the CAR due to lower profits. Interest rate variables act as expected, by increasing the

usually yields higher R^2 , and tends to include relatively more variables, the BIC being known for possibly over-penalise additional variables.

Table D.1: Ranges of sensitivity parameters

Parameter	Reference values	Range
$\bar{\mu}$	0.065	[0.0585, 0.0715]
\bar{lev}	0.2	[0.14, 0.26]
β_e	0.1	[0.07, 0.13]
γ_C	0.073	[0.0657, 0.803]
$\lambda_{i,j}, i, j \in \{1, 2, 3\}$	0.06 -0.03 otherwise (Ruled by a single parameter λ_λ with value 0.06, on which the value of the other Tobin coefficients are computed)	[0.048, 0.96]
λ_{KLC}^*	3	[2.4, 3.9]
λ_o^*	1	[0.7, 1.3]
ν	0.1	[0.07, 0.13]
ν_{w_1}	0.7	[0.63, 0.77]
ν_{w_2}	1.1	[0.088, 1.32]
ν_u	0.04	[0.028, 0.052]
ω_p	0.2	[0.14, 0.26]
r_D	0.005	[0.035, 0.065]
r_{CB}	0.01	[0.007, 0.013]
r_{GB}	0.02	[0.014, 0.026]
σ_{CH}	0.025	[0.1225, 0.5]
σ_{IN}	0.025	[0.1225, 0.5]
σ_{NBFI}	0.025	[0.1225, 0.5]
σ_{lev}	0.025	[0.1225, 0.5]
τ_{Tob}	0.5	[0.25, 1]
φ_1	8.17	[7.96, 8.37]
φ_2	7.925	[7.1325, 8.7175]
ϖ_1	2	[1.8, 2.2]
ϖ_2	2	[1.4, 2.6]
ϖ_3	6	[4.2, 7.8]
ξ_B	0.4	[4.2, 7.8]
ξ_{Funds_B}	0.1	[0.07, 0.13]
ξ_{NBFI}	0.9	[0.81, 0.99]

*Starting value before the learning period of the model

minimum CAR. However, negative non-linear effects emerge for σ_{IN} and σ_{CH} , highlighting that too high interest rates can weigh on the borrowers' ability to repay and foster financial instability, in a classical Minskian way (Nikolaïdi 2017). The same goes for the benchmark leverage retained by banks. Parameters ruling default probability and credit rationing act as expected with nonetheless a positive non-linear effect of φ_2 , suggesting that very high default cleanse counterparts' balance sheets, restoring their payment abilities and therefore limiting

future defaults. However, the linear effect is of the expected style, and with a much higher magnitude, confirming that an increase in φ_2 affects the CAR negatively in most cases. Lower low-carbon technologies (higher λ_{KLC}) increase the resilience of the challenge sector, resulting in fewer NPLs. The passthrough rate, through higher Incumbent profits, and the carbon intensity improvement coefficient improve banks' resilience by making counterparts more robust. Yet, it may transit through lower absolute NPLs and through a decrease in NBFi default probability more than through lower Incumbent default propensity. Finally, the Tobin premium seems to decrease the minimum CAR, which suggests that higher values introduce larger capital losses and higher NBFi default probability.

- Most of the parameters affect the mean NBFi default probability in expected ways. Inflation, however, has a negative non-linear effect, suggesting that high inflation can increase the dividends going eventually to NBFi through the growth channel. Also, because inflation is mostly wage inflation, higher wages imply higher unit purchases, which increases the resilience of NBFis. Higher payout ratios have a negative non-linear effect, while more competition from banks in financial market (higher ξ_{Funds_B} , by decreasing dividend flows), has a positive effect. Interest rate variables almost all act as expected, with a clear non-linear effect from $\bar{\mu}$ and \bar{lev} . Puzzling, however, is the effect of interests on government bonds, which, at face value, should act positively since interest flows on bonds positively affect NBFi profits. The effect may transit through lower growth: the government targeting a constant deficit with higher interest on public debt tends to decrease government consumption and hamper growth. Since government bonds are a minor part of NBFi portfolios, this effect must outweigh the positive effect. The linear, positive effect of government bond interest on Incumbent default probability corroborates this interpretation. Furthermore, surprisingly, the sensitivity analysis reveals a positive non-linear effect of φ_1 , although this parameter should intuitively play out negatively. It is because of the maturity of NBFi loans: since they only last for one period, non-performing loans offer relief to NBFis in that their subsequent principal repayments are lower. Hence, lower NPL on average may weigh on repayment capabilities over some periods. Other variables play out as expected, as discussed above.

- Finally, the mean Incumbent default probability is affected by much fewer variables, all of them playing out as expected, except for the interest rate on government bonds discussed above. Causality channels either relate to higher cash flows (inflation parameters), allowing firms to repay their debts more easily, or to demand channels (for instance, higher NBF1 ratios increase growth by redistributing more of the profits to households).

Table D.2: Sensitivity analysis –OLS

	<i>Dependent variable:</i>		
	Minimum CAR (2020-2050)	Average φ_{NBF1}	Average φ_{HC}
	(1)	(2)	(3)
ν_{w_1}	-0.370*** (0.128)	0.167** (0.065)	
$\nu_{w_1}^2$	0.270*** (0.091)	-0.134*** (0.046)	-0.002*** (0.001)
ν_{w_2}		-0.122* (0.065)	-0.003*** (0.001)
$\nu_{w_2}^2$		0.045 (0.029)	
γ_C^2	2.155*** (0.633)	-2.642*** (0.316)	
γ_C			-0.193*** (0.016)
ξ_{NBF1}^2		0.013*** (0.001)	-0.001*** (0.0002)
ν_u	1.222*** (0.248)	-0.636*** (0.107)	
ν_u^2	-14.685*** (3.091)	7.705*** (1.326)	
$\xi_{Funds,B}$	-0.210** (0.099)		
$\xi_{Funds,B}^2$	1.104** (0.496)	-0.116*** (0.017)	
r_{GB}^2		2.974*** (0.406)	
r_D	-0.337** (0.153)	-0.438*** (0.066)	
σ_{CH}	0.907** (0.389)	-0.347** (0.168)	

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	<i>Dependent variable:</i>		
	Minimum CAR (2020-2050)	Average φ_{NBFI}	Average φ_{HC}
	(1)	(2)	(3)
σ_{CH}^2	-13.699* (7.775)	8.710*** (3.364)	
σ_{IN}	0.720* (0.407)	-0.279 (0.174)	
r_{GB}			0.012** (0.006)
σ_{IN}^2	-16.323** (8.117)	6.859** (3.469)	0.772*** (0.095)
σ_{NBFI}	0.150*** (0.031)	-0.320* (0.181)	
σ_{NPL}	0.184*** (0.031)		
σ_{NBFI}^2		6.656* (3.600)	
σ_{NPL}^2		0.763*** (0.266)	
$\bar{\mu}$	-2.301* (1.390)	1.768*** (0.596)	0.053*** (0.005)
$\bar{\mu}^2$	20.796* (10.685)	-9.898** (4.577)	
\overline{lev}	-0.086* (0.050)	0.038* (0.022)	
\overline{lev}^2	0.196 (0.124)	-0.114** (0.053)	
ω_{CG}	0.011*** (0.004)	-0.118* (0.062)	
ω_{CG}^2		0.094* (0.052)	
φ_1	0.352* (0.210)	-0.311*** (0.091)	
φ_1^2	-0.021 (0.013)	0.019*** (0.006)	-0.002*** (0.00002)
φ_2	-0.192*** (0.066)	0.144*** (0.028)	0.024*** (0.0002)
φ_2^2	0.011*** (0.004)	-0.009*** (0.002)	
ϖ_2		-0.005**	

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	<i>Dependent variable:</i>		
	Minimum CAR (2020-2050)	Average φ_{NBF1}	Average φ_{HC}
	(1)	(2)	(3)
ϖ_1		(0.002)	0.001*** (0.0003)
ϖ_2^2		0.001** (0.001)	-0.0001*** (0.00003)
ϖ_3	-0.003* (0.002)	0.002*** (0.001)	
ϖ_3^2	0.0003** (0.0001)	-0.0002*** (0.0001)	
λ_λ	1.322*** (0.360)	-0.307* (0.157)	
λ_λ^2	-10.380*** (2.993)	2.259* (1.308)	
$\lambda_{K_{LC},0}$	0.002*** (0.0004)	-0.019*** (0.003)	0.005*** (0.001)
$\lambda_{K_{LC},0}^2$		0.002*** (0.001)	-0.0004** (0.0002)
$\lambda_{o,0}$	0.002** (0.001)	-0.007* (0.004)	-0.003*** (0.0001)
ν	-0.153 (0.096)		
ν^2	0.710 (0.476)		
$\lambda_{o,0}^2$		0.003 (0.002)	
τ_{Tob}	0.066*** (0.020)	-0.024*** (0.009)	
τ_{Tob}^2	-0.064*** (0.020)	0.023*** (0.009)	
ω_p	0.007** (0.003)		-0.001** (0.0004)
ω_p^2		-0.006** (0.003)	
β_e	0.015* (0.008)	-0.010*** (0.004)	
β_e^2			-0.070*** (0.007)

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	<i>Dependent variable:</i>		
	Minimum CAR (2020-2050)	Average φ_{NBF1}	Average φ_{HC}
	(1)	(2)	(3)
Below 2C	-0.0005 (0.0004)	0.010*** (0.0002)	0.003*** (0.0001)
Delayed Action	-0.009*** (0.0004)	0.012*** (0.0002)	0.004*** (0.0001)
Divergent Net Zero	-0.014*** (0.0004)	0.014*** (0.0002)	0.010*** (0.0001)
NDCs	-0.00000 (0.0004)	0.006*** (0.0002)	0.003*** (0.0001)
Net Zero 2050	-0.009*** (0.0004)	0.014*** (0.0002)	0.007*** (0.0001)
Constant	-0.425 (0.748)	0.802** (0.325)	-0.028*** (0.002)
Observations	3,354	3,354	3,354
R ²	0.427	0.816	0.927
Adjusted R ²	0.420	0.813	0.926
Residual Std. Error	0.007 (df = 3313)	0.003 (df = 3306)	0.001 (df = 3332)
F Statistic	61.759*** (df = 40; 3313)	311.539*** (df = 47; 3306)	2,002.637*** (df = 21; 3332)

Note:

*p<0.1; **p<0.05; ***p<0.01

The reference value for the Scenario Variable is the Current Policy scenario.

I complement this OLS-based analysis with an ANOVA decomposition to highlight which parameters explain the most variance. The objective is to provide a sense of the importance of each parameter in driving the variation of the outcomes explored above. Using the same specifications as those given by the AIC procedure, results are shown on Table D.3, where parameters and corresponding non-linear effects are ranked based on the share of the variance they explain.

As can be seen, a very large share of the variance of the minimum CAR and the average Incumbent is explained by the scenarios, which is expected. Then, the base loan markup on loans seems to play a key role for all outcomes. It underscores the role of interest rates in driving results and financial instability. Finally, parameters ruling the default probability equations have important impacts, as could be expected.

Table D.3: ANOVA analysis

Minimum Capital Adequacy Ratio		Average NBF1 Default Probability		Average Incumbent Default	
Parameter	% of explained variance	Parameter	% of explained variance	Parameter	% of explained variance
Scenarios	74.24	Scenarios	58.13	Scenarios	60.12
$\bar{\mu}$	6.75	$\lambda_{KLC,0}$	17.46	φ_2	31.38
φ_2	4.57	$\bar{\mu}$	7.46	$\lambda_{KLC,0}$	3.23
σ_{LC}	2.64	γ_C^2	6.30	ν_{w_2}	2.31
σ_{NPL}	1.89	φ_2	2.92	$\lambda_{KLC,0}$	1.12
$\lambda_{KLC,0}$	1.13	ξ_{NBF1}^2	2.20	γ_C	0.63
σ_{NBF1}	1.13	ν_{w_2}	1.95	φ_1^2	0.48
ξ_{FundsB}^2	0.87	σ_{LC}	0.60	ξ_{NBF1}^2	0.39
γ_C^2	0.67	τ_{GB}^2	0.38	β_e^2	0.1
λ_λ	0.64	φ_2^2	0.32	$\bar{\mu}$	0.07
ν_u^2	0.59	ξ_{FundsB}^2	0.25	σ_{HC}^2	0.05
ν_{w_1}	0.48	φ_1	0.19	ϖ_1	0.03
ω_{CG}	0.47	ϖ_2^2	0.19	ω_p	0.03
τ_{Tob}^2	0.44	ν_u^2	0.17	$\lambda_{KLC,0}^2$	0.03
λ_λ^2	0.41	ω_{CG}	0.16	$\nu_{w_1}^2$	0.01
φ_1	0.33	λ_λ	0.14	ϖ_2^2	0.01
ξ_{FundsB}	0.31	ν_{w_1}	0.14	r_{BG}	0
φ_2^2	0.27	r_D	0.12		
$\lambda_{o,0}$	0.26	$\nu_{w_2}^2$	0.12		
σ_{HC}	0.26	ϖ_3^2	0.09		
ν_u	0.22	$\lambda_{KLC,0}^2$	0.07		
r_D	0.19	ϖ_3	0.07		
σ_{HC}^2	0.17	ϖ_2	0.07		
ϖ_3^2	0.16	φ_1^2	0.06		
\overline{lev}^2	0.12	τ_{Tob}^2	0.06		
$\bar{\mu}$	0.12	\overline{lev}	0.06		
τ_{Tob}	0.11	σ_{NBF1}^2	0.04		
σ_{LC}^2	0.11	σ_{HC}^2	0.04		
ν^2	0.1	ω_{CG}^2	0.04		
φ_3	0.09	σ_{NPL}^2	0.04		
\overline{lev}	0.08	$\lambda_{o,0}$	0.03		
$\nu_{w_1}^2$	0.05	λ_λ^2	0.02		
ν	0.05	σ_{LC}^2	0.02		
φ_1^2	0.04	\overline{lev}^2	0.02		
ω_p	0.01	σ_{HC}	0.02		
β_e	0.01	$\lambda_{o,0}^2$	0.02		
		ν_u	0.01		
		$\bar{\mu}^2$	0.01		
		σ_{NBF1}	0.01		
		τ_{Tob}	0.01		
		$\nu_{w_1}^2$	0.00		
		β_e^2	0.00		
		ω_p^2	0.00		

Note: Only the variables explaining more than 0.01% of the variance are displayed.

The average NBF1 default propensity, on the other hand, seems much more affected by the cost parameter, which reflects the key role of Challenger dividends in ensuring the financial viability of NBFIs. Furthermore, the mean NBF1 default probability seems much more affected by other variables, like growth and inflation, and, as could be expected, the payout on NBF1 profits. These results highlight the higher sensitivity

of the NBFi sector to parameters, which may flow from the fact that NBFi default propensity is defined differently from that of the two other sectors. It effectively depends on more parameters in the first order but also on the behaviour of all the other agents in the second order. This somehow vindicates the choice of modelling this sector on its own: by aggregating it to households, it would loosen its dependence on other key sectors of the economy, and key linkages would not be captured.

E. Additional Results and Elements

I display here some additional results. I start with the growth and inflation behaviour of our model along transition pathways. I then show the emission and carbon price trajectories for the 2021 and 2020 NGFS vintages and finally discuss some results from the 2020 vintage.

E.1. Growth and inflation schedules - 2022 vintage

As can be seen, past the start of the transition, which brings inflation and growth to 3-6% growth – within the upper ranges of other SFC models, like Gourdel, Monasterolo, Dunz, et al. (2022) – the economy reverts back to a growth path slightly higher than the steady-state target, around 2.7%, and a slightly higher inflation path. The transition within the model is, therefore, Keynesian, with short-term multiplier effects but also more long-run positive effects on growth due to the necessary replacement of a large part of the capital stock. Thus, the model bypasses the need for large macroeconomic shocks in identifying transition risks and shows that they can emerge even if it is assumed that the transition has positive macroeconomic effects overall.

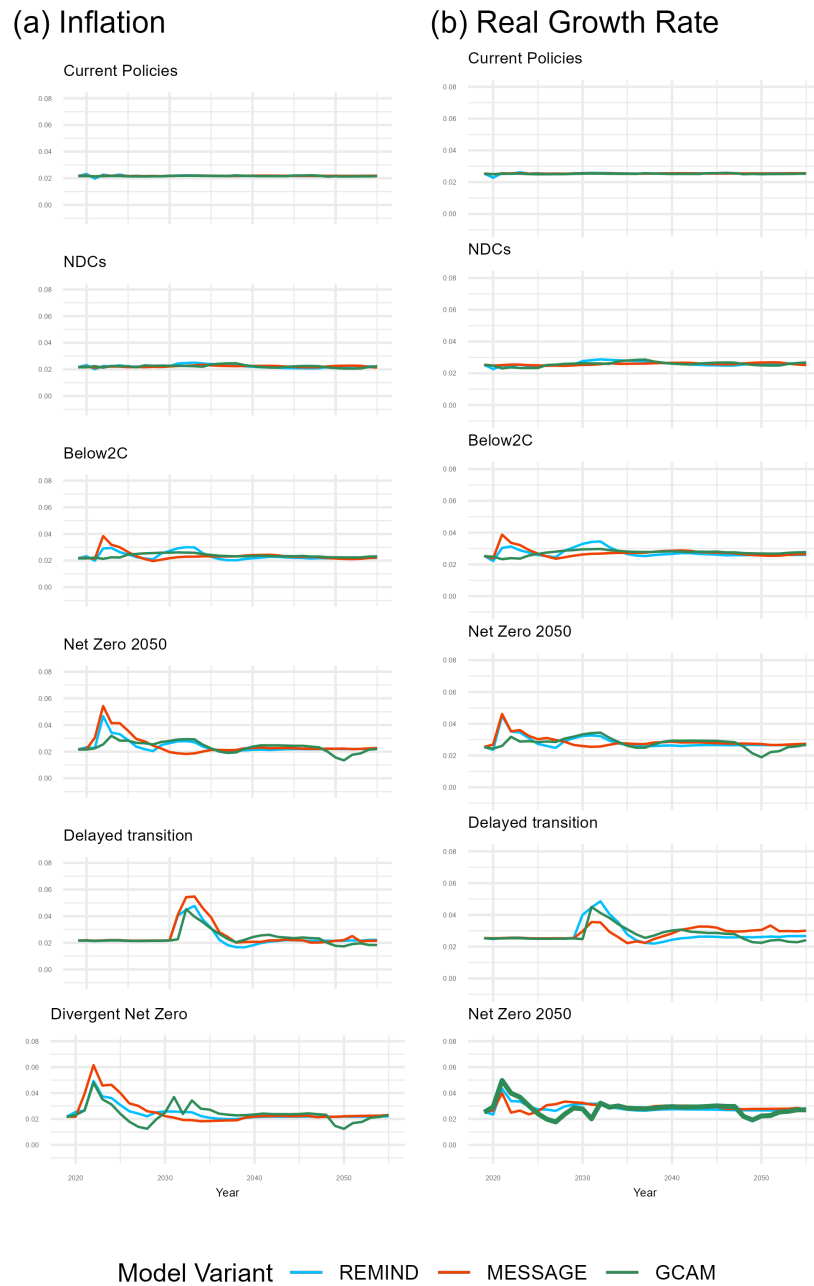


Figure E.1: Macroeconomic Behaviour (2022 vintage). Each color is a scenario variant. Panel (a) displays inflation, while Panel (b) shows the real growth rate.

E.2. Decarbonisation trajectory and carbon price paths – 2021 vintage

Figure E.3 shows the decarbonisation trajectory and carbon price paths for the 2021 vintage. These scenarios are roughly similar in terms of decarbonisation dynamics to those of the 2022 vintage, with slightly lower carbon prices, except for GCAM, which shows higher and more rapidly increasing carbon prices in stringent scenarios, and also more disruptive decarbonisation dynamics.

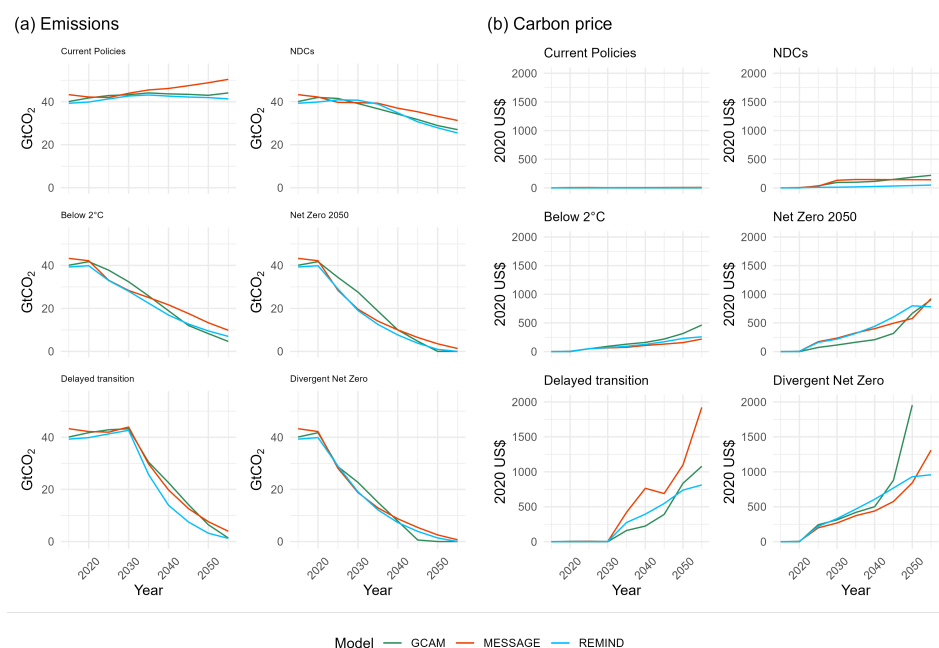


Figure E.2: NGFS Scenarios (2021 Vintage) – Emission trajectories and carbon price schedules. Each line is a scenario variant. Panels (a) and (b) display emissions and carbon prices respectively.

E.3. Decarbonisation trajectory and carbon price paths – 2020 vintage

Figure E.3 shows the decarbonisation trajectory and carbon price paths for the 2020 vintage. Note that this series of scenario comprised eight instead of six scenario variants, with not all models generating all variants. As can be seen, this vintage included a series of very stringent scenarios, some of them more than those of the 2021 and 2022 vintages. It is notably the case of the scenarios supposing a limited presence

of carbon dioxide removal technologies. This higher stringency is mostly visible in terms of decarbonisation dynamics, carbon price assumptions being overall lower.

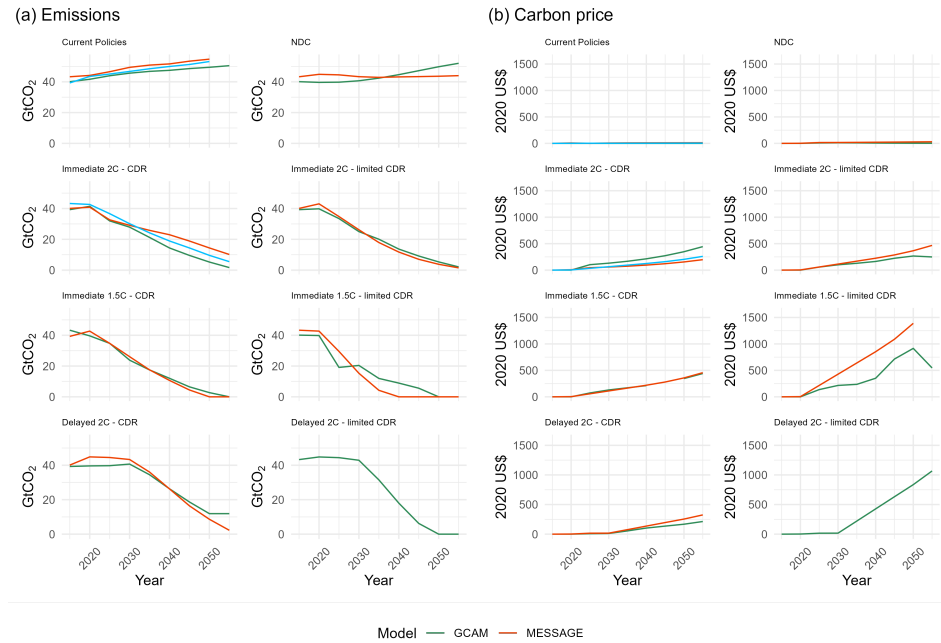


Figure E.3: NGFS Scenarios (2020 Vintage) - Emission trajectories and carbon price schedules. Each line is a scenario variant. Panels (a) and (b) display emissions and carbon prices respectively.

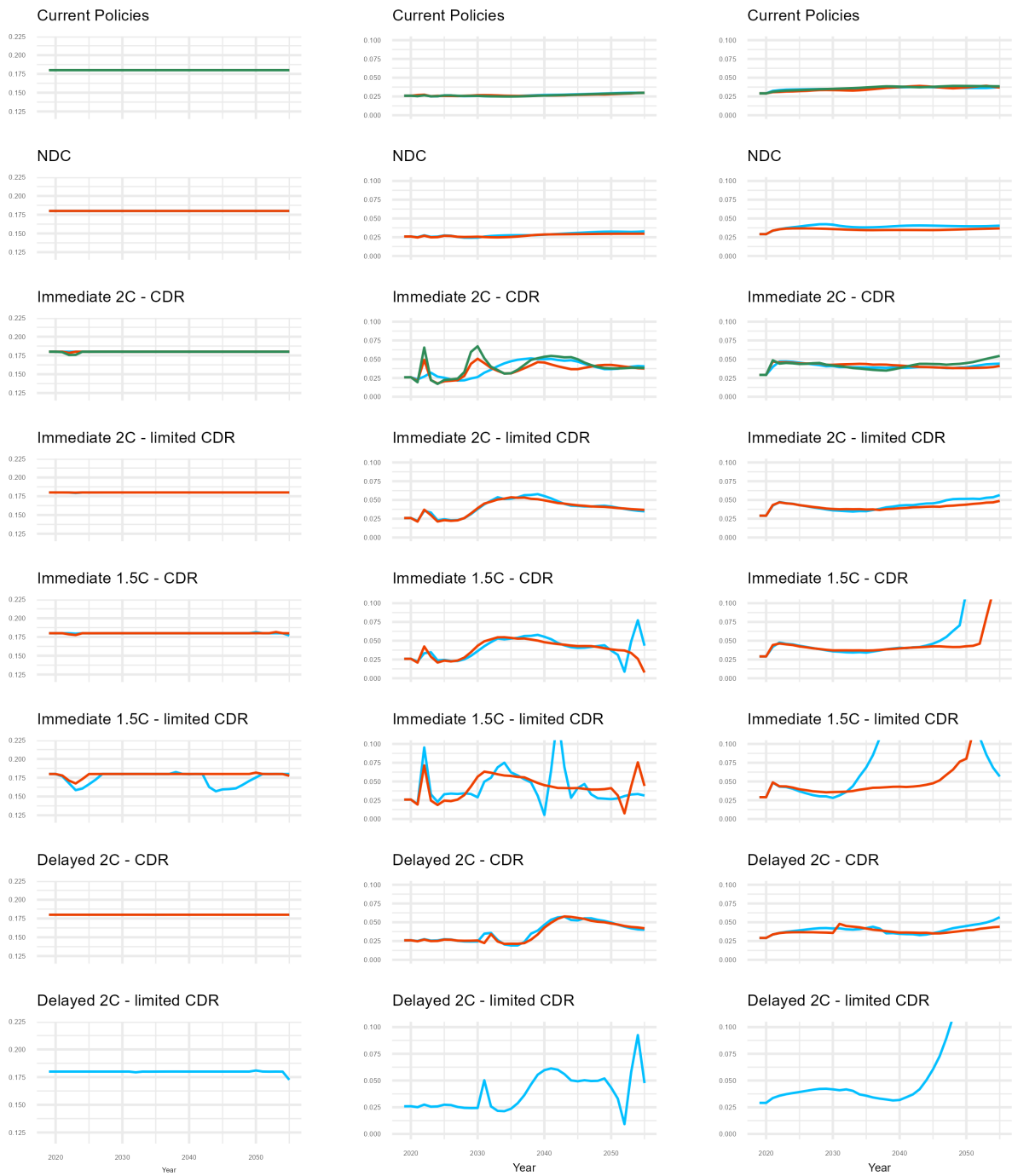
E.4. Results for 2020 scenario vintage

Figure E.4 shows the result of our simulations for key outcomes applied to the 2020 scenario vintage. As can be seen in Figure E.3, orderly, early-action scenarios exhibit very low transition risks, even for NBF1. On the other hand, disorderly scenarios exhibit significant risk, especially in the long run, by giving rise to behaviours similar to the “green bubble” narrative exhibited by GCAM in the 2022 and 2021 vintages. This highlights the potentially large differences across scenario vintages with distinct underlying narratives. Further, it shows the risks associated with deep-decarbonisation scenarios.

(a) Capital Adequacy Ratio

(b) Default Probability – NBFIs

(c) Default probability – Inc.



Model Variant — REMIND — MESSAGE — GCAM

Figure E.4: Macroprudential risks – Worst-case NGFS scenarios (2022 vintage). Each line represents a model variant. Note that, for readability purposes, some axes have been cut. Panel (a) shows the capital adequacy ratio. Panel (b) shows the default probability of NBFIs. Panel (c) shows the default probability of Incumbents.

Chapter 3

Financial transition risks and the multiverse of mitigation pathways

WITH CÉLINE GUIVARCH (CIRED-ENPC)

Abstract

This article proposes a novel methodology for forward-looking low-carbon transition risk assessment based on a large set of scenarios. We build upon the IPCC Assessment Report 6 scenario database to explore the types of transition pathways most prone to financial instability. We start by clustering scenarios based on the form of decarbonisation schedules and on the profile of their carbon price trajectories to generate a classification of mitigation pathways. We then select the best representative within each of our 50 clusters, which we simulate with a stock-flow consistent to quantify indicators relevant to low-carbon transition risks. We then tackle uncertainty on future macroeconomic developments by running each scenario on different calibrations corresponding to the five Shared Socioeconomic pathways. We finally deal with uncertainty on model parameters by generating these macroeconomic regimes with an important number of parameter combinations. In the end, we simulate several thousand trajectories that differ by (i) decarbonisation pathway, (ii) macroeconomic regime and (iii) parametrisation of the macroeconomic regime. We also use scenario discovery techniques to explore how low-carbon transition risks vary across decarbonisation pathways, macroeconomic regimes and parametrisations. We find that while most decarbonisation profiles lead to mild transition risks, a handful of scenarios lead to strong instability potentials across states of the world. These scenarios are either delayed-action or deep-decarbonisation pathways featuring steep carbon price schedules.

Acknowledgements

The authors are grateful to Emanuele Campiglio, Bruno Conte, Jérôme Deyris, Francesco Lamperti, Hubert Massoni, Esther Marie Shears, Alessandro Spiganti and Roberta Terranova for helpful feedback and comments. All remaining errors are ours.

Introduction

As emphasised by the IPCC (2022a), the low-carbon transition will require much more than marginal adjustments to our current fossil-intensive development models. From electrification to sweeping energy efficiency improvements through the shift to sufficiency in our ways of life, keeping global warming below 1.5 to 2°C will require transformative changes. However, the IPCC has always insisted on the diversity of possible pathways compatible with Paris climate targets (IPCC 2022a). Paraphrasing de Haan et al. (2016), there are “Many Roads to Rome” for the same decarbonisation target. A good illustration of this diversity of transition pathways is the high number of decarbonisation scenarios reviewed by the IPCC. The AR6 surveys no less than 1,500 scenarios, around 800 of which are compatible with below-2°C global warming. A suite of around 20 models generates these scenarios, with often several frameworks simulating scenarios with similar narratives and core assumptions. These variants can provide quite different pictures of a transition path, with different climate policies, energy mix changes, macroeconomic policy costs, land use, and many other outcomes (IPCC 2022c).

On the one hand, this diversity of pathways is reassuring from a policymaking standpoint because it suggests that there may be a degree of flexibility in achieving climate targets. However, it creates uncertainty for many economic agents. For instance, whether an investor should bet on large-scale renewable energy deployment in the short run or on gas for short to medium-run developments is challenging to disentangle from scenarios alone. The same goes for the value of carbon, which varies vastly from one model to another. This uncertainty is a well-mapped topic within the Integrated Assessment Model (IAM) literature (Tavoni and Valente 2022; van Asselt and Rotmans 2002), which has explored how scenarios were sensitive to *ex-ante* assumptions (Gillingham et al. 2018), the models used to generate the scenarios (Kriegler, Petermann, et al. 2015), or the definition of the baselines (Marangoni et al. 2017). In the face of a possibly extensive range of outcomes, the IAM literature has insisted on considering various scenarios from many modelling frameworks to map

related uncertainties as exhaustively as possible (*e.g.* Marangoni et al. 2017).

The uncertainty around the precise unravelling of the transition recently emerged as an important topic regarding the issues of asset stranding and low-carbon transition risks for finance. Stranded assets are those (natural, physical or financial) most at risk of losing value along a transition path (Caldecott 2017). In contrast, financial low-carbon transition risks relate to the risk of financial instability or crisis as the economy decarbonises (Carney 2015). As put by Semieniuk, Campiglio, et al. (2021), three factors drive these risks: climate policy, technological displacement and changes in consumer preferences. These three factors are characterised by deep uncertainty (Chenet, Ryan-Collins, and van Lerven 2021) and map almost one-to-one the realms of uncertainty highlighted by the IPCC that we mentioned above. Hence a necessary exploration of many different scenarios in assessing low-carbon transition risks (FSB and NGFS 2022).

If some approaches have embraced the diversity of transition pathways in assessing financial transition risks (Battiston, Mandel, et al. 2017; Battiston, Monasterolo, Riahi, et al. 2020; Roncoroni et al. 2021), most scenario-based exercises have relied on a different strategy. “Climate stress tests” have mostly built on a handful of scenarios and used a small number of models to assess transition risks (T. Allen et al. 2020; Vermeulen et al. 2021; ECB/ESRB Project Team on climate risk monitoring 2022). In particular, the workhorse approach in the field, proposed by the Network for Greening the Financial System (NGFS), has proposed a small number of scenarios (8 in the first scenario vintage (NGFS 2020a), 6 in the most recent one (NGFS 2021b)), generated by three Integrated Assessment Models (NGFS 2021b). This choice was intended to provide regulators with a readily available discussion tool with regulated institutions and to avoid too large an assortment of pathways in running regulatory exercises (Clerc, Bontemps-Chanel, et al. 2021).

However, it has not been demonstrated whether these approaches fully map the extent of uncertainties surrounding the transition that would be relevant to studying low-carbon transition risks. So far, the literature has mostly made a difference between

“orderly” and “disorderly transition”, with an emphasis on the timing of implementation of climate policies and technological change. “Orderly” transitions are pathways in which climate policies start early, are easily anticipated, where technological displacement is limited or easy to navigate by economic agents or with less stringent climate targets. “Disorderly” transitions, by contrast, are pathways in which climate policies are introduced late, suddenly and are unanticipated by agents, or where technological displacement is substantial. They represent disruptive states of the world that should be avoided from a societal standpoint. However valid, this dichotomy may only partially overlap with uncertainties regarding decarbonisation’s precise pace and shape. For instance, scenarios (or scenario variants yielded by distinct IAMs) for the same climate target can exhibit a wide array of decarbonisation timings, differing in technological choices, emission reduction timing and economic activity. The implications in terms of transition risks are likely to be different, either in terms of intensity or regarding the sectors that will be affected (Gasparini, Baer, and Ives 2022). Furthermore, at the energy system level, a scenario involving gas as a bridge technology before the complete introduction of renewables will likely have less impact on fossil fuel companies than a scenario in which renewables are introduced early and quickly (Coulomb, Lecuyer, and Vogt-Schilb 2019). Hence, there is a dire need to explore various scenarios to better assess transition risk potentials along transition paths.

Thus, this paper proposes a novel methodology to assess low-carbon transition risks for a large number of transition pathways in order to account for three levels of uncertainty.

We first deal with uncertainty regarding future macroeconomic variables and business-as-usual decarbonisation dynamics by considering the five “macroeconomic worlds” embedded in the Shared Socioeconomic pathways (SSP). The SSPs are high-level (“meta-”) scenarios embedding macroeconomic, societal and technological hypotheses on the unravelling of the 21st Century in the absence of climate policy. These assumptions imply greater or lesser obstacles to decarbonisation, which may

alleviate or worsen transition risks for finance. We reduce SSPs to a mean growth target in a no-policy scenario and to an exogenous reduction in carbon intensity meant to match no-policy emissions.

We then deal with uncertainty regarding mitigation pathways (MP) and corresponding climate policies by taking advantage of the large variety of pathways in the IPCC scenario repository. After reducing the scenarios to their emission and carbon price schedules, we classify them into fifty clusters representing “typical” transition pathways thanks to a functional clustering algorithm. Across these clusters, we select fifty best representatives for our analysis.

We then simulate these scenarios with a stock-flow consistent model amenable to the emulation of transition pathways described in Daumas (2022) (Chapter 2). This framework allows the simulation of many scenarios at a relatively low computational cost. To make for the parametric uncertainty embedded in this model, we further generate 500 sensitivity calibrations for each scenario that we simulate to observe the dependence of our result on chosen parameters. We additionally simulate each MP along each SSP. We consider a sample of 125,000 simulations, 2,500 for each scenario (around 500 sensitivity calibrations per SSP). We use this sample to characterise low-carbon transition risks across all SSP-MP pairs through various outcomes.

Our findings indicate that transition risks for finance remain contained for many SSP-MP pairs we study, including MPs with high climate ambition and relatively high carbon price schedules. More precisely, Banks are significantly affected only in a minority of MPs. The picture is less favourable for non-bank financial agents, which incur more significant losses for a larger swath of projections. The most adverse MPs, overall, feature either very sharp decarbonisation dynamics in the short run, or, most notably, a low climate policy efficiency with respect to climate ambition. In other words, scenarios in which very high carbon prices must be implemented to achieve low or mid-range climate targets feature the highest transition risks content. We further show that acute transition risks can emerge far beyond the short run and last over extended periods, both for Banks and non-Banks. It highlights that the transition

dynamics can prompt periods of financial fragility. However, our results suggest that financial low-carbon transition risks are reduced except for very adverse scenarios and that adequate regulatory efforts may not represent a brake on transition dynamics.

We further show that SSPs affect results in two ways. SSPs implying more rapid reductions in carbon intensity are more prone to “green bubble” patterns because they give an advantage to Incumbent high-carbon technologies. Indeed, they reduce the profitability and financial viability of new, disruptive low-carbon projects. Furthermore, high-carbon reduction dynamics interact with growth assumptions. SSPs with rapid carbon intensity reductions and high growth exacerbate green bubble patterns by putting more investment pressure on green technologies. In contrast to the *ex-ante* assumption they embed, SSPs with higher obstacles to mitigation in their narrative do not necessarily entail more adverse outcomes on financial variables. This feature emerges notably because of more favourable growth assumptions, higher growth allowing financial agents to grow away from financial disturbances.

Our paper speaks to various literatures. We first expand the methodology of long-run climate stress tests (NGFS 2022; ECB/ESRB Project Team on climate risk monitoring 2022; Vermeulen et al. 2021; Fazekas et al. 2021) by increasing the number of scenarios explored in transition risk assessments. Furthermore, as in Daumas (2022) (Chapter 2), we explicitly account for the interaction between the financial sector and the ongoing low-carbon transition by modelling financial agents’ behaviour along the transition path. Only very few papers belonging to the stock-flow consistent (Monasterolo and Raberto 2018; Gourdel, Monasterolo, Dunz, et al. 2022; Dafermos, Nikolaidi, and Galanis 2018) and agent-based (Lamperti, Dosi, et al. 2018; Lamperti, Bosetti, et al. 2019) literatures have carried out this endeavour.

We also relate to this former literature by deploying a stock-flow consistent model of decarbonisation trajectories. Stock-flow consistent and agent-based models have been applied to physical (Lamperti, Bosetti, et al. 2019) and transition risks (Dafermos, Nikolaidi, and Galanis 2018; Dafermos, Monserand, and Nikolaidi 2022; Gourdel, Monasterolo, Dunz, et al. 2022). However, to our knowledge, stock-flow consistent

and agent-based models have yet to be used to simulate fully-fledged decarbonisation scenarios. Our model is dedicated to this purpose and examines low-carbon transition risks along existing decarbonisation scenarios.

We finally call out to the broader Energy-Economy-Environment integrated assessment literature. We do so first by building on the large variety of scenarios it has produced and by applying them to research questions outside the focus of the community. Typical IAMs do not incorporate a financial sector (Keppo et al. 2021) and cannot provide relevant metrics for the study of low-carbon transition risks, leading to many calls to bridge this gap from the research community (Battiston, Monasterolo, Riahi, et al. 2021; Keppo et al. 2021; Mercure, Knobloch, et al. 2019). We take on this research agenda by directly tying links between decarbonisation scenarios and methodologies amenable to studying transition risks.

Our paper is structured as follows. Section 1 reviews the literature in more detail to motivate our approach further. Section 2 briefly describes the model we will deploy for our analysis. Section 3 discusses our simulation approach, while Section 4 presents our indicators of interest. Section 5 presents our results before we conclude.

1 Literature review and motivation

Transition risks have given birth to a rapidly developing literature, prompting many theoretical and methodological innovations (see Daumas 2023, Chapter 1 for a review). Notably, “climate stress tests” of various flavours (Cartellier 2022) have emerged as the workhorse methodology to explore transition risks. Facing deep uncertainty regarding the modalities of the transition — technological change (Grubb, Drummond, and Hughes 2020), climate policy implementation (Batten, Sowerbutts, and Tanaka 2016), and consumer preference shift (Semieniuk, Campiglio, et al. 2021), these climate stress tests have relied on scenario-based approaches to study short- or long-run transition risks. Because this paper deals with whole transition pathways, we focus on the research focused on the latter. The related literature is divided into

three main strands.

The more traditional integrated assessment modelling literature has mainly studied transition risks through the lens of asset stranding. Based on various decarbonisation scenarios, these studies have primarily consisted in quantifying the financial losses incurred by high-carbon non-financial companies along the transition path. They usually reach significant potential losses in balance sheet losses due to premature decommissioning (Fisch-Romito et al. 2021) or foregone profits (Mercure, Pollitt, N. R. Edwards, et al. 2018). These losses depend positively on the intensity and delay of climate policies and are lower if agents are supposed to be forward-looking (Daumas 2023). However, because the models used in these pieces of work do not represent the financial sector, the transmission channels from asset stranding to transition risks are not modelled. It calls for using models amenable to stranded assets but including the financial sector (Botte 2019; Hafner et al. 2020; Battiston, Monasterolo, Riahi, et al. 2021; Keppo et al. 2021).

Financial supervisors have proposed approaches to include the financial sector in the analysis. These methods are mobilised in the context of large-scale, data-intensive regulatory exercises. They typically involve several coupled models, usually an integrated assessment model, a macroeconomic model, and a module computing finance-relevant outcomes (*e.g.* T. Allen et al. 2020; Vermeulen et al. 2021). These works include applications of the NGFS methodology based on six overarching scenarios (Bertram, Jérôme Hilaire, et al. 2020) that serve as a reference point for regulators and financial companies (NGFS 2021b; NGFS 2022). These works usually point at relatively low transition risks, even in the case of delayed-action scenarios, concentrated in the years following climate policy's introduction (ECB/ESRB Project Team on climate risk monitoring 2022). In particular, they highlight the incommensurability of physical risks (*i.e.* financial losses due to climate damage) compared to transition risks. Hence a trade-off explicitly favouring fast transitions and aiming for ambitious decarbonisation targets (Carney 2015).

However, these studies come with some limitations. First, although they generate

results relevant to finance and financial instability, the models mobilised in the above do not represent the interactions between the financial sector and the real economy. Financial modules translate transition developments into signals that typically do not feed back onto the economy (see ESRB (2020) for an exception). They, therefore, do not capture the “double materiality” of transition risks, according to which transition pathways are not only exogenously applied to the financial system but are also shaped by the reaction of the financial sector (Chenet, Ryan-Collins, and van Lerven 2021; Gourdel, Monasterolo, and Gallagher 2023). Second, these exercises rely on tools relatively resilient to shocks, which poses identification (T. Allen et al. 2020) and circularity (Borio, Drehmann, and Tsatsaronis 2014) issues. It also reduces relevant transition events to large macroeconomic shocks at one point (Batten, Sowerbutts, and Tanaka 2016), while the low-carbon transition will mostly be about medium-to-long-run structural change (Daumas 2023). Third, these methods do not address the issue of stranded assets (Jacquetin 2021). Finally, regulatory exercises have only made use of a reduced number of scenarios, between three (T. Allen et al. 2020) and six (ECB/ESRB Project Team on climate risk monitoring 2022), depending on whether the authors considered model variants of the same scenario. As noted by Daumas (2023) and FSB and NGFS (2022), such a reduced number of scenarios does not allow us to explore all the uncertainties related to the low-carbon transition and associated risks. In particular, the precise shape of decarbonisation schedules (Daumas 2022) (Chapter 2) or hypotheses about the evolution of the energy mix (Gasparini, Baer, and Ives 2022) can have a considerable influence on the extent of transition risks for the same decarbonisation target.

Some works have used different modelling approaches, notably stock-flow consistent (Dafermos, Nikolaidi, and Galanis 2017; Monasterolo and Raberto 2018; A. Jackson and T. Jackson 2021, among others) and agent-based (Lamperti, Dosi, et al. 2018; Botte et al. 2021) methods. Compared to supervision exercises, these studies rely on more behavioural models, with heterogeneous agents at various degrees of disaggregation. These models build on Schumpeterian and post-Keynesian traditions

that have traditionally emphasised the importance of the financial sector in economic dynamics. They typically include a built-in representation of financial relationships (notably credit contracts) and a representation of the interactions between financial and non-financial companies. They thus represent a promising complement in that they can provide insights into the evolution of financial stocks and the issue of financial instability. These models have mainly explored the effects of financial policies, like green bonds (Monasterolo and Raberto 2018), differentiated capital requirements (Dafermos and Nikolaidi 2021) or shifting consumption patterns (Dafermos, Monserand, and Nikolaidi 2022). Some works tackle the issue of physical risks (Lamperti, Bosetti, et al. 2019) or asset stranding (Botte et al. 2021). However, to the best of our knowledge, these applications have not used existing mitigation pathways (Daumas 2023) or have not focused on achieving climate targets (Gourdel, Monasterolo, Dunz, et al. 2022). They, therefore, do not provide insights into how macro-financial risks could emerge along transition pathways.

This paper intends to bridge the gaps identified above. First, it draws a link between the IAM literature and the transition risk field by considering scenarios from the IAM literature. To do so, it builds on the stock-flow consistent model proposed in Daumas (2022), which is amenable to the simulation of transition pathways achieving a climate target. The model includes a built-in representation of the financial sector and its reaction to sweeping structural changes as the economy decarbonises. We finally apply this methodology to many scenarios and calibrations to explore as many aspects of uncertainty as possible. Through this approach, we intend to pin down the conditions most prone to transition risks and the dependence of expected macro-financial risks on macroeconomic and parameter hypotheses.

2 The model

This study uses the model presented in Daumas (2022) (Chapter 2), FASM-ID (Financial Asset Stranding Model – Instability and Decarbonisation). The model is a

stock-flow consistent framework of structural change dedicated to simulating transition pathways, initially applied to the scenario set provided by the NGFS.

2.1 General model description

FASM-ID is a seven-sectors SFC model of structural change and financial instability calibrated worldwide with a yearly time step. It depicts a process of low-carbon transition and associated macro-financial risks. To do so, it represents the progressive replacement of an Incumbent, high-carbon sector by Challenger companies investing in low-carbon technology. Because they rely on leverage and equity emissions, these sectors have liabilities towards the financial sector. The financial sector first comprises a banking branch that extends loans based on firms' demand. It also includes Non-Bank Financial Institutions (NBFIs) that provide equity finance. The banking sector pays financial incomes to households, which also receive wages in exchange for their labour for firms. An independent investment goods sector, wholly owned by households, provides investment goods. The government levies taxes, provides subsidies, and emits bonds to finance expenses that Banks and NBFIs buy. Finally, the Central Bank fixes the base rate, buys excess government bonds and provides advances to Banks if needed to close their balance sheets. Figure 1 provides a flow chart of the model.

2.2 Key mechanisms for financial instability

The model focuses on low-carbon transition risks implied by asset stranding and structural change along decarbonisation paths. We force the model to follow an exogenous decarbonisation pathway and apply a carbon tax on emitting firms to mimic the effect of climate policy. Decarbonisation emerges through investment in low-carbon capital, the lower utilisation of high-carbon capital, and decommissioning. Decommissioning high-carbon capital is our way to figuring capital asset stranding for firms (Daumas 2023; Caldecott 2017). For simplicity, the Challenger sector is the only one to invest in greenfield low-carbon capital. However, we assume that the

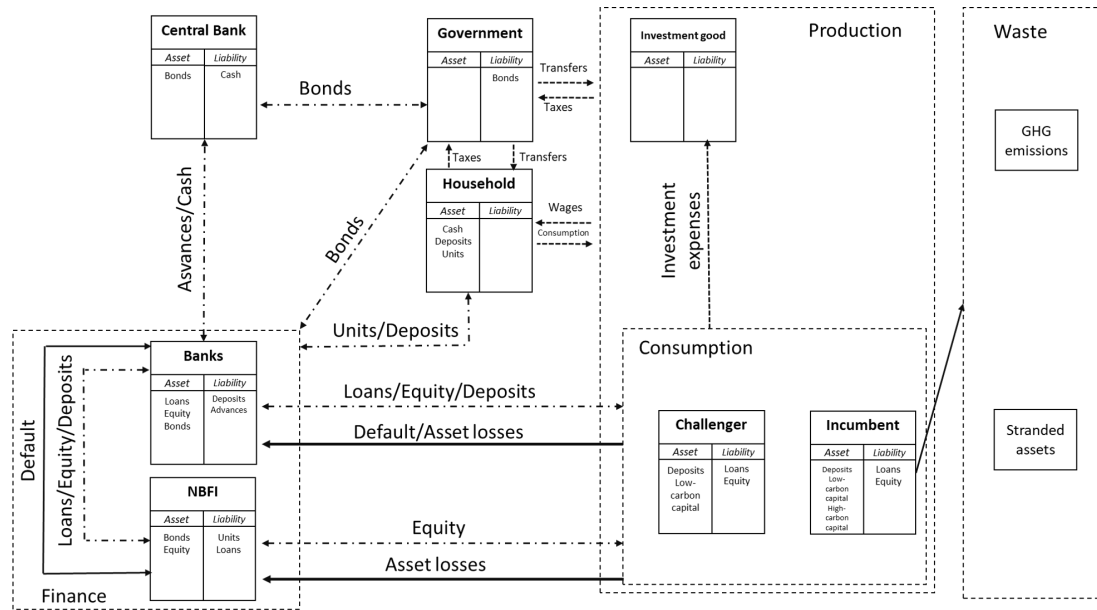


Figure 1: Diagram representation of FASM-ID. Dashed lines represent financial flows, while solid lines highlight transition risk exposures.

high-carbon sector can retrofit part of its capital stock in each period to avoid asset stranding. Figure 2 displays how we simulate the transition in the model.

In the model, financial instability emerges through various channels. Technological displacement will imply a fall in high-carbon firms' proceeds, resulting in a lower ability to pay back loans and, therefore, higher defaults. High-carbon firms will also be affected by asset stranding, which will affect their leverage, increasing the risk premium on their loans and limiting their ability to repay past loans. These mechanisms will affect Banks' balance sheets through their leverage and capital adequacy ratios. The carbon tax will also affect proceeds and firms' ability to repay their loans. Losses in market shares will decrease the demand for polluting firms' equity, limiting further cash inflows. It will also drive equity prices down, affecting NBFI's available liquidity and making their position more fragile. Finally, the model accommodates the possibility of "green bubbles" scenarios. Both the Challenger and the Incumbent sectors being able to invest in low-carbon technology, they must take on additional loans. This increase, in general, may also make their position more fragile due to

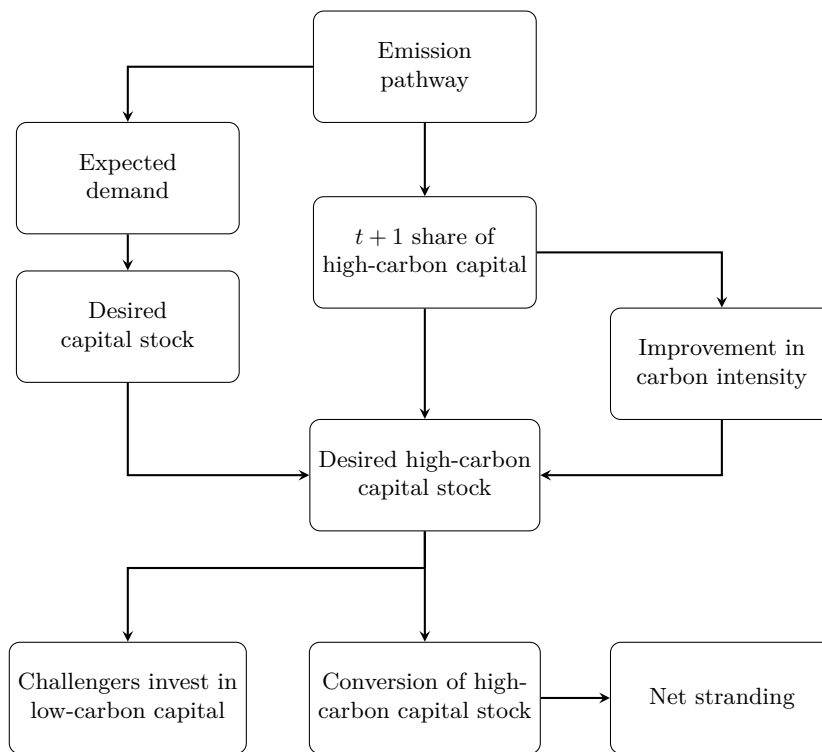


Figure 2: Representation of the transition process in FASM-ID

higher interest rates and if more than additional proceeds are needed to cover loan costs. Figure 3 summarises the main causality channels present in the model.

One important caveat regarding the exogenous application of carbon prices drawn from pre-existing scenarios onto other models should be considered. As noted by IPCC (2022c), the carbon price schedules produced by IAMs should be interpreted more as an overall measure of the climate policy stance and its disruption than as an outright carbon price set by the regulator. In some of these models, such carbon prices are shadow prices as usually encountered in linear programming or may bear little macroeconomic meaning when they are the outcome of partial-equilibrium frameworks such as bottom-up energy models. As a result, although we do consider these carbon prices as actual taxes levied onto polluting firms within the model's framework, it must be kept in mind that this interpretation is extreme, especially for extremely high carbon price schedules (more than US\$15,000 in 2040) as produced

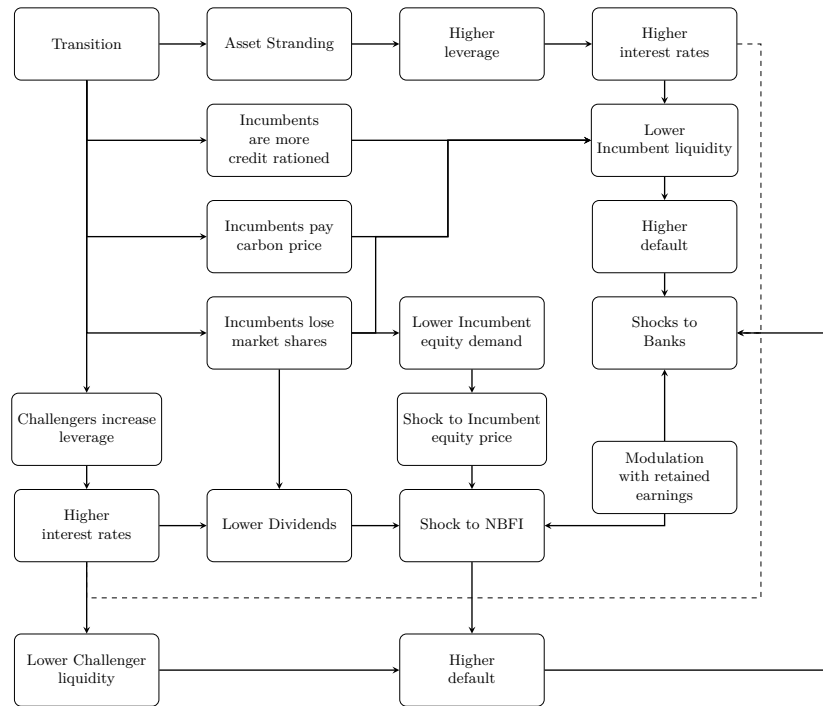


Figure 3: Causality channels to financial instability

by some IAMs. It is especially the case for partial equilibrium, bottom-up IAMs, such as POLES, which do not account for the second-round macroeconomic effects of carbon prices.

3 Simulation approach

Our approach aims to take advantage of the extensive array of decarbonisation scenarios to examine various transition profiles' low-carbon transition risk content. Figure 4 summarises our process.

We calibrate our model to match the five baseline Shared Socioeconomic Pathways regarding emission trajectories and GDP growth. We also make the model match some macroeconomic stylised facts and data not provided within the SSP framework but relevant to studying low-carbon transition risks (1). We then build a database of sensitivity calibrations (around 500 per SSP), which consist of deviations from the

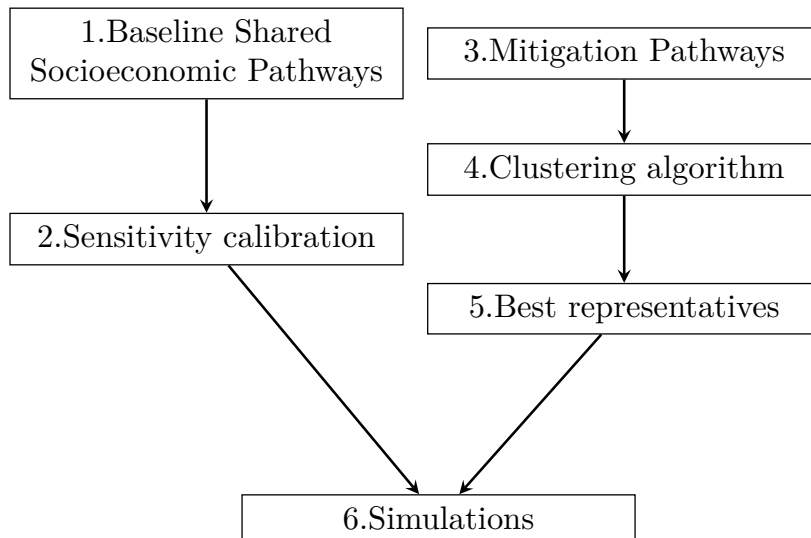


Figure 4: Summary of our simulation process

master calibration that yield similar macroeconomic dynamics. We do this to make for the uncertainty linked to our modelling framework around relevant parameters (2). We consider around 600 MPs from the IPCC database (3). Because some scenarios can be very similar, and to reduce the number of simulations necessary for this research, we use a functional clustering algorithm to group our transition scenarios into clusters with similar decarbonisation and carbon price trajectories (4.). Within each group, we select a “best representative” scenario for our simulations (5). We finally run all the selected scenarios for each macroeconomic world across all sensitivity calibrations and consider a range of well-chosen outcomes relevant to studying low-carbon transition risks (5). We detail each step further in the following.

3.1 Baseline calibrations

We consider the Shared Socioeconomic Pathways (SSPs) to build our baseline calibrations. The Energy-Economy-Environment (E3) integrated assessment literature developed the SSP framework based on the observation that many macroeconomic worlds could correspond to the same decarbonisation pathway or at least the same long-run decarbonisation target (O’Neill, Kriegler, Riahi, et al. 2014). SSPs are thus

broad narratives about the unravelling of the 21st Century. They feature distinct macroeconomic, technological, societal and geopolitical hypotheses, which depend on whether mitigation or adaptation to climate change will be most challenging (see Figure 5). Five scenarios available on the IPCC repository¹ embody the SSPs. Like most scenarios reviewed by the IPCC, the SSPs are high-dimensional objects, with many outcomes drawn from large-scale integrated assessment models (IAMs). Our modelling framework is much more simplified, so we reduce the SSPs to two dimensions.

First, we consider the SSPs' emission schedules and force our model to match them in each period. To do so, we assume that our "Challenger sector" does not emerge in a world without climate policy. Instead, we suppose that the Incumbent sector benefits from an exogenous improvement in the carbon intensity of its production that allows it to match the emission schedule perfectly. This hypothesis allows us to keep tractable baseline values for our primary outcomes and maintain comparability across scenarios.

Second, we consider the mean growth rate between 2020 and 2055 for each SSP and calibrate the model to match it. SSPs also differ in terms of long-run growth assumptions, which we display on Table 2. SSP5, consistently with its narrative, maximises GDP growth at a yearly 4.3% rate on average. SSP1 adopts the second-highest growth assumptions, with 3.1% per year, on the ground that the deployment of low-carbon technologies allows for productivity gains. SSP2 and SSP4 adopt middle-ground assumptions, respectively 2.8% and 2.65% on average, close to existing projections. SSP4 has slightly lower growth due to the unequal development across nations supposed by its narrative. Finally, SSP3 features the lowest growth assumptions due to its narrative based on a lack of international cooperation and centring on national issues at the expense of trade and development. These assumptions are summarised in Table 1.

Unfortunately, SSPs do not provide hypotheses on relevant macroeconomic variables

¹The database can be accessed at : <https://data.ene.iiasa.ac.at/ar6/#/workspaces>.

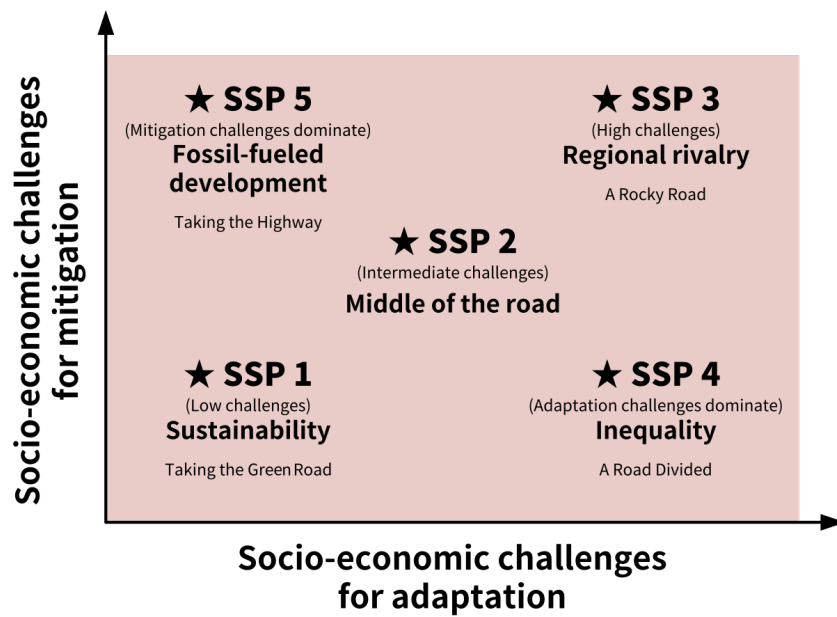


Figure 5: Classification of Shared Socioeconomic Pathways. Borrowed from O’Neill, Kriegler, Ebi, et al. (2017).

like inflation or public deficits. Neither do they *a fortiori* on pertinent metrics to financial low-carbon transition risks. As a result, and to avoid an unnecessary increase in the dimensionality of our exercise, we make the model target the same macroeconomic behaviour for a range of relevant macroeconomic and macro-financial variables as in Daumas (2022) (see Chapter 2 Appendix C.). More details on the calibration values are provided in Appendix B.

3.2 Selection of sensitivity parameters and ranges

The model in Daumas (2022) contains several behavioural parameters that affect the dynamics of transition risks. To make for this dependence on parameters and explore the dependence of transition risks on crucial dimensions of the model, we build sensitivity calibration around the main SSP parametrisations.

To do so, we adopt the same methodology as in Daumas (2022) (Chapter 2) and consider a set of parameters relevant to macroeconomic and financial dynamics. We then

Table 1: Economic growth assumptions embodied in SSPs

SSP	Name	Average economic growth (2020-2050)
SSP1	“Sustainable Development”	3.5%
SSP2	“Middle of the Road”	2.78%
SSP3	“Regional Rivalry”	1.93%
SSP4	“Inequality”	2.64%
SSP5	“Fossil-fuelled development”	4.3%

draw sensitivity intervals around the values retained for the master calibration. We proceed in two steps. We first draw a 90%-110% interval around each parameter and run 10,000 simulations for each master calibration. We retain only simulations remaining sufficiently close to the behaviour of the master calibration, *i.e.*, within a 20% range of the values targeted in the master calibration, depending on the outcome.² We then use a Morris method to determine which parameters affect the probability of retaining a given calibration to help us choose meaningful parameter ranges to select our sensitivity calibrations. For the most critical parameters, we adopt 95%-105%. We choose a 70%-130% range for all other parameters, a reasonable range found in other sensitivity analyses (P. Jacques et al. 2023). These differentiated parameter ranges intend to explore a breadth of values to make our sensitivity analysis more robust while allowing us to constitute a large enough sample of sensitivity calibrations. Appendix B. provides the value ranges for our parameters of interest.

We then use these ranges to sample parameter sets through Latin Hypercube Sampling and run simulations until we retain at least 1,000 sensitivity calibration for each SSP. 25,000 simulations were required. In the end, we ended up with a database of around 1,000 calibrations across our SSPs. To obtain a balanced dataset in the following, we draw a random 500 calibration per SSP, consider the mean trajectory for each outcome, and compute the corresponding variance. The importance of parameter variations will be assessed in Appendix. Each of these calibrations will be used as a baseline to simulate representative MPs that we take from the IPCC database.

²This tolerance margin was chosen as compromise between not drifting too far from the master calibration and exploring meaningful range of parameter values.

3.3 IPCC Scenarios and selection

The Working Group III IPCC (IPCC 2022c) reviews a wide range of decarbonisation scenarios provided by the IAM E3 literature. It synthesises their insights to inform policy choices regarding climate change mitigation. These scenarios are submitted to the IPCC by modelling teams from well-established institutions, ranging from the International Energy Agency (IEA) to specialised research labs (PIK, PNB...). Scenarios are specific to the institution or part of multi-model programmes such as intercomparison exercises.

The IPCC makes all these scenarios and their relevant outcomes publicly available, and we take advantage of this large scenario repository (Byers, Edward et al. 2022). The database features around 1,500 scenarios, simulated by approximately 20 different models. Among all these scenarios, about 800 are scenarios featuring emission pathways compatible with 1.5°C to 2°C global warming. These scenarios all feature some climate policies synthesised with a carbon price schedule. Hence, this “carbon price” variable should not be interpreted as a putative carbon price path; instead, it is a general measure of the intensity of climate policies necessary to achieve the climate objective.

As in the case of SSPs, IAM-generated scenarios are highly dimensional objects that we cannot fully reproduce with our simplified model. Therefore, reducing these scenarios to their emission trajectories³ and carbon price paths allows us to explore how the shape and pace of decarbonisation dynamics and the intensity of climate policies affect transition risks. Unfortunately, some IAMs used by the IPCC suite, or some scenarios focused on regional dynamics, do not provide a straightforward measure of a “carbon price” at the world level that we need as a model input for our simulations. To avoid any mismatch, we dropped all of those scenarios from the database and ended up with a sample of 584 decarbonisation scenarios.

To reduce the dimensionality of our problem, we propose a classification of decarbonisation scenarios based on the profile of their emission schedules and their carbon

³Since our model does not feature negative-emission technologies, we build gross emission series.

price path to select “best representatives” within the IPCC database. To do so, we apply a functional clustering method. Functional clustering is the time-series equivalent of traditional clustering, whereby a data scatter is gathered into groups with similar characteristics. Functional clustering fulfills the same goals by grouping curves based on shape and level. Several methods exist, ranging from the depreciation of well-chosen measures (Ieva et al. 2013) to more complex likelihood maximisation algorithms based on the decomposition of curves into well-defined essential components or “splines” (Bouveyron and J. Jacques 2011). This paper uses the funHDDC algorithm proposed by Schmutz et al. (2018), based on likelihood maximisation and spline decomposition. We chose this algorithm first because the spline-decomposition method is better at capturing the dynamic profile of curves, which is crucial for our purpose. Second, a comparison exercise proposed by J. Jacques and Preda (2014) showed that funHDDC performed very well on curves with relatively monotonic behaviours, such as emission and carbon price schedules (see Schmutz et al. (2018) for more precision on funHDDC).

funHDDC supports bivariate clustering. As a result, we could have directly clustered MPs according to their emission and carbon price paths. We applied this method in the first instance. However, it resulted in a relatively low number of representative scenarios. We, therefore, used a two-step approach and clustered scenarios first by their emission schedule and then, within each emission cluster, based on the corresponding carbon price profiles. We chose to cluster by emission first to emphasise the importance of the emission reduction target in the design of scenarios, carbon prices usually being outcomes of the simulations. Also, it seemed more meaningful to first categorise scenarios based on the policy target and then classify them based on the policy intensity necessary to achieve each target.

This process yields 50 clusters. To select the best representative amongst each of them, we first consider an abstract “mean curve” for each cluster within the (Emission, Carbon Price) space, which we obtain by taking the mean (Emission Carbon Price) couple at each point in time between 2020 and 2055. For each scenario, we

compute its distance⁴ to the mean curve and consider the scenario closest to the mean curve the best representative. This process leaves us with 50 “best representatives” of the IPCC dataset. Because they are provided at a 5-year time step, we interpolate them to a yearly time step to make them consistent with our model’s term structure.

3.4 Simulations

We implement this methodology through Python. For each SSP-Scenario couple, we start by solving the model to make it fit the emission schedule of the scenario with the master calibration. We proceed in two steps. We first solve for the development path of low-carbon energy compatible with the emission trajectory. For this purpose, we implemented a gradient descent method minimising the cumulated squared deviation from the reference trajectory.

Our algorithm was not able to converge for all our sensitivity calibrations.⁵ Therefore, our final dataset is not composed of precisely 125,000 simulations ($50 \times 500 \times 5$) but of around 100,000 simulations across SSPs, sensitivity calibrations, and decarbonisation scenarios. The following section discusses the different outcomes we will consider and how we relate them to SSPs and decarbonisation scenarios.

4 Outcomes and indicators

Given the many scenarios we consider and the many possible outcomes our model can yield, we synthesise our results and relate them systematically to our inputs. We start by depicting how we classify SSPs and our MPs with *ex-ante* measures of transition risks. We present our outcomes of interest, which will measure *ex-post* transition risks, *i.e.* the “actual” realisation of transition risks and financial instability potentials after the scenario is simulated.

⁴We consider a square norm normalised by standard errors at each point in time.

⁵In particular scenarios 1 (POLES-ENGAGE, EN_NPi2020_600) and 35 (EN_INDCi2030_600f) are highly stringent scenarios with the two highest carbon price schedules and were very difficult to simulate. Only 250 simulations are available for these two scenarios.

4.1 *Ex-ante* transition risk measures

To study our database, it is first helpful to draw an *ex-ante* classification of SSPs and MPs. Because we study many scenarios, it is essential to distinguish between scenarios expected to contain high transition risks and those implying *a priori* milder disruptions. This subsection depicts how we distinguish between scenarios and SSPs regarding *ex-ante* transition risk content.

4.2 Mitigation Pathways

The IPCC usually ranks scenarios based on their climate target, *i.e.*, whether a scenario implies emissions consistent with a 2°C, 1.7°C or 1.5°C warming at specific dates or with a peak temperature at certain periods. However, this ranking is insufficient for our exercise for two reasons.

First, among our 50 best representatives, multiple scenarios correspond to the same or similar climate targets. There is a need to differentiate between scenarios adopting, *e.g.*, a monotonous decarbonisation schedule and those exhibiting more staggered mitigation dynamics. For instance, as put forward by the NGFS (2022), delayed-action scenarios, which can feature very high decarbonisation rates over short timespans, can be expected to be riskier than early-action ones.

Second, our dataset features many different carbon price paths. Similar decarbonisation schedules may be achieved with more or less steep or staggered carbon price paths. Those with more severe (or suddenly more stringent) climate policy should be classified as riskier *ex-ante* than those with less stringent measures.

To differentiate across scenarios, we build a series of five indicators summarising the decarbonisation and climate policy profiles of our scenarios:

- “Decarbonisation Intensity” defined as ratio the between emissions in 2020 and emissions in 2050:

$$D_{Int} = \frac{Em_{2020}}{Em_{2050}}$$

- “Decarbonisation Steepness” measures the “staggeredness” of decarbonation dynamics. We define it as the absolute value of the maximum period-to-period decarbonisation rate over 2020-2055, which corresponds to the minimum growth rate of emissions – which can be negative – over the period:

$$D_{Steep} = 100 \times \left| \min_{i \in [0:6]} \frac{Em_{2020+5(i+1)} - Em_{2020+5i}}{Em_{2020+5i}} \right|$$

- A measure of “Climate policy stringency”, *i.e.*, the increase in the carbon price between 2020 and the peak value of the carbon price. We consider the peak value and not the value in 2055 to make for non-linear carbon price paths that our scenarios may exhibit. We consider a log scale due to possibly very high carbon price values.

$$CP_{Str} = \log \max_{i \in [0:6]} \frac{CP_{2020+5i}}{CP_{2020}}$$

- An indicator of “Climate Policy Steepness”, measuring the “staggeredness” of climate policy implementation, that we write as the maximum period-to-period carbon price increase rate over 2020-2050. We also consider a log scale.

$$CP_{Steep} = \max_{i \in [0:6]} \frac{CP_{2020+5(i+1)}}{CP_{2020+5(i)}}$$

- The “Start of the transition”, namely the year of peak emissions:

$$Peak = \max_{i \in [0:6]} Em_{2020+5i}$$

The higher these indicators, the more transition risks a scenario contains *ex-ante*. For instance, a very ambitious climate target (high D_{int}) would require more sweeping change than transitions aiming at lower targets. Likewise, a transition with an overall higher carbon price schedule is riskier *ex-ante* than a pathway with a lesser climate policy stance.

⁶Some scenarios feature a zero carbon price at the beginning of the transition; in such cases, we considered the growth rate between the first non-zero carbon price and the prevailing price in 2050.

Figure 6 summarises the profile of each of our 50 best representatives along each of these dimensions. For readability, we display three graphs. Panel (a) displays emission trajectories, while Panel (b) describes carbon price paths. Panel (c) displays the profile of each trajectory along our five dimensions in the form of a parallel coordinate chart.

Regarding decarbonisation dynamics, our population of trajectories gathers a wide variety of decarbonisation intensities. Regarding decarbonisation steepness, our selection comprises a mass of scenarios spanning values between 10 and around 35% decarbonisation rates. Then, a population of more extreme methods exhibits period-to-period decarbonisation rates between 40% and about 70%. Although there is a clear correlation between Decarbonisation intensity and Decarbonisation steepness for most scenarios, some representatives can exhibit high steepness for modest decarbonisation targets. Panel (a) offers a more detailed view of decarbonisation dynamics along our transition paths by allowing us to grasp the precise shape of the decarbonisation schedule, which can be more or less concave, convex, sigmoid, or linear.

As for climate policy, the gradient is much broader across our scenarios, reflecting the significant uncertainties around the intensity of climate policy necessary to achieve decarbonisation targets (IPCC 2022c). Strikingly, scenarios with mild targets can exhibit very high carbon prices in the long run, with up to eight-fold increases between 2020 and the climate policy peak. Conversely, ambitious targets could be achieved with low carbon price paths. The same goes for the steepness of the ramping up of climate policies, with up to a five-fold increase in the climate policy stance in five years. Similarly to Panel (a), Panel (b) offers a more detailed view of carbon price paths. In particular, one of our scenarios exhibits a non-monotonous path, with a peak carbon price in 2040.

Finally, most of our scenarios imply transitions starting in 2020. Around five scenarios indicate slightly delayed transitions, beginning in 2025, while only one starts in 2030. This imbalance between early-start transitions and a more delayed course of events translates the relative novelty of these kinds of scenarios and related research

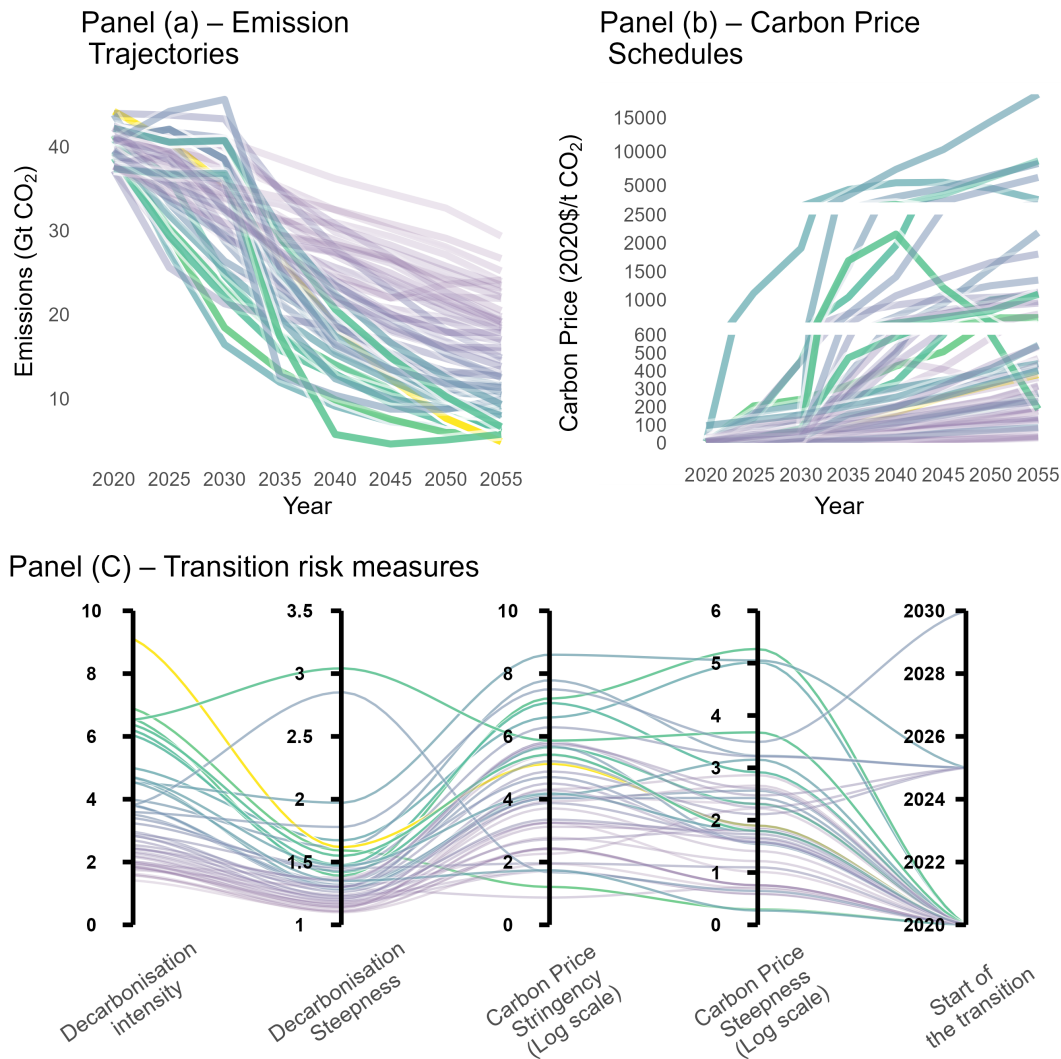


Figure 6: *ex-ante* transition risk profiles of the best representatives of our 50 clusters. Colors are indicative, and set according to the Decarbonation Intensity indicator.

questions, such as the issue of disorderly transitions due to the late and sudden introduction of climate policies (Batten, Sowerbutts, and Tanaka 2016; NGFS 2022).

Our scenarios will also vary regarding transition risks according to their underlying macroeconomic assumptions. Hence, we must discuss the *ex-ante* transition risk content of the five SSPs we take as base calibrations. In particular, a rough ranking of each SSP in terms of *ex-ante* transition risks will be helpful to facilitate the

interpretation of results.

4.3 Ranking the Shared Socioeconomic Pathways

We rely on the classification provided by the IPCC (O'Neill, Kriegler, Riahi, et al. 2014) that we summarise in Figure 5. SSPs rank according to the challenges they pose to mitigation and adaptation. For instance, SSP5 is a challenging state of the world regarding mitigation, as it assumes an accelerated development of fossil fuels to maximise GDP growth. Hence, very high emission levels hamper the achievement of climate targets. By contrast, SSP1 represents a future in which technology and societal developments will feature the penetration of low-carbon technologies and a commitment to sufficiency. It is usually seen as the least challenging course of events regarding transition dynamics. For our purpose, we are primarily interested in challenges to mitigation. Within the SSP framework, they are well proxied by emissions. Figure 7 shows the different emission profiles for the various SSPs.

Using baseline emissions as a measure of mitigation challenge, SSP1 is a state of the world in which low-carbon transition risks are lowest, while SSP5 are highest. SSP3 exhibits the second-highest mitigation challenges, as per Figure 5. SSP4 and SSP2 are more difficult to disentangle, given the quantitative proximity of their emission schedules. Challenges to mitigation differ through time, with SSP4 implying faster emissions in the short run but less in the longer term than SSP2. However, the traditional SSP classification shown in Figure 5 ranks SSP2 above SSP4 in terms of challenges to mitigation. We, therefore, follow these guidelines. Table 2 summarises our ranking of SSPs, which also recalls the average growth assumptions matched in each SSP.

4.4 *Ex-post* transition risk measures

As in Daumas (2022), we first distinguish market and credit risk. Market risks concern asset prices and have an impact, within our model's structure, on Non-Bank

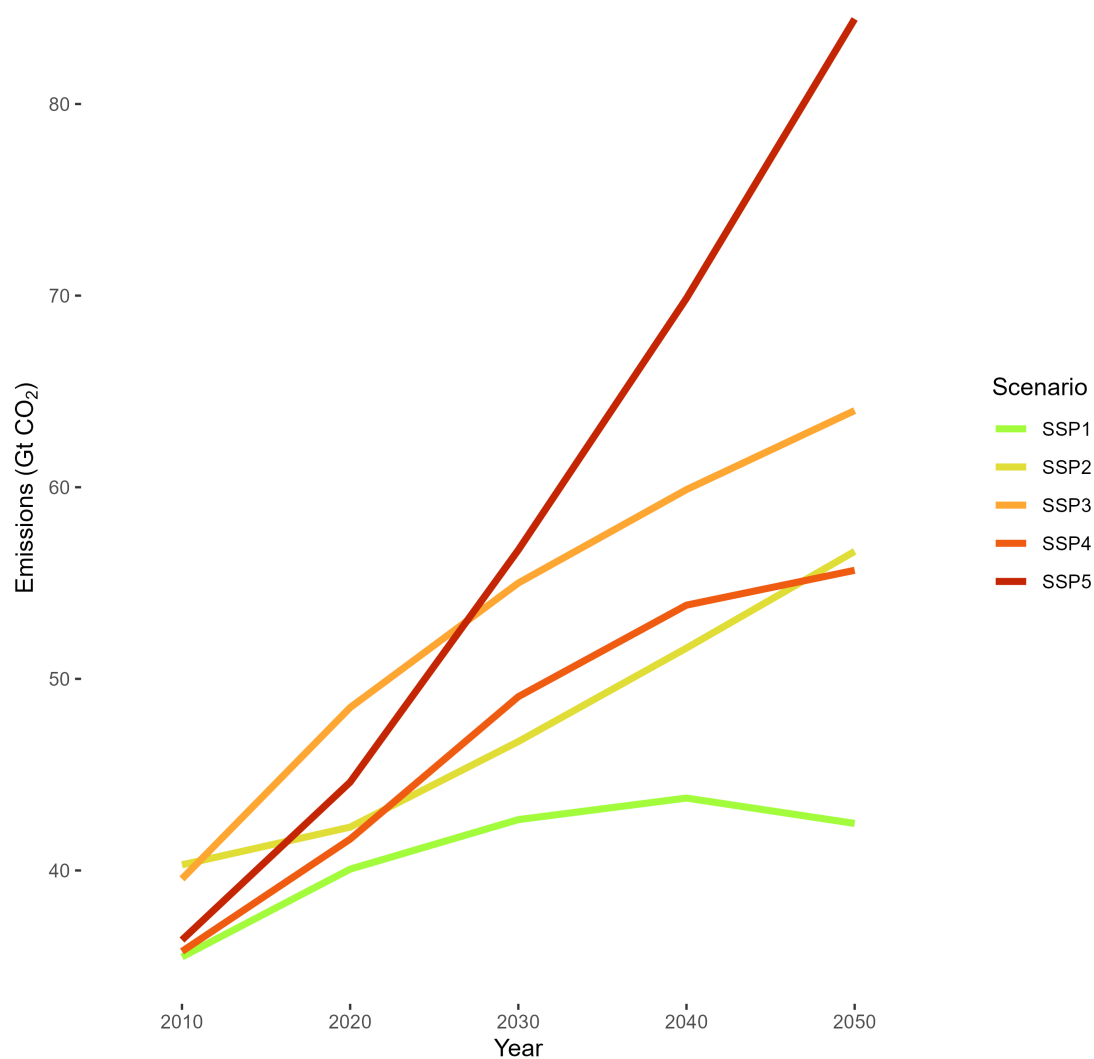


Figure 7: Emission trajectories of Shared Socioeconomic Pathways (No-Policy Baseline). Color indicates SSP. Different starting points are due to differences in marker models used to generate the baselines.

Financial Institutions. Credit risks, by contrast, transit through defaults on credits and will affect the viability of Banks' balance sheets.

We further separate transition risk realisations and vulnerability to transition risks. The first category concerns the financial shocks incurred by the non-financial sector due to technological displacement and climate policies. The model primarily

Table 2: Ranking of Shared Socioeconomic Pathways

Rank	SSP	Label	Average Growth Rate	Challenge to mitigation
1	SSP5	“Fossil-fueled Development”	4.3%	Very High
2	SSP3	“Regional Rivalry	1.9%	High
3	SSP2	“Middle of the Road”	2.8%	Medium
4	SSP4	“Inequality”	2.65%	Medium
5	SSP1	“Sustainability”	3.5%	Low

Notes: The ranking is by decreasing order

represents them through lower equity prices regarding market risks and higher default propensities. Transition risk vulnerability, on the other hand, sheds light on how realisations affect the financial sector. Indeed, the financial sector may navigate seemingly dire transition risk realisations if it can absorb shocks. For the current study, given its high dimensionality, we focus primarily on transition vulnerability indicators. In contrast, we will only discuss transition risk realisations to explain the patterns we find for transition vulnerability.

We use 11 indicators to study the financial sector’s vulnerability to transition risks and divide them into two types. Across our sensitivity calibrations, we consider the average across simulations. We also consider a dispersion measure, discussed in Annex C.1. To correct for outliers, notably in computing the dispersion measure, we use the Winsorised mean at 95%.⁷

4.4.1 Magnitude Indicators

We first use *magnitude* indicators, which indicate the size of macro-financial shocks in terms of market and credit risk. For market risks, we consider the maximum default probability of NBFIs over the time horizon. Although it more exactly designates the financial counterparty risk associated with NBFIs, it is a direct translation of NBFIs losses on financial markets. We thus adopt this denomination for convenience. The market risk indicator ρ_M thus writes:

⁷This method only affects the mean marginally, such that results in Section 5 are not different from using a non-Winsorised mean.

$$\rho_M = \max_{2020-2050} \varphi_{NBFI_t}.$$

For credit risks, we consider a similar indicator relating the minimal Capital Adequacy Ratio (CAR) obtained over the time horizon to the baseline value. In all our calibrations, the Capital Adequacy has a value of 0.18. Hence, we define the credit risk indicator ρ_C as:

$$\rho_C = 100 \times \frac{\min_{2020-2050} CAR^* - \min_{2020-2050} CAR}{\min_{2020-2050} CAR^*} = 100 \times \frac{0.18 - \min_{2020-2050} CAR}{0.18}.$$

Since the CARs we obtain are capped at 18%, the indicator lies within $[0, 100]$, with 0 denoting an absence of shock and 100 a full-blown financial crisis.

This indicator is nonetheless partial in that it does not allow determining whether shocks to Banks are due to an increase in default probabilities in the Incumbent polluting or the Challenger low-carbon sector. Although the literature has more focused on transition risks arising from asset stranding and losses in high-carbon sectors, our model can also, in principle, give rise to “green bubbles” dynamics, whereby low-carbon companies would spur instability due to high leverage (Nikolaïdi 2017). We, therefore, build two complementary indicators gauging the maximum default probability in the Incumbent (ρ_{IN}) and the Challenger (ρ_{CH}) sectors along the run.

4.4.2 Timing indicators

A second range of indicators explores the timing of shocks to the financial sector. For credit risk, we measure the length of the (longest) period over which credit or the market risk indicator deviates from the value of 0.18 and reaches the minimum and the time step with the minimum credit risk indicator. We provide similar indicators for market risk but measure the period over which NBFI default probability is above

average. These indicators allow us to determine whether shocks to the financial sector are short-lived or if a whole period of financial fragility emerges during the transition. It also indicates the timing of transition risks related to the start of the transition. We also compute these indicators for the Incumbent and the Challenger. With these definitions, the length of the high transition risk period will be centred around the period at which the apex of the measured risk is reached.

Whether disturbances emerge as a one-period, short-lived shocks bear distinct implications to a situation where financial troubles prevail over long hauls, even if the magnitude of related shocks is lower. Furthermore, it is usual in the transition risk literature to focus on transition risks in the short run, *i.e.*, immediately following the implementation of low-carbon policy (Semieniuk, Campiglio, et al. 2021) or the emergence of new technology (Vermeulen et al. 2021). By contrast, transition risks resulting from the build-up of imbalances at the macroeconomic level, in the spirit, *e.g.*, of Godley (2012), are relatively under-explored (Daumas 2023). Hence, timing indicators can provide insights into the time profile of longer-run transition risks. Table 3 summarises our set of indicators.

5 Results

We discuss here the main takeaways of our analysis. All results are values averaged across our sensitivity calibrations, with corresponding variances displayed when relevant.

5.1 Overview of transition risks

We start with an overview of the results in Figures 8 and 9. These scatterplots display, for all SSPs, our measures for firm and financial risks in a locus, with indicative thresholds for high risks.

Starting with firm risks, a sizeable proportion (73.6% across SSPs) of our best representatives implies low firm risks. For Incumbents or Challengers, high firm risk

Table 3: Indicators

Indicator	Notation	Description
Magnitude		
Market risk indicator	ρ_M	Maximum NBF1 default probability over the scenario
Credit Risk indicator	ρ_C	Maximum Absolute deviation from 18% CAR over the scenario
Incumbent fragility	ω_{IN}	Maximum Incumbent default probability
Challenger fragility	ω_{CH}	Maximum Challenger default probability
Timing		
Market risk year	L_M	Length of period around market risk apex
Credit risk year	L_C	Length of period around credit risk apex
High market risk period	T_M	Time step of maximum market risk
High credit risk period	T_C	Time step of maximum credit risk
Incumbent Risk Year	T_{IN}	Time step of maximum Incumbent default probability
Challenger Risk Year	T_{CH}	Time step of maximum Challenger default probability
High Incumbent risk period	T_{IN}	Length of period around Incumbent risk apex
High Challenger risk period	T_{CH}	Length of period around Challenger risk apex

only emerges for a relative minority of scenarios. Some 17.2% of best representatives across SSPs carry high Incumbent risks only, while a tiny minority (3.2%) carry high Challenger risks only. Finally, a small scenario population has high Incumbent and Challenger risks (6% of the sample).

Furthermore, this figure highlights a relative dependence on the underlying SSP assumptions. SSP5 and SSP3 carry the highest risk for Incumbents, with SSP5 exhibiting the lowest risks for the Challenger. SSP2 and SSP4 show a middle-range pattern, with lower Challenger risk for the SSP4. Finally, SSP1 shows the lowest Incumbent risks and the highest Challenger risks for extreme scenarios and occupies a middle ground for low-risk scenarios.

This difference in pattern between SSP1 and SSP5 flows from our definition of SSPs. First, because, in SSP1, the Incumbent's carbon intensity decreases rapidly, the Challenger sector develops less and does not fully evict the Incumbent sector. Furthermore, asset stranding is lower in the Incumbent sector, reducing expansion potentials for the Challenger and available funding. As a result, in stringent scenarios where investment in low-carbon capital is high, the Challenger sector is more financially fragile than the Incumbent. The opposite goes for SSP5, in which the Incumbent sector is more penalised due to slow improvements in carbon intensity. This result illustrates the importance of competition between emerging low-carbon intensity

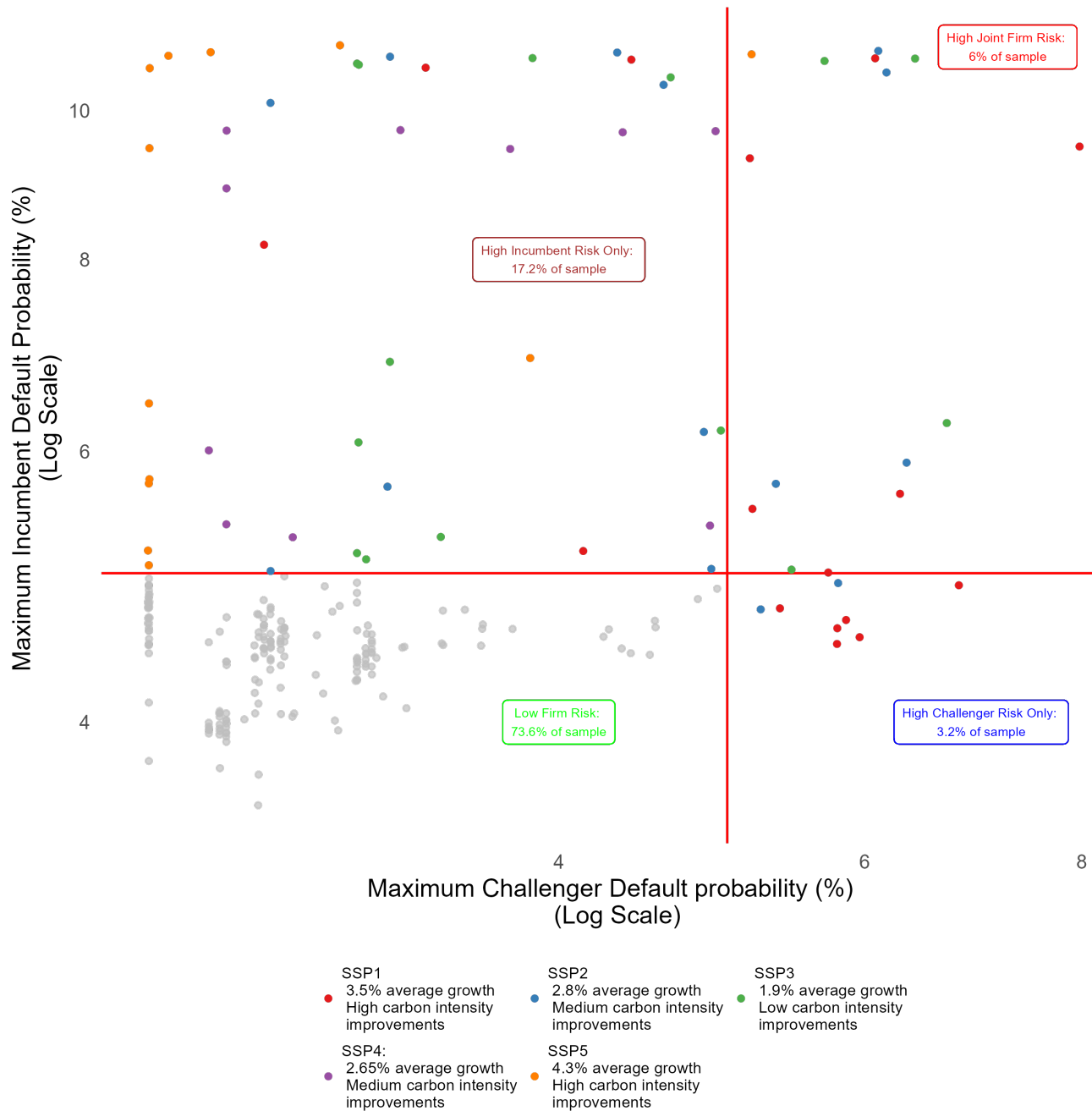


Figure 8: Overview of transition risks –Non-Financial Sector. Colors indicate the underlying SSP. The thick red lines are indicative risk thresholds. Only values beyond the thresholds are highlighted. The SSP characteristics are recalled for clarity. Take care of the log scale on both axes.

and Incumbents that may partially adapt to the transition in driving firm risks. A situation in which Incumbents can keep significant market shares can penalise the emergence of new activities which may generate dynamics similar to “green bubbles” (Borio, Claessens, and Tarashev 2021).

On the other hand, letting the Challenger develop will affect sunset activities. SSP5 implies very high growth rates, around 4.2% per year, more than 25% higher than those prevailing under SSP1. As shown in Daumas (2022) (Chapter 2), growth can benefit Banks’ capital adequacy ratio by allowing firms to grow away from financial fragility. Given the Keynesian aspect of our model, this aspect may largely compensate for losses incurred by the financial sector. SSPs also differ in terms of average growth rates. This feature also affects results. SSP3 exhibits relatively high risk for both Challengers and Incumbents because of its low growth rates and modest carbon intensity improvements. On the other hand, for low-risk scenarios, the high growth rates of SSP5 allow the Challenger sector to develop with low risks.

Finally, carbon intensity improvements and growth rates interact, as illustrated by SSP2 and SSP4. These two SSPs carry relatively similar growth rates but with different carbon intensity improvements, concave for SSP2 and convex for SSP4, as per Figure 7. SSP4 carries relatively lower risks than SSP2, suggesting that long-run improvements to carbon intensity are more beneficial than in the short run. Furthermore, the lower growth rate in SSP4 may shield the Challenger sector from the rapid (and risky) development that would prevail in higher-growth scenarios like SSP1.

All this translates differently into financial risks, as shown in Figure 9. Credit risks are overall very low across best representatives, ranging between 1 and 3%, with a relatively high dispersion across SSPs. This behaviour is consistent with the results shown in Daumas (2022) (Chapter 2), whereby Banks are relatively resilient to transition risks for low- firm-risk scenarios. However, a small population of scenarios (around 10%) exhibit very high credit risk. These risks come with high market risk. Market risks are more spread upwards, consistent with the results in Daumas (2022)

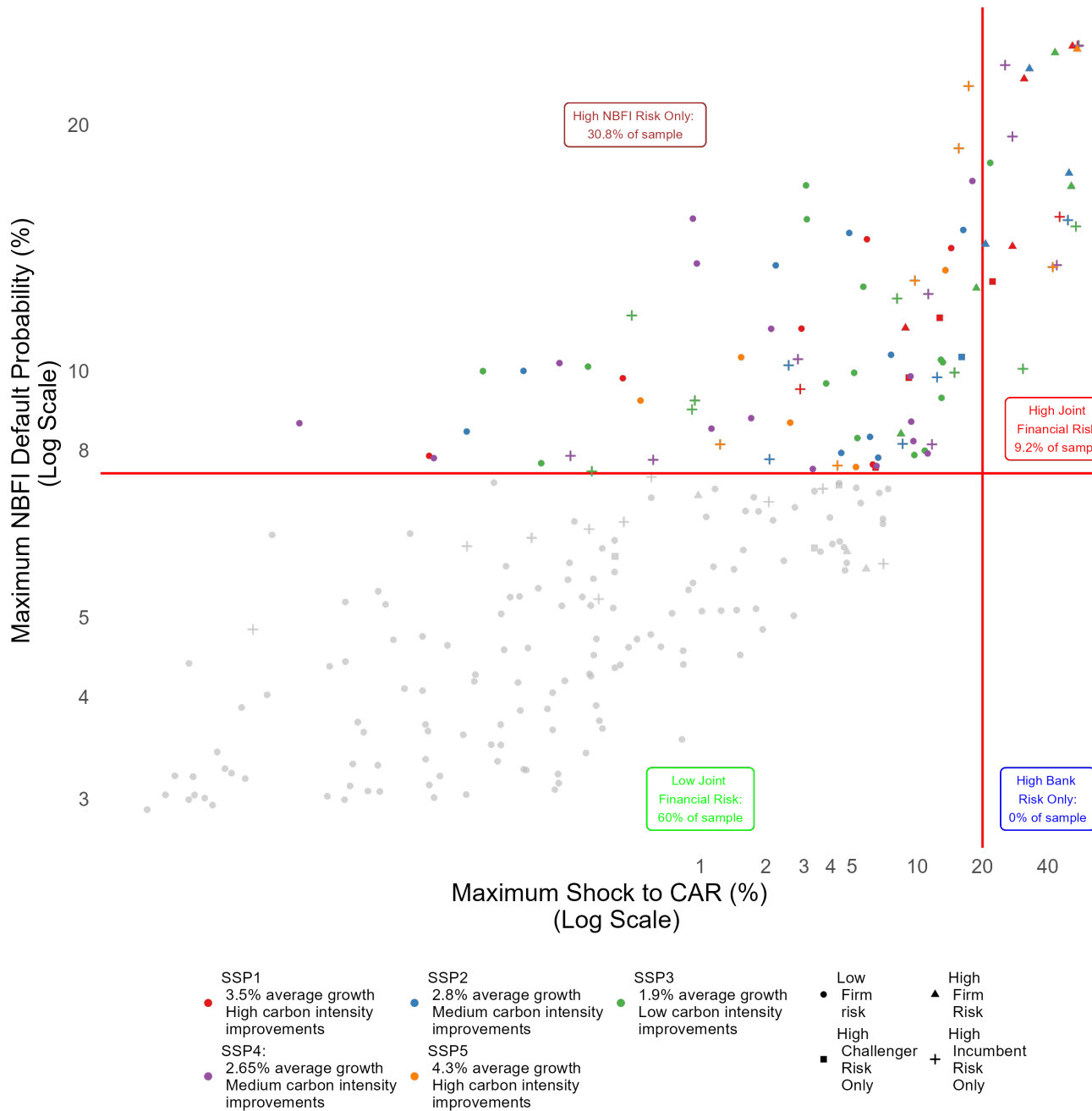


Figure 9: Overview of transition risks –Financial sector. Colors indicate the underlying SSP. Shapes denote whether scenarios are in the higher quadrants of Figure 8 and provide a view of the overlap between the two figures. The thick red lines are indicative risk thresholds. Only values beyond the thresholds are highlighted. Take care of the log scale on both axes.

(Chapter 2), and more dispersed across scenarios than credit risks. A relatively large population of scenarios stand above the indicative threshold of 10%, showing the higher fragility of NBFIs in the model. We also see, overall, a general correlation between market and credit risks, which may suggest the presence of amplification effects.

There is a high degree of overlap between Figures 8 and 9, with a sizeable share of scenarios in the high firm risk quadrants found in the high financial risks zones. However, the source of high financial risks can differ across scenarios. While Incumbent risk seems to drive financial risks in most cases, some scenarios associate high Challenger risk and high financial risk. Hence, financial risk can emerge both from sunrise and sunset industries alike, depending on the scenario.

Finally, it is noteworthy that many high-risk scenarios neither feature high Incumbent nor Challenger risk. This is attributable to two elements. First, the source of financial risks comes more from changes in asset prices. The latter can fall even if default probabilities do not increase much because loans are repaid before dividends, whose level directly affects the attractiveness of equity investment and thus asset prices through lower demand for equity. Second, like in Chapter 2, for credit risk, shocks to CAR can also emerge in case of rapid Challenger development alone through a transitory increase in Banks' exposures. Finally, conversely, some high firm risk scenarios do not necessarily translate into high financial risks: like in Chapter 2, the financial sector can absorb shocks under some circumstances.

A first important takeaway from our results is that from the standpoint of firm and financial risks, there is a large proportion of MPs with low or medium transition risks, representing "feasible" scenarios from the perspective of financial instability. Yet, the population of problematic scenarios is far from anecdotal. It begs us to examine the characteristics of these scenarios compared to their less risky counterparts. Furthermore, interestingly, our results only partially match our *ex-ante* ranking of SSPs based on their transition risk content. Because we assume a Challenger-Incumbent structure to depict the low-carbon transition, SSPs advantaging the Incumbent rel-

atively more can carry significant risks. Because the Challenger needs to develop, it represents an ever larger share of financial institutions' exposures. If the sector is more fragile, it results in higher NPLs and more significant asset losses. Given that SSPs advantaging the Incumbents exhibit higher credit risks on average, it suggests that, for this type of risk, slowing down the development of new activities, or protecting Incumbents may result in higher financial risks than letting sunset industries entirely disappear.

Building on this discussion, we explore transition risks in more detail in the following. For brevity, we focus on financial risks only, with results on firm risk and policy costs displayed in Appendix C.

5.2 Linking *ex-post* risks with *ex-ante* risk indicators

Since we are interested in the relationship between scenario characteristics and our outcomes, we link our *ex-ante* transition risk measures to our *ex-post* transition risk measures.

5.2.1 Magnitude

We first discuss the magnitude of financial risks. Because Banks are affected by market risks, through NBFI leverage, we first discuss market risks to highlight possible amplification effects.

Results are shown in Figure 10, which follows the parallel coordinate template used in Figure 6 with the outcome of interest added to our *ex-ante* transition risks metrics and results split across SSPs. As in the above, results are mean values across simulations.

Across SSPs, 3 to 4 scenarios exhibit risk metrics above 15%, while around 5 stand between 7.5 and 15%. Although a majority of scenarios stand as “feasible”, a substantial proportion falls even beyond the boundaries drawn by NGFS scenarios (Daumas 2022, Chapter 2). The severity of market risk mainly follows the stringency of climate policy. The carbon tax burden reduces dividends, which affects NBFI default

through lower cash flow and decreases. However, the high NBF1 risks emerge from the scenarios with the highest decarbonisation steepness, although their carbon prices are low. In these cases, the brisk shift towards low-carbon technology entails very high losses on equity, diminishing available liquidity.

Due to amplification mechanisms, these differences across SSPs in terms of market risk may partly explain differences found in credit risks, to which we turn now. Results are displayed in Figure 11.

A sizeable proportion of scenarios do not give rise to high credit risks, with shocks below 10%. These scenarios feature low to high climate ambitions and low to medium-high carbon prices. This pattern is highly reassuring regarding the financial feasibility of MPs since the economy seems to be able to accommodate even high climate ambition with relatively high carbon price levels.

We find a population of problematic scenarios, some leading to an outright financial crisis – a 50-60% credit risk in our model means that Banks reach the prudential value of 8% CAR over the run and that the government had to step in to bail them out. However, severity varies across SSPs. Notably, SSP5 only exhibits three highly problematic scenarios, while SSP3 and SSP1 seem more adverse. SSP2 and SSP4 hold a middle ground, with SSP4 showing relatively low transition risks. Across SSPs, these problematic scenarios feature high carbon prices or steep decarbonisation dynamics and delayed action until 2025 or 2030 for some. In this latter case, credit risks are high but contained overall.

These scenarios mix a high carbon price with middle-ground climate ambition, steepness, and a sharp period-to-period carbon price increase. Hence, they suppose that climate policy is inefficient and comes with an extreme rise in carbon prices, in the sense that substantial policy pressure should be imposed from some point in time onwards to reach even a mild climate target. This feature implies that the carbon tax burden onto Incumbents is disproportionately high over a longer duration, affecting Banks directly through higher NPL.

The impact of delayed action shows significant differences across SSPs. In SSP1 to 3,

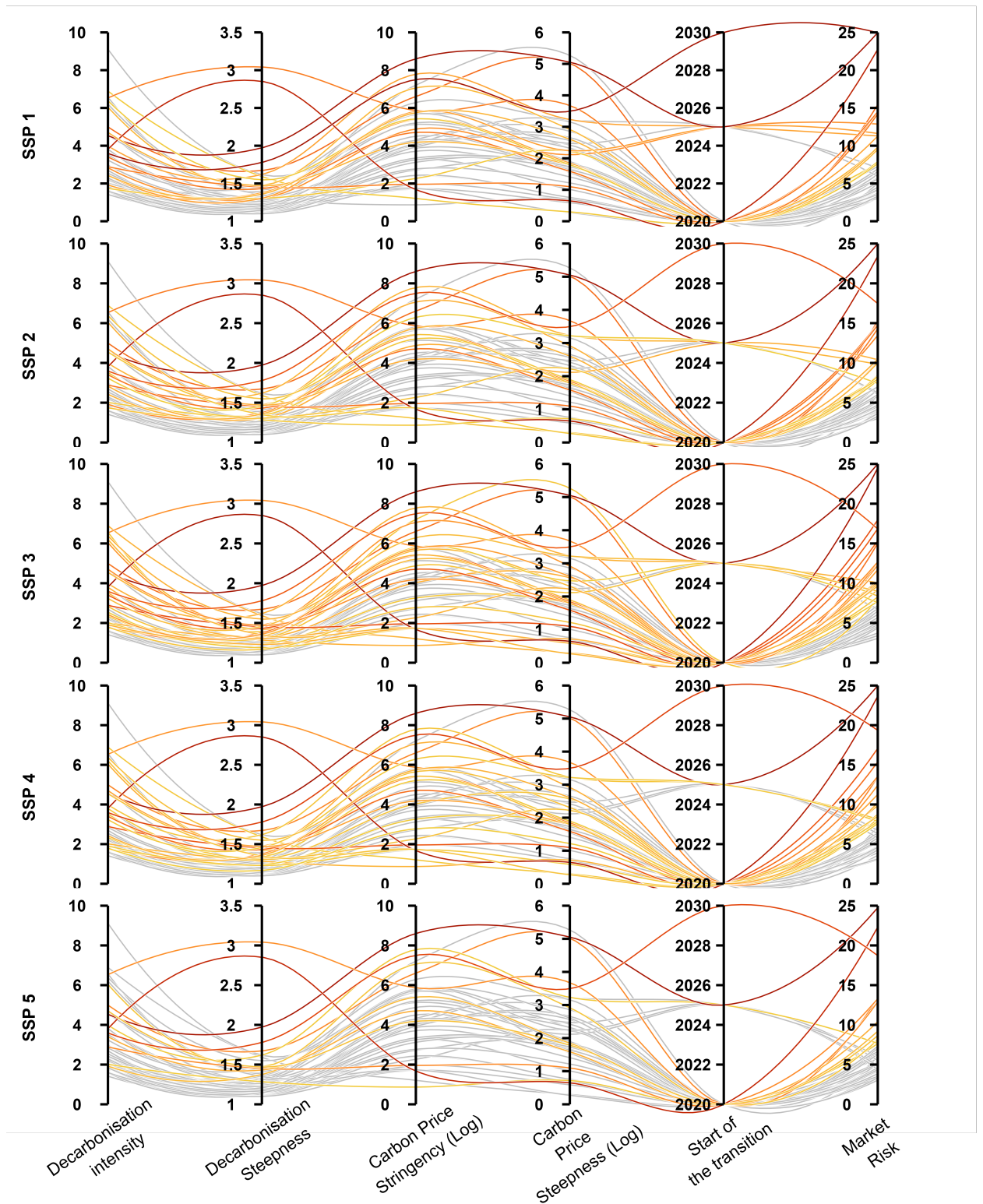


Figure 10: Mapping between market risks and scenario characteristics. Each line joins a combination of scenario characteristics with the value of the market risk indicator, which shows on the far-right axis. Colors indicate market risks, with only scenarios above the 7.5% threshold highlighted.

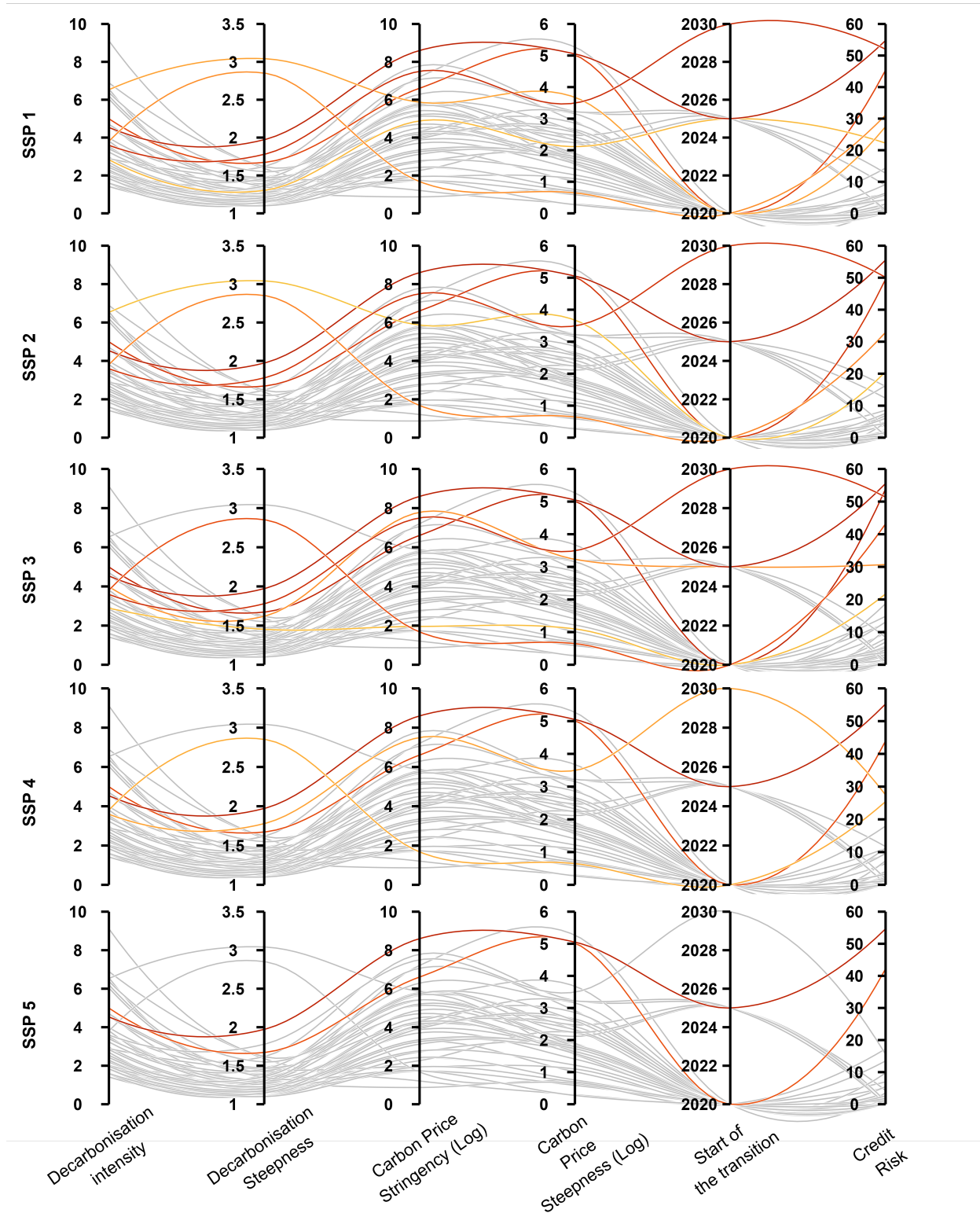


Figure 11: Mapping between credit risks and scenario characteristics. Each line joins a combination of scenario characteristics with the value of the credit risk indicator, which shows on the far-right axis. Colors indicate credit risks, with only scenarios above the 20% threshold highlighted.

delayed action can have very adverse consequences, while in SSP2 and SSP5, they are lower. It flows from the interplay between carbon intensity reduction and growth, which, in turn, affects the relative frailness of the Challenger and the Incumbent sector.

Conversely, in SSP1 and SSP2, both carbon intensity reduction and growth dynamics penalise the Challenger sector, resulting in greater fragility. Furthermore, as sketched above, market risk is higher for 2025 delayed-action scenarios in SSP1. Hence, higher credit risk flows partly from the amplification mechanism flowing from NBF1 leverage. For SSP3, shallow growth hampers Incumbents and Challengers by preventing them from enjoying multiplier effects. This interpretation is comforted by Figure 8, which clearly shows that Delayed-Action scenarios feature amongst those with the highest firm risks, especially for SSP1 to 3. This result highlights the importance of the Challenger sector in driving shocks to Banks. More precisely, they further highlight that Challenger risks need not be as high as Incumbent risks to trigger disturbances: due to its fast development, a higher default probability will result in more NPLs in absolute than the Incumbent sector, whose size in Banks' portfolio decreases through time (see Appendix C.2.). Because this sector expands and represents, in the longer run, Banks' main loan outlet, a higher Challenger fragility can exacerbate the risks posed by sunset industries. Thus, some SSP-scenario combinations give rise to "green bubble" behaviours (Nikolaidi 2017).

5.2.2 Timing

To complement this analysis in terms of magnitude, it is worth considering the timing of financial risks to characterise the transition risk profile of our scenarios better. As highlighted in Daumas (2022) (Chapter 2), transition risks can extend beyond the short run. For brevity, we only focus here on the indicator showing the apex of credit and market risks and postpone the discussion of the length of high financial risk periods to Appendix C.1.

Figure 12 shows the period of maximum market risk (x-axis) and credit risk (y-axis)

in the same locus. To give a sense of how timing relates to the characteristics of mitigation pathways, we display results in two separate panels, one relating timing indicators to intensity measures and the other to steepness measures.

Results show a wide gradient of occurrences, ranging from early years (2021) to late periods (as late as 2050 for credit risks). Thus, our results clearly show the existence of long-run financial transition risks across scenarios. Furthermore, compared to results in Daumas (2022) (Chapter 2), credit risk for Banks can also emerge in the long run. It is especially the case for delayed-action scenarios. In addition, results exhibit a rough positive correlation between the two indicators. Given the interaction between NBFi leverage and Banks' capital adequacy ratio, it was expected because of the transition process.

Furthermore, the patterns of timing can meaningfully be attributed to the characteristics of our best representatives. Three cases can be highlighted.

For a few scenarios, credit risks occur earlier than market risks, around 2021, and with the market risk apex emerging in the medium to long run. It mostly concerns scenarios with low carbon prices overall, medium to high ambitions and low steepness indicators. It suggests that progressive decarbonisation and slowly increasing carbon price schedules give more easily rise to long-run market risk. This feature arises because asset losses in these scenarios are postponed relatively to other cases. The carbon price burden increases slowly and is high relatively late, while decarbonisation is equally slow, leading to late losses in market shares for the Incumbent. This configuration is very close to the one encountered by Daumas (2022) (Chapter 2), whereby Banks' NBFi risk grows in the medium to long run with Banks being able to navigate it. The scenarios with high ambition and medium-high carbon prices exhibit NBFi risks emerging around 2035, suggesting that the conjunction of these two factors accelerates the emergence of NBFi risks due to earlier and more important losses on dividend proceeds and equity prices.

Other scenarios exhibit credit risks occurring later than market risks. Most of these scenarios feature amongst the highest carbon price paths, which are often associated

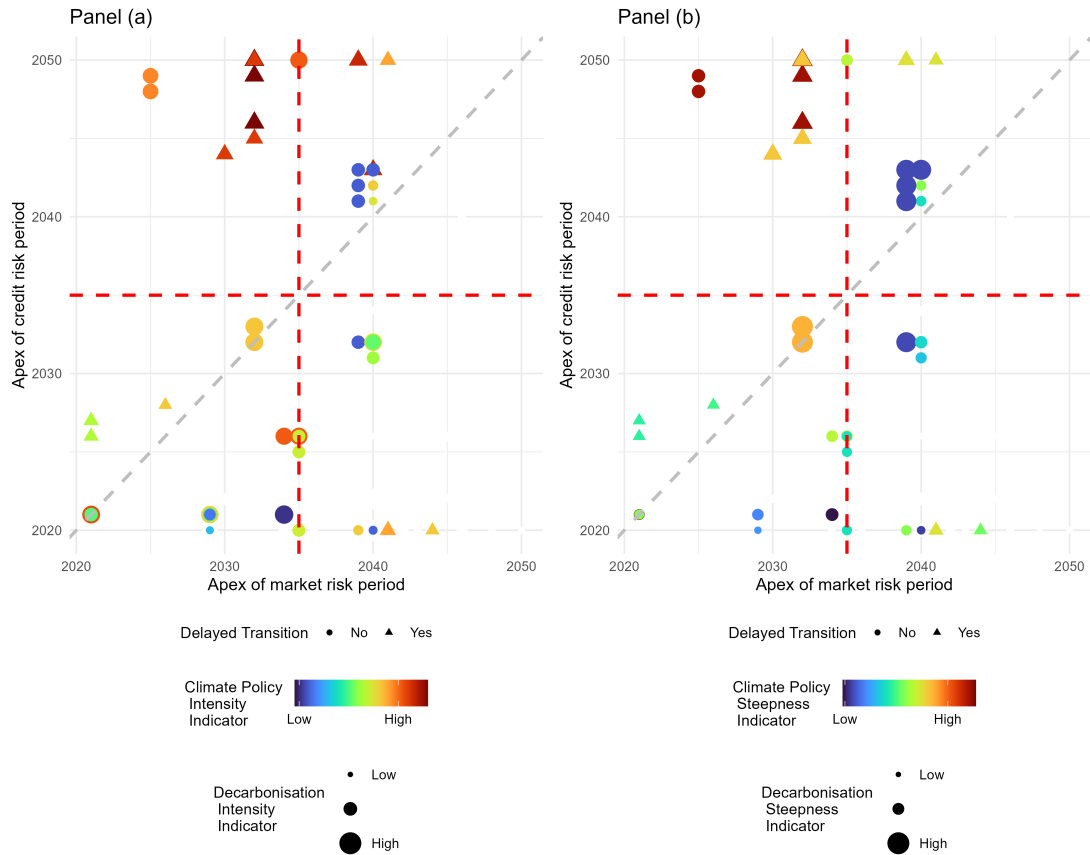


Figure 12: Timing of financial risk events. In both figure, on the x-axis the year of market risk apex, on the y-axis the apex year of market risk. In Panel (a), these two values are associated with intensity indicators. Color indicates Climate Policy Stringency and Size indicates Decarbonisation Steepness. In Panel (b), market and credit risk apices are associated with steepness indicators. Color indicates Climate Policy Steepness and Size indicates Decarbonisation Steepness. In both Panels, Shape indicates whether the transition starts after 2025 (Delayed Action). Only scenarios with a credit risk ρ_C above 20% or a market risk ρ_M above 7.5% are displayed.

with low or medium decarbonisation targets (Figure 11). It shows that scenarios with low climate policy efficiency affect credit risk in the longer run more than in the short run. It is because the tax burden on Incumbents becomes gradually unsustainable for this sector, weighing on its repayment abilities in the long run. In contrast, NBFIs can benefit from the development of the Challenger, which pays enough dividends to avoid disturbances in the long run.

Finally, around a third of our scenarios come very close to the 45° line. For this group,

credit and market risks occur roughly simultaneously. It suggests that within-finance interactions are at play. It mostly occurs for scenarios with high decarbonisation steepness, regardless of the carbon price schedule. Hence, amplification from within the financial sector emerges mostly in case of strong decarbonisation shocks at some point in time.

These results illustrate the importance of mitigation pathways's characteristics on the qualitative profile of financial risk and on the time distribution of financial shocks, with possibly very large differences across our best representatives.

6 Conclusion and discussion

6.1 Summary and takeaways

The results above bear some takeaways. First, there is no strict relationship between the ambition of climate policy and the stringency of climate policy on the one hand and the transition risk content of scenarios on the other. Many climate-ambitious scenarios do not pose very high transition risks, even with relatively high carbon prices. This perspective is reassuring regarding the low-carbon transition. High climate targets with medium to medium-high carbon prices are achievable without threatening financial institutions.

Yet, the population of scenarios with high financial risks is far from anecdotal, with 40% of our best representatives crossing one of our high-risk boundaries. Like in Daumas (2022) (Chapter 2), Non-Bank Financial Institutions seem more at risk than Banks across all scenarios. The extent of market transition risks seems higher. In particular, ambitious scenarios are only achievable by reaching a 7% peak NBF1 default probability, a high number by historical standards. It calls for caution in handling these institutions along transition pathways. However, in the riskiest scenarios, large shocks are short-lived and confined to the immediate aftermath of the start of the transition. Banks seem more sheltered, although they can be direly affected in some high-risk scenarios.

We find first some dependence on underlying macroeconomic and carbon intensity reduction assumptions as embodied in SSPs. Low-growth assumptions entail higher risks. However, growth assumptions interact strongly with assumptions on carbon intensity reductions. Indeed, scenarios with stronger autonomous carbon intensity improvements are riskier. This pattern is due to our Challenger-Incumbent structure. Within the boundaries of our model, more significant carbon intensity reductions favour the Incumbent sector at the expense of the Challenger sector. The Challenger sector will have a more fragile financial position because it will snatch fewer market shares and benefit from lesser cash flows and asset stranding will be lower in the Incumbent sector. In some scenarios, this high fragility ripples off to the financial sector, pointing at possible “green bubble” dynamics. More precisely, the model shows that the structure of competition between Incumbents and Challengers matters: a relative advantage to the Incumbent sector can bear substantial risks.

Beyond variations across SSP assumptions, transition risks are, in this study, primarily driven by the shape of emission reduction and carbon price schedules.

First, the pace of emission reduction matters. Scenarios featuring very sharp period-to-period emission reductions from some point onward are among the highest-risk profiles. It is notably valid for market risks, which depend heavily on changes in market shares between the Incumbent and the Challenger sectors. Brisk changes introduce sudden asset revaluations that weigh on NBFIs’ default probabilities. Our results thus qualify the need for a progressive deployment of low-carbon technologies along the NGFS’s “orderly” scenario category (NGFS 2022). The study instead shows that the new low-carbon economy should deploy at a workable but sustained rate: too progressive a transformation postponing high efforts in the medium to long run features high risks.

However, the highest-risk scenarios for market and credit risk feature high and rapidly increasing carbon prices with relatively low and slow decarbonisation processes. Scenarios with high or very high carbon prices for mid-range climate ambition and relatively slow decarbonisation processes imply that the carbon tax burden on In-

cumbents is high and stays long, increasing their fragility.

In the end, the most significant driver of financial transition risks in this study is the efficiency of climate policies in achieving given targets. These results highlight the importance of accounting for the uncertainties surrounding the precise unravelling of the low-carbon transition and the degree of policy pressure put on sunset industries necessary to achieve climate targets.

Regarding the pace of low-carbon technology deployment – and associated structural change, a definite cause of worry is that it is only partly a policy variable. Our results show that it is better to be relatively ambitious in the short run and avoid postponing significant adjustments – even if the transition starts early. However, the speedy development of low-carbon technology can flow from market mechanisms. As evidenced by previous technological shifts, technologies can autonomously develop following an S-shape curve, possibly very sharp, that may put Incumbents in difficulty (Grubb, Drummond, and Hughes 2020).

Second, regarding climate policy, our results highlight the risks associated with the uncertainties related to the efficiency of climate policies. Indeed, although the international community agreed on an adequate price of around US\$100 per ton of carbon (Stiglitz and Stern 2017), the possibility of catastrophic climate change effects may bring the range of optimal carbon prices much higher (Kemp et al. 2022). As evidenced by Green (2021), carbon prices have, most of the time, had a modest effect on emission reductions. Conversely, Tvinnereim and Mehling (2018) highlighted that carbon prices have failed to trigger deep decarbonisation efforts. Finally, even relatively higher carbon prices in some jurisdictions have failed in cancelling high-carbon projects, which are still in the pipeline (Kühne et al. 2022). Although the recent increases in the EU exchange trading system have brought hope in a strong reaction of concerned industries, whether they will actually carry out large-scale their decarbonisation efforts in the longer run is still pending. As a result, this study highlights the need for strong macro-prudential policies to best hedge possibly inefficient climate policies.

6.2 Limits and further work

This work, nonetheless, comes with some caveats.

First, although we allow for capital conversion on the part of the Incumbent, it does not invest directly in low-carbon capital. As a result, the transition risk impacts on Incumbents should be taken as an upper bound. On the other hand, our assumptions on autonomous carbon intensity improvements provide Incumbents with another lever of decarbonisation. The model's behaviour with these assumptions offers us a preliminary grasp of how greenfield low-carbon investment from the Incumbents would play out. Indeed, as we saw, favouring the Incumbent sector makes the Challenger sector more fragile. As a result, allowing for a more active role for the Incumbent would push the model towards “green bubble” dynamics, whereby the birth of new industries is eventually thwarted by the Incumbent, with possible implications for financial instability.

Then, how we modelled SSPs in the model led to counter-intuitive results, notably how we dealt with carbon intensity improvements. Due to this approach, SSP1, while the least risky of all SSPs *ex-ante*, becomes one of the riskiest. Conversely, SSP5 is the least risky of all – also because of its very optimistic growth assumptions. A way to bypass this caveat would have been to solve the model for each SSP, like any other scenario. However, it would have required making additional assumptions on the relative behaviour of carbon intensity improvements (or worsening) and the penetration of low-carbon technology through the Challenger. If it would have been relatively straightforward for SSP1 and SSP5, the three other SSPs would have been much less determined. Our choice thus obeyed a constraint of clarity and simplicity.

Finally, as mentioned above, the “carbon prices” we impose upon the model should be taken cautiously. In particular, the POLES-ENGAGE modelling framework generated the riskiest scenarios we obtained. POLES-ENGAGE is a bottom-up integrated assessment model solved in partial equilibrium. As a result, it does not account for the macroeconomic and welfare effects. This feature potentially leads it to yield prohibitively high carbon prices in generating its solutions. Hence, although these

extreme scenarios illustrate the relevance of carbon pricing in driving potential crises, applying POLES-generated carbon prices is maximalist and represents an extreme-tail course of events.

Further work thus includes refining the modelling framework in various directions, along with those put forward in Daumas (2022) (Chapter 2): increasing financial sector heterogeneity and implementing a degree of geographical disaggregation. For this article, more specifically, allowing for greater Incumbent adaptability, for instance, by allowing greenfield investment in low-carbon technologies, would also allow us to be more precise in disentangling Challenger and Incumbent-related risks. It would require an explicit representation of competition across both sectors. More generally, adopting a more technology-rich approach, with a greater disaggregation of industries and energy types, could allow for a finer-grain picture of transition risks associated with sunset and sunrise industries, our current Challenger-Incumbent distinction being quite stylised. Furthermore, FASM-ID is currently geared to study transition financial risks associated with completed decarbonisation processes (see Chapter 2). Allowing for failed transition, and therefore more comprehensive interactions between the financial sector and transition dynamics (see Battiston, Monasterolo, Riahi, et al. 2020; Gourdel, Monasterolo, and Gallagher 2023), could allow us to determine more precisely which scenarios within our population of best representatives are truly “unfeasible” from the standpoint of financial instability.

Finally, we confined ourselves to the scenarios featured in the IPCC database. Although they represent a large population of projections meant to map best the uncertainties related to the low-carbon transition, they do not span the entirety of possible transition pathways and leave aside many dimensions relevant to financial risks. For instance, very low-growth or degrowth scenarios are currently not in the set studied by the IPCC – the lowest baseline growth assumptions are slightly below 2% per year on average in SSP3. Given the importance of growth assumptions in driving some of our results, studying transitions towards a low-growth or a steady-state economy (as in T. Jackson and Victor (2015) or P. Jacques et al. (2023)) could be a valuable addi-

tion to studying transition risks. Finally, the macroeconomic assumptions embodied in SSPs could be augmented in various directions, for instance, with complementary climate or macro-financial policies that may alleviate transition risks.

This third chapter closes the first movement of this dissertation by providing a direct answer to its research question. By applying FASM-ID to a wide array of scenario representatives, this chapter directly studied the transition risk properties of canonical mitigation pathways provided by the IPCC. It further built on the latter's methodology by offering a treatment of assumptions embodied in the Shared Socioeconomic Pathways. As highlighted, however, this work is limited by scenario and modelling assumptions. The two following chapters aim to dig more into this latter direction by focusing on two avenues highlighted in Chapter 1. Chapter 4 proposes a novel way to model expectations, which could be adapted to transition-relevant scenarios within FASM-ID in later works. Chapter 5 digs more into the details of portfolio choices away or into carbon-intensive companies at the investor level. Its goal will be to pinpoint what kind of investors have been most prone to increase their investments in high-carbon companies.

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Appendices

A. Scenario references

Table A1: Best representative – References

ID	Model	Scenario	Reference
1	POLES ENGAGE	EN_NPi2020_600	Bertram, Riahi, et al. (2021)
2	MESSAGEix-GLOBIOM_1.2	COV_SelfReliance_550	Kikstra et al. (2021)
3	WITCH 5.0	EN_NPi2020_1200f	Bertram, Riahi, et al. (2021)
4	POLES EMF33	EMF33_Med2C_nofuel	Vinichenko, Cherp, and Jewell (2021)
5	MESSAGEix-GLOBIOM_1.1	EN_NPi2020_1000f_COV	Bertram, Riahi, et al. (2021)
6	REMIND-MAgPIE 2.1-4.2	EN_NPi2020_300f	Bertram, Riahi, et al. (2021)
7	AIM/CGE 2.1	CD-LINKS_NPi2020_400	Bertram, Riahi, et al. (2021)
8	POLES ENGAGE	EN_NPi2020_400f	Bertram, Riahi, et al. (2021)
9	POLES ENGAGE	EN_INDCi2030_700f	Bertram, Riahi, et al. (2021)
10	REMIND-MAgPIE 1.7-3.0	PEP_2C_red_netzero	Bertram, Riahi, et al. (2021)
11	IMAGE 3.0	EN_INDCi2030_1000	Bertram, Riahi, et al. (2021)
12	REMIND 2.1	CEMICS_opt_2C	Strefler et al. (2021)
13	MESSAGEix-GLOBIOM_1.1	EN_INDCi2030_1000f	Bertram, Riahi, et al. (2021)
14	POLES ENGAGE	EN_NPi2020_900	Bertram, Riahi, et al. (2021)
15	REMIND-Transport 2.1	Transport_Budg1100_Conv	Rottoli et al. (2021)
16	MESSAGEix-GLOBIOM_1.1	EN_NPi2020_600f_DR4p	Riahi, Bertram, et al. (2021)
17	REMIND 2.1	TechCost-SSP2-B1100-windH	Giannousakis et al. (2020)
18	POLES GECO2019	CO_2Deg2020	Morris et al. (2021)
19	POLES ENGAGE	EN_NPi2020_1000_COV	Bertram, Riahi, et al. (2021)
20	EPPA 6	2CNow_Gradual	Morris et al. (2021)
21	GEM-E3_V2021	EN_NPi2020_1400f	Bertram, Riahi, et al. (2021)
22	IMAGE 3.0	EN_NPi2020_1000	Bertram, Riahi, et al. (2021)
23	COFFEE 1.1	EN_INDCi2030_1000_NDCp	Bertram, Riahi, et al. (2021)
24	TIAM-ECN 1.1	EN_NPi2020_1200f	Bertram, Riahi, et al. (2021)
25	TIAM-ECN 1.1	EN_NPi2020_1600	Bertram, Riahi, et al. (2021)
26	COFFEE 1.1	EN_NPi2020_1200	Bertram, Riahi, et al. (2021)
27	WITCH 5.0	EN_NPi2020_700f	Bertram, Riahi, et al. (2021)
28	MESSAGEix-GLOBIOM_1.2	COV_Restore_1000	Bertram, Riahi, et al. (2021)
29	POLES ENGAGE	EN_INDCi2030_1000f_COV_NDCp	Bertram, Riahi, et al. (2021)
30	GEM-E3_V2021	EN_INDCi2030_1000	Bertram, Riahi, et al. (2021)
31	POLES ENGAGE	EN_INDCi2030_1200	Bertram, Riahi, et al. (2021)
32	TIAM-ECN 1.1	EN_INDCi2030_1000f	Bertram, Riahi, et al. (2021)
33	MESSAGEix-GLOBIOM_1.1	EN_INDCi2030_1200f_COV	Bertram, Riahi, et al. (2021)
34	COFFEE 1.1	EN_INDCi2030_600f	Bertram, Riahi, et al. (2021)
35	POLES ENGAGE	EN_INDCi2030_300f	Bertram, Riahi, et al. (2021)
36	REMIND-MAgPIE 2.1-4.2	EN_INDCi2030_600_COV_NDCp	Bertram, Riahi, et al. (2021)
37	COFFEE 1.1	EN_INDCi2030_600	Bertram, Riahi, et al. (2021)
38	POLES ENGAGE	EN_INDCi2030_900f	Bertram, Riahi, et al. (2021)
39	REMIND-MAgPIE 2.1-4.2	EN_INDCi2030_600f_COV	Bertram, Riahi, et al. (2021)
40	MESSAGEix-GLOBIOM_1.1	EN_INDCi2030_600f_COV	Bertram, Riahi, et al. (2021)
41	MESSAGEix-GLOBIOM_1.1	EN_INDCi2030_700f_COV	Bertram, Riahi, et al. (2021)
42	POLES GECO2019	CO_Bridge_notax	COMMIT Database
43	TIAM-ECN 1.1	EN_NPi2020_900f	Bertram, Riahi, et al. (2021)
44	COFFEE 1.1	EN_NPi2020_500f	Bertram, Riahi, et al. (2021)
45	MESSAGEix-GLOBIOM_1.1	EN_NPi2020_1400f_COV	Bertram, Riahi, et al. (2021)
46	MESSAGEix-GLOBIOM_GEI 1.0	SSP2_noint_lc_50	Guo et al. (2021)
47	COFFEE 1.1	CO_2Deg2020	COMMIT Database
48	IMAGE 3.0	CO_Bridge	COMMIT Database
49	REMIND-MAgPIE 2.1-4.2	EN_NPi2020_1200	Bertram, Riahi, et al. (2021)
50	POLES ENGAGE	EN_NPi2020_1200	Bertram, Riahi, et al. (2021)

B. Calibration details

The calibration method is the same as in Chapter 2, to the difference that stylised facts and starting values are targeted over a no-policy steady-state and not a baseline scenario involving some degree of decarbonisation. We target the same starting values and stylised facts as in Chapter 2. Parameter values are the same as in Chapter 2, except for the moving calibration parameters presented in Chapter 2. The latter differ across SSPs to yield the desired macroeconomic properties. Finally, given differences in growth rate, the number of iterations necessary to reach target starting values could also change across SSPs.

B.1. Sensitivity ranges

We display again in Table B.1.1 Table D.1 of Chapter 2 reproducing the sensitivity ranges for the parameters involved in sensitivity calibrations. Note the absence of the carbon improvement coefficient β_e , whose effect is neutralised in the model due to our assumption of autonomous carbon intensity improvements.

B.2. SSP-specific parameters

Like in Chapter 2, the reference calibrations are generated by moving the parameter ruling the response of consumption, γ_C and the parameter ruling trend inflation $\nu_{w,2}$.
Table B.2.1

C. Complementary results

C.1. Length of high financial risk periods

Another aspect of timing is the length of higher-risk periods. It complements the apex date metric by providing a sense of how protracted tension periods are and can give a sense of whether credit and market risk periods overlap. We report this result in Figure C.1.1, which shows the duration of market and credit risk shocks in the same locus, with the same two Panels as in Figure C.3.2.

Table B.1.1: Sensitivity parameters and corresponding ranges

Parameter	Reference values	Range
$\bar{\mu}$	0.065	[0.0585, 0.0715]
lev	0.2	[0.14, 0.26]
γ_C	0.073	[0.0657, 0.803]
$\lambda_{i,j}, i, j \in \{1, 2, 3\}$	0.06 -0.03 otherwise (Ruled by a single parameter λ_λ with value 0.06, on which the value of the other Tobin coefficients are computed)	[0.048, 0.96]
λ_{KLC}^*	3	[2.4, 3.9]
λ_o^*	1	[0.7, 1.3]
ν	0.1	[0.07, 0.13]
ν_{w_1}	0.7	[0.63, 0.77]
ν_{w_2}	1.1	[0.088, 1.32]
ν_u	0.04	[0.028, 0.052]
ω_p	0.2	[0.14, 0.26]
r_D	0.005	[0.035, 0.065]
r_{CB}	0.01	[0.007, 0.013]
r_{GB}	0.02	[0.014, 0.026]
σ_{LC}	0.025	[0.1225, 0.5]
σ_{HC}	0.025	[0.1225, 0.5]
σ_{NBFI}	0.025	[0.1225, 0.5]
σ_{lev}	0.025	[0.1225, 0.5]
τ_{Tob}	0.5	[0.25, 1]
φ_1	8.17	[7.96, 8.37]
φ_2	7.925	[7.1325, 8.7175]
ϖ_1	2	[1.8, 2.2]
ϖ_2	2	[1.4, 2.6]
ϖ_3	6	[4.2, 7.8]
ξ_B	0.4	[4.2, 7.8]
ξ_{Funds_B}	0.1	[0.07, 0.13]
ξ_{NBFI}	0.9	[0.81, 0.99]

*Starting value before the learning period of the model

Table B.2.1: SSP-Specific parameters

Variable	SSP1	SSP2	SSP3	SSP4	SSP5	Sensitivity range
γ_C	0.081	0.77	0.063	0.074	0.1	$\pm 10\%$
$\nu_{w,2}$	0.635	0.66	0.77	0.69	0.49	$\pm 20\%$

Strikingly, the pattern of the scatter plot is L-shaped, suggesting that, except for a few scenarios, long-lasting tension periods only concern one or the other risk.

Credit risk periods are protracted under low climate-efficiency scenarios, possibly including delayed action. In these best representatives, the carbon price is so high relative to decarbonisation dynamics that it puts the banking sector under pressure for a very long time due to increased default probabilities of Incumbents over a long period. These dynamics also emerge under high decarbonisation stringency, confirming that strong decarbonisation shocks can ripple off to the long run.

By contrast, long market risk periods emerge under scenarios with more progressive decarbonisation and climate policy schedules while being relatively ambitious. Hence, a sustained but progressive pressure can give rise to longer-lasting fragility periods for NBFIs.

Scenarios in which both market and credit risk periods are protracted are all delayed action scenarios with very stringent characteristics. It suggests that the shock of delayed action is high enough to create a long-lasting period of financial fragility.

A sizeable set of scenarios exhibits short-lived financial risks for both indicators with similar characteristics to those with long-run market risks. They differ, however, in featuring either delayed action or low climate ambitions. It suggests that these two characteristics shorten the length of market risk periods.

C.2. Timing results for medium-range financial risks

We then display complementary results about the timing of financial risks for medium-risk profiles. To define such profiles, we isolate scenarios with a credit risk between 10 and 20% and a market risk between 5 and 7.5% and exclude from this selection the SSP-scenario pairs studied in Figures 12 and C.1.1. In that respect, some SSP-scenario pairs discussed above could appear in this Appendix as well because they exhibit smaller risks than their counterpart.

We first display results on the timing of both types of risk. Given our many scenarios, we restrict ourselves to a brief description of the results.

Strikingly, the scenarios with lower financial risks exhibit distinct patterns from those studied in Section 5. In most cases, the high market risk period emerges in the

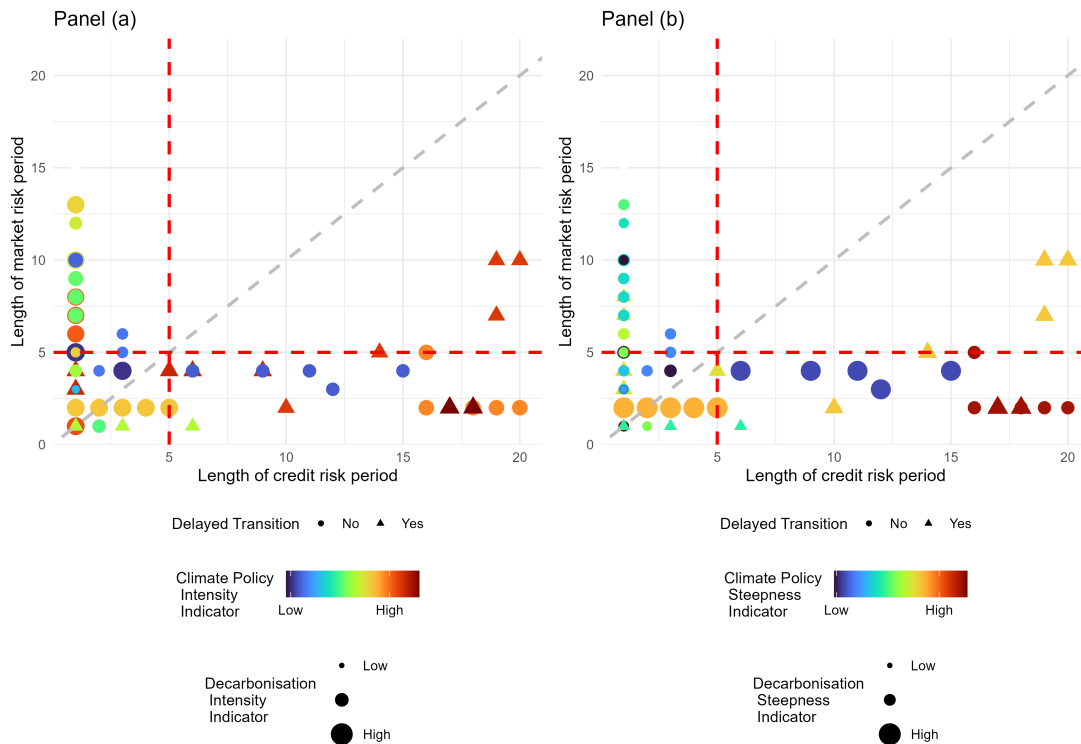


Figure C.1.1: Length of financial risk periods. In both figure, on the x-axis the year of market risk apex, on the y-axis the length of the high credit risk period. In Panel (a), these two values are associated with intensity indicators. Color indicates Climate Policy Stringency and Size indicates Decarbonisation Steepness. In Panel (b), market and credit risk apexes are associated with steepness indicators. Color indicates Climate Policy Steepness and Size indicates Decarbonisation Steepness. In both Panels, Shape indicates whether the transition starts after 2025 (Delayed Action). Only scenarios with a credit risk ρ_C above 20% or a market risk ρ_M above 7.5% are displayed.

medium to long run after the high credit risk period. These patterns align with those found in Daumas (2022) (Chapter 2), whereby a wave of high NBFi risk emerged in the medium to long run when the price of Incumbent equity starts decreasing sufficiently. Most scenarios exhibit a market risk apex in the short-medium run, around 2028. Similarities in apex dates across some scenario groups are primarily due to similar turning points in transition dynamics across scenarios (see Figure 6). Most of these scenarios exhibit a low decarbonisation steepness and low carbon prices, suggesting that a critical factor for the emergence of short-medium-run market risk is the progressive development of low-carbon technologies with relatively efficient

climate policies. Higher carbon prices characterise scenarios with later market risk apex. It highlights that relatively less efficient climate policies postpone market risks in the longer run.

However, compared to Daumas (2022) (Chapter 2), credit risk troughs can emerge relatively late, sometimes beyond 2030, even in scenarios that do not assume delayed action. Scenarios with late credit-risk troughs are of several kinds. First, these scenarios with high decarbonisation intensity likely bring the Incumbent sector close to extinction, triggering some financial disturbances. Second, they include scenarios with high long-run carbon prices and sluggish transitions, confirming our result on the relative efficiency of climate policy.

We move to Figure C.2.2, the equivalent of Figure C.1.1 showing the length of high-risk periods around the apex for medium-range risk scenarios.

Again, patterns are different from those prevailing under high-risk scenarios. First, the length of credit risk events is much smaller, rarely above five years. It suggests that in medium-risk configurations, credit risks mainly consist of transitory shocks that Banks eventually absorb.

By contrast, market risk periods can be more protracted. Some scenarios remain within the boundaries of Figure C.1.1, but others exhibit periods ranging between ten and fifteen years, three times those prevailing under high-risk scenarios. Longer-lasting market risk scenarios mostly feature medium-range values for most of our *ex-ante* indicators, highlighting that sustained policy pressure, with relative efficiency, leads to longer-lasting periods of financial fragility. Consistent with the discussion above, the scenarios showing the longest-lasting fragility periods feature relatively low ambition but with either high carbon prices or steeply increasing schedules. Again, it confirms the detrimental role of relatively less efficient climate policy.

C.3. Firm risk

We then consider another set of complementary results on firm risks. Similarly to the results of Section 5, we first discuss the extent of firm risks for Challengers and

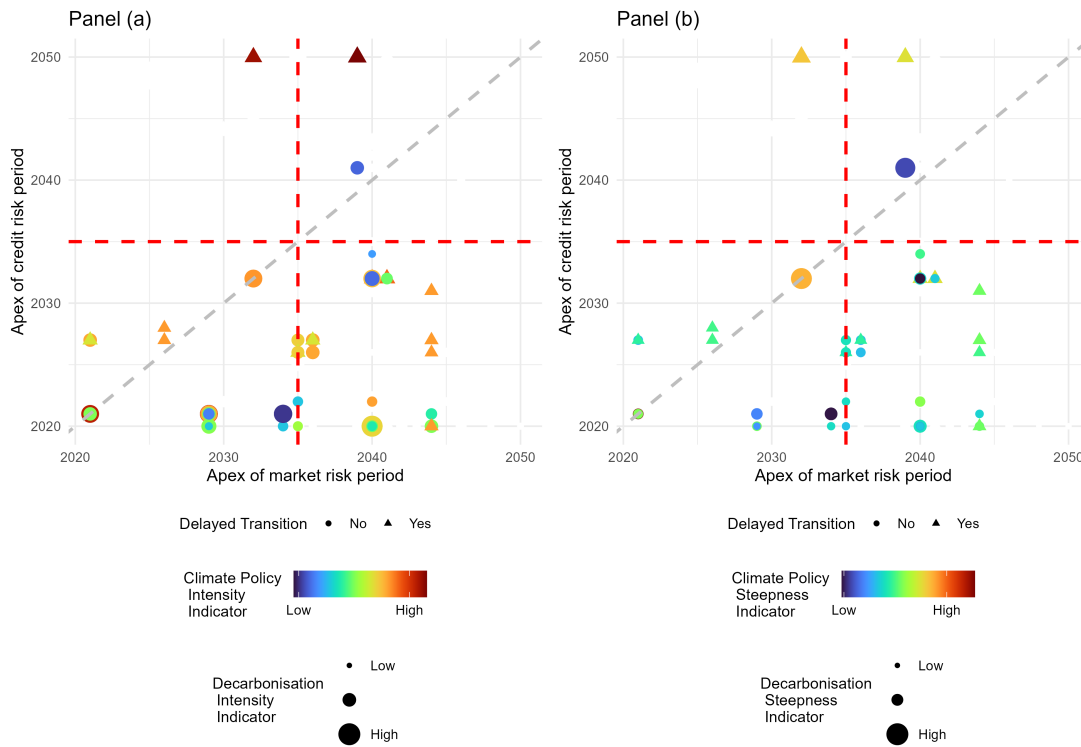


Figure C.2.1: Timing of financial risk events – Medium-range risk. In both panels, on the x-axis the year of credit risk apex, on the y-axis the year of market risk apex. In Panel (a), these two values are associated with intensity indicators. Color indicates Climate Policy Stringency and Size indicates Decarbonisation Steepness. In Panel (b), market and credit risk apexes are associated with steepness indicators. Color indicates Climate Policy Steepness and Size indicates Decarbonisation Steepness. In both Panels, Shape indicates whether the transition starts after 2025 (Delayed Action). Only scenarios with a credit risk ρ_C between 10 and 20% or a market risk ρ_M between 5 and 7.5% are displayed.

Incumbents across all scenarios.

Figure C.3.1 displays our magnitude results for the Incumbent. Unsurprisingly, the highest financial risks concentrate in scenarios with the highest carbon prices or the latest transition start. Interestingly, many scenarios with relatively high climate ambitions do not feature high Incumbent risks, which suggests that progressive transitions can be well-managed by this sector. Furthermore, it shows that the most significant determinant of Incumbent risk is the price of carbon, well above technological displacements, which is only problematic for a single scenario. We see a

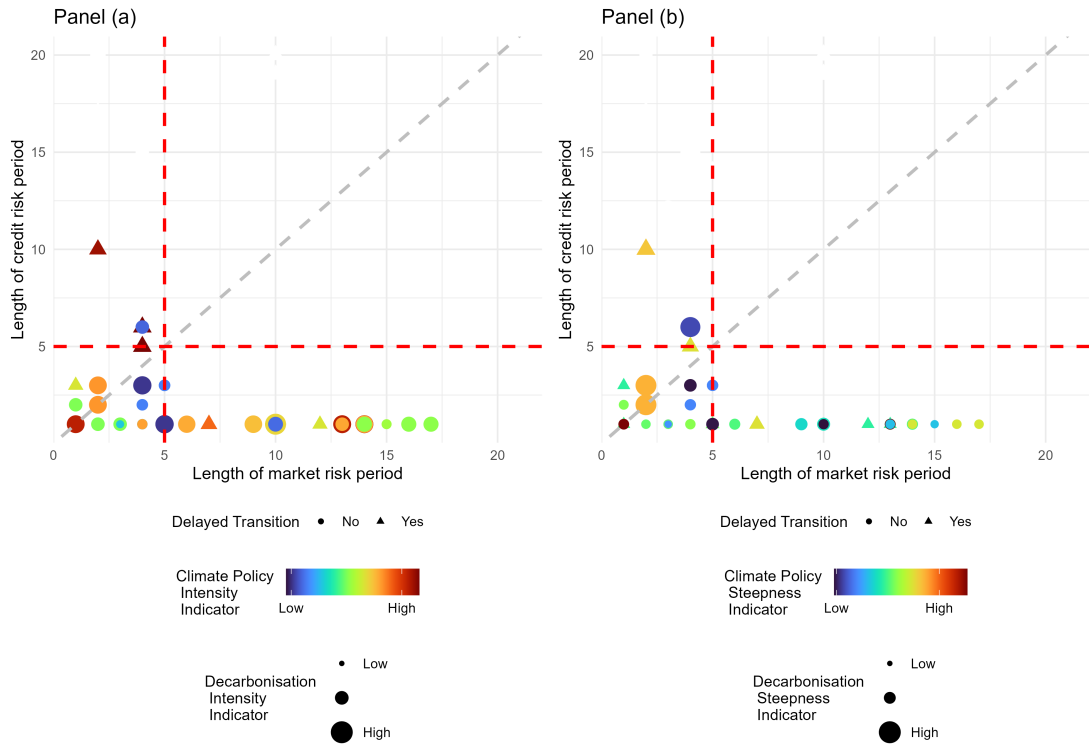


Figure C.2.2: Length of high financial risk periods – Medium Range Risks. In both figure, on the x-axis the year of market risk apex, on the y-axis the apex year of market risk. In Panel (a), these two values are associated with intensity indicators. Color indicates Climate Policy Stringency and Size indicates Decarbonisation Steepness. In Panel (b), market and credit risk apexes are associated with steepness indicators. Color indicates Climate Policy Steepness and Size indicates Decarbonisation Steepness. In both Panels, Shape indicates whether the transition starts after 2025 (Delayed Action). Note: Only scenarios with a credit risk ρ_C between 10 and 20% or a market risk ρ_M between 5 and 7.5% are displayed.

relatively low variation across SSPs, with SSP5 and SSP1 ranking very high, followed by SSP2 and SSP3. SSP4, by contrast, exhibits comparatively lower Incumbent risk. Regarding SSP1 and SSP5, results are interesting in showing that carbon intensity improvements do not necessarily shelter the Incumbent sector very much and that growth hypotheses only partially allow it to escape from its financial doldrums. It further confirms that a significant share of financial disturbances, in extreme scenarios, can be attributed to different Challenger dynamics.

SSP2 and SSP4 further illustrate the importance of carbon intensity improvement

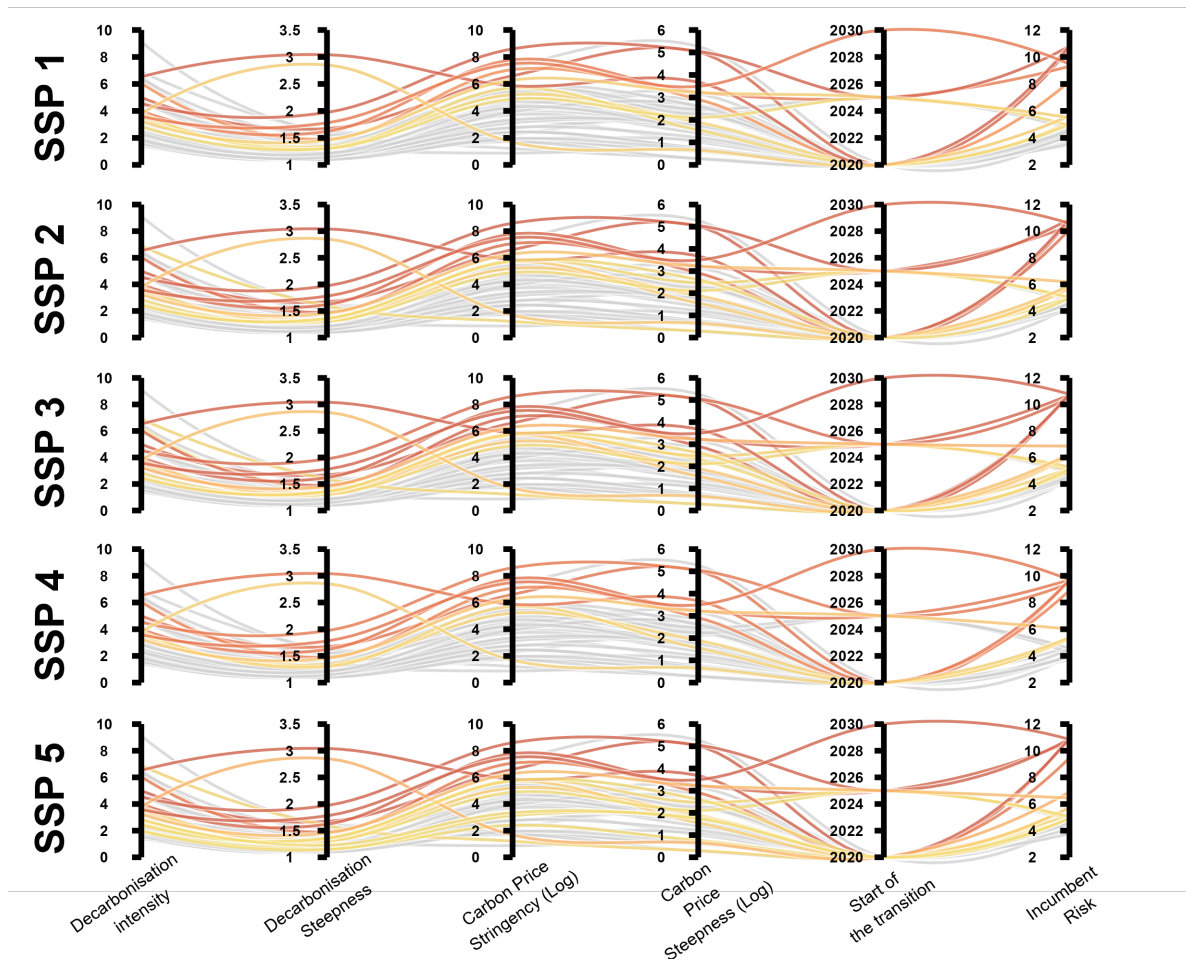


Figure C.3.1: Mapping between firm risk and scenario characteristics for each SSP – Incumbent. Each line joins a combination of scenario characteristics with the value of the outcome of interest, which shows on the far-right axis. Colors indicate Incumbent firm risk. Only combinations with an Incumbent risk above 5% are highlighted.

hypotheses. Being more favourable in SSP4 than in SSP2, they allow the Incumbent sector to partially escape financial turmoil and lower growth, limiting investment needs.

Results finally show the non-linear effects of growth and its interactions with carbon price assumptions. Because of higher growth, investment needs for the Incumbent do not decrease as much as in other instances in SSP1 and SSP5, leading to greater instability overall. In SSP3, low growth impairs the Challenger sector in case of high

carbon price, but not in other scenarios.

We now move on to timing indicators for Incumbent risks. For brevity, and given the lesser interactions between Challenger and firm risks, we group all related timing indicators in one graph. That is, we display the time of highest Incumbent risk and the length of the period in the same locus. We only focus on the timing of firm risk events by focusing on the most severe cases, *i.e.*, when the firm risk indicator is above 5%.

The apparent negative correlation between both indicators suggests that, in these cases, the default probability of Incumbent reaches a peak and then decreases more or less late depending on the scenarios, in line with the behaviours shown in Daumas (2022) (Chapter 2). Scenarios with the earliest shocks and the highest shock duration feature high carbon prices or vigorous decarbonisation intensity. Delayed-action scenarios shift the Incumbent risk apex by five to ten years, depending on the transition. Finally, the latest shocks and shortest durations are less stringent scenarios, which postpone financial disturbances to the 2050s.

We now move on to Challenger risk, which shows distinct patterns to Incumbent risk. First, we see a much more significant variation across SSPs. SSP5 and SSP4 exhibit the lowest Challenger risk, while SSP1 shows the highest results. It is consistent with the discussions held in Section 5. Either the Challenger is penalised due to a relative advantage given to the Incumbent thanks to autonomous carbon intensity improvements, or it is affected by lower growth.

Across best representatives, the highest Challenger risks emerge under delayed-action scenarios or those with the highest climate ambition. Investment needs for the Challenger being higher in these scenarios, the sector needs to be improved with a more fragile position due to higher leverage. These effects are exacerbated in scenarios with higher carbon intensity improvements for the Incumbents. Results also highlight a non-linear effect of growth hypotheses. SSP3 (low growth) shows higher Challenger risk, suggesting that a brake on its development can harm its financial position. On the other hand, too high growth, in the presence of carbon intensity improvement,

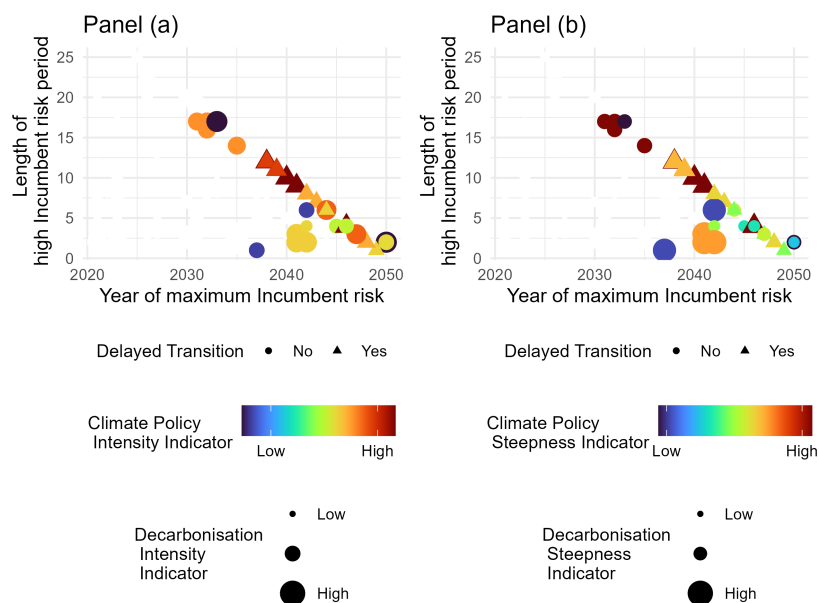


Figure C.3.2: Time structure of firm risk events – Incumbent. In both panels, on the x-axis the year of Challenger risk apex, on the y-axis the length of the high Challenger risk period. In Panel (a), these two values are associated with intensity indicators. Color indicates Climate Policy Stringency and Size indicates Decarbonisation Steepness. In Panel (b), market and credit risk apexes are associated with steepness indicators. Color indicates Climate Policy Steepness and Size indicates Decarbonisation Steepness. In both Panels, Shape indicates whether the transition starts after 2025 (Delayed Action). Only scenarios with a Incumbent risk ρ_{CH} above 5% are displayed

can be highly detrimental. Indeed, in such a case, the Challenger is in charge of most of the investment effort, while its market share does not grow enough for it to cover investment expenses. This development also makes its position more fragile.

Regarding timing, we show results in Figure C.3.4, with the same display as in Figure C.3.2. Very few scenarios exhibit severe Challenger risks. Most show a Challenger risk apex emerging in the early periods of the transition, with a high-risk period lasting for around five years. These scenarios are, overall, the least stringent ones, characterised by some short-run adjustments at the start of the transition. More problematic scenarios feature delayed-action scenarios and scenarios with very high decarbonisation intensity (climate ambition). Again, very high climate targets significantly put much pressure on the challenge sector when carbon intensity improvements

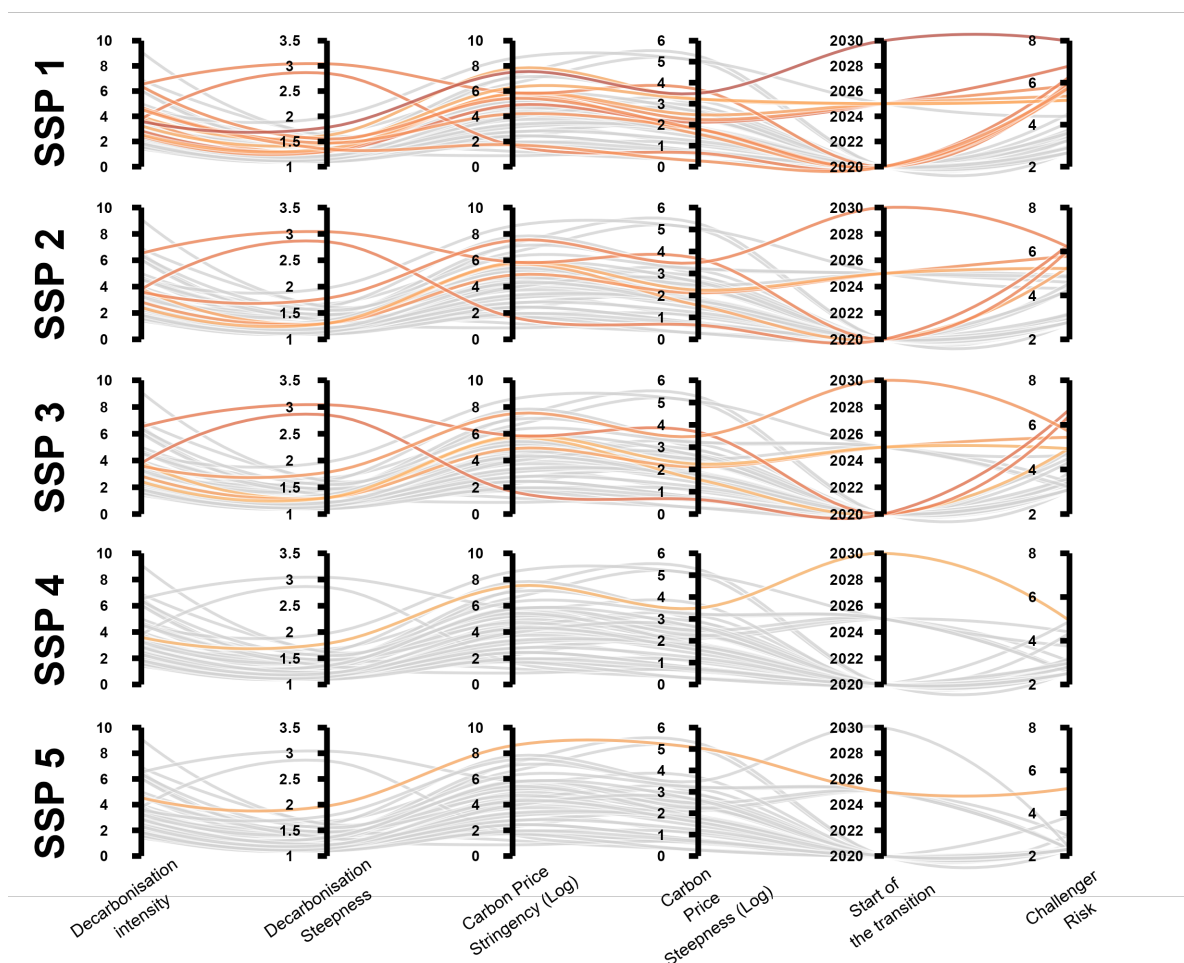


Figure C.3.3: Mapping between firm risk and scenario characteristics for each SSP – Challenger. Each line joins a combination of scenario characteristics with the value of the outcome of interest, which shows on the far-right axis. Colors indicate Challenger firm risk. Only combinations with a Challenger risk above 5% are highlighted.

hamper its development.

D. Sensitivity simulations

In this Appendix, we use our numerous sensitivity calibrations to analyse how outcomes vary for the same Scenario-SSP pair but with different calibrations. For brevity, We also only report results for two outcomes: market and credit risk.

To do so, we first show the dispersion of our outcomes across scenario-SSP pairs. To

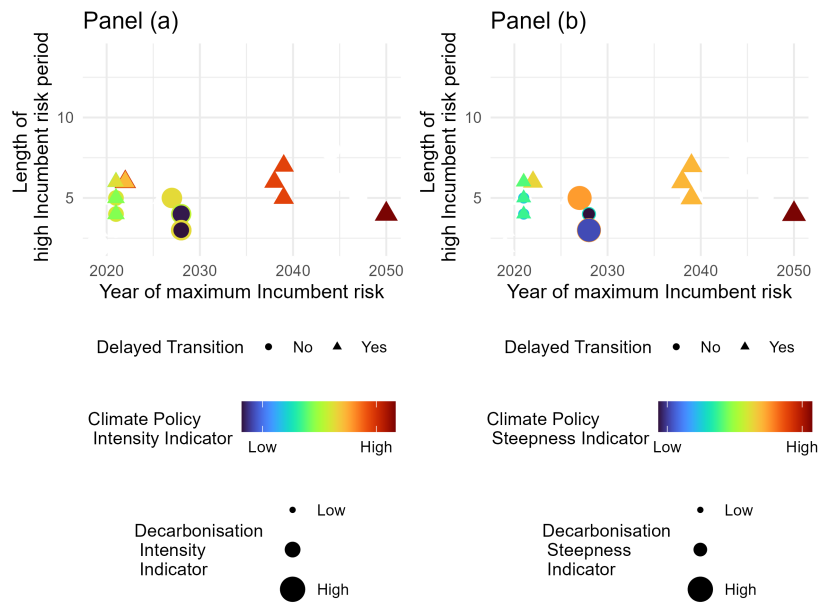


Figure C.3.4: Time structure of firm risk events – Challenger In both panels, on the x-axis the year of Challenger risk apex, on the y-axis the length of the high Challenger risk period. In Panel (a), these two values are associated with intensity indicators. Color indicates Climate Policy Stringency and Size indicates Decarbonisation Steepness. In Panel (b), market and credit risk apexes are associated with steepness indicators. Color indicates Climate Policy Steepness and Size indicates Decarbonisation Steepness. In both Panels, Shape indicates whether the transition starts after 2025 (Delayed Action). Only scenarios with a Challenge risk ρ_{CH} above 5% are displayed

do so, we resort to a variation coefficient defined as follows:

$$C = 100 \frac{SD_W(X)}{\bar{X}_W},$$

where the W subscript highlights that we use Winsorised (95%) values for the standard deviation ($SD(X) = \sqrt{V(X)}$, $V(X)$ the variance of X) and the mean (\bar{X}). We use this index to provide a normalised measure of our outcomes' dispersion, their means being potentially very different. Here, the (Winsorised) standard deviation is divided by the (Winsorised) mean. Hence, the index must be interpreted as an average deviation from the mean, as a percentage of the mean. Finally, we prolong the sensitivity analysis of Chapter 2 by including the role of SSPs.

D.1. Variance of outcomes

To study the variance of our outcomes, we replace the mean result across sensitivity calibrations presented in Section 5 with the corresponding variance using our parallel coordinate plot template. We first report results for market risk and then for credit risk.

As shown in Figure D.1.1, the variance of our result is very low for market risks for a large swath of scenarios. For SSP4 and 5, no scenario exhibits a market risk indicator with a standard above 40% of the mean. The others *exhibit* relatively higher variances, with some scenarios showing a higher variance due to outliers. These scenarios have the highest *ex-post* and transition risk content. They illustrate that a stronger sensitivity to transition risks also introduces a higher sensitivity to parameter assumptions. Note that these results also hold for the scenarios yielding the highest mean outcome, increasing confidence in our results.

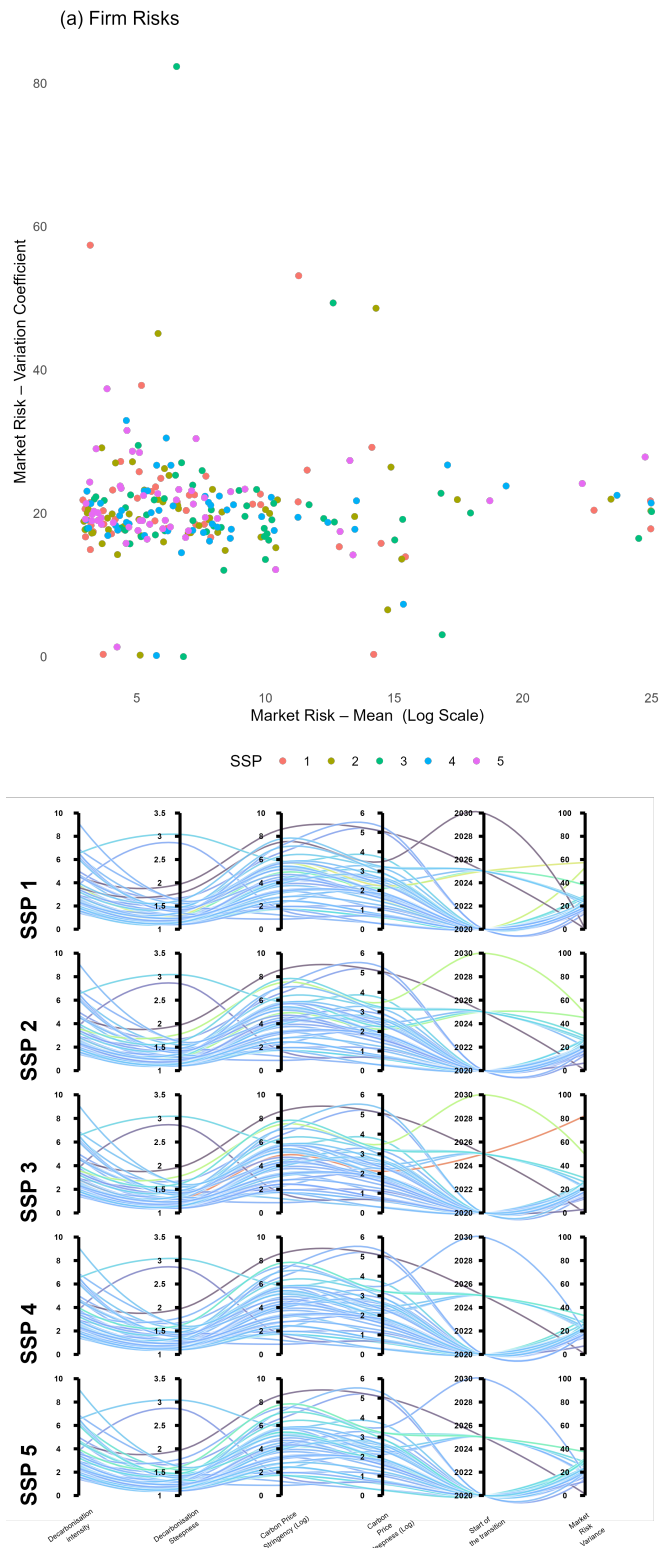


Figure D.1.1: Mapping between market risk variance and scenario characteristics for each SSP. In Panel (a) Each bubble is a scenario, with colors giving the SSP. In Panel (b), the variation coefficient of the outcome is associated with mitigation pathways' characteristics. Each line joins a combination of scenario characteristics with the value of the outcome of interest, which shows on the far-right axis. Colors indicate the variance of the outcome for a given scenario.

Figure D.1.2 shows a distinct picture of credit risk. Overall, deviations can be much higher, reaching values above 1,000%. These high numbers indicate a higher presence of outliers for some SSP-scenario pairs and, therefore, a higher degree of non-linearity between parameter assumptions and credit risk. Overall, scenarios with high variation coefficients are scenarios with low decarbonisation intensity and stringency relative to their climate policy assumptions, except for our highest-ambition scenario. As a result, scenarios with low climate policy efficiency relative to modest climate targets seem more sensitive to calibration assumptions, highlighting the destabilising potential of low-efficiency climate policy.

However, there is very little uncertainty in high-risk scenarios, which suggests that, above a certain threshold, inefficient climate policies are adverse in any state of the world. Finally, regarding SSPs, while SSP1-4 exhibits very similar patterns, with roughly the same population of high-variance scenarios, SSP5 exhibit one scenario with very high variation, highlighting the presence of some outliers. Hence, albeit safer on average, SSP5 scenarios can exhibit high sensitivity to macroeconomic data.

D.2. Sensitivity analysis across SSP-MP pairs

We follow, link in Chapter 2, by regressing our parameters on our two outcomes of interest by selecting the best-fit model with an AIC criterion. To be consistent with the above dispersion measures, we run regressions on Winsorised outcomes at 95%. We report the results in Table D.2.1. Note that for the credit risk outcome ρ_C , the interpretation of the signs should be reversed with respect to Chapter 2, since a higher ρ_C implies a lower minimum CAR.

Table D.2.1: Sensitivity Analysis – OLS

	<i>Dependent variable:</i>	
	Credit risk ρ_C	Market Risk ρ_M
	(1)	(2)
ν_{w_1}	-25.123*** (3.668)	-0.125*** (0.019)
ν_{w_2}		-0.012*** (0.002)
γ_C		-1.106*** (0.145)
γ_C^2	-338.588*** (25.154)	2.762*** (0.843)
ξ_{NBFI}	-42.693*** (10.553)	-0.128** (0.055)
ξ_{Funds_B}	37.696*** (11.738)	
r_{BG}	-32.911*** (4.532)	0.085*** (0.024)
σ_{CH}	-103.567*** (9.453)	0.132*** (0.049)
σ_{IN}	-11.091*** (1.451)	0.113*** (0.008)
σ_{NBFI}	-11.441***	0.134***

Continued on next page

	<i>Dependent variable:</i>	
	Credit risk ρ_C	Market Risk ρ_M
	(1)	(2)
	(1.451)	(0.008)
σ_{NPL}	-43.093***	
	(9.431)	
$\bar{\mu}$	-823.896***	1.002***
	(163.133)	(0.022)
\overline{lev}	-17.887***	-0.157***
	(5.862)	(0.030)
φ_1	103.696***	-0.003***
	(21.375)	(0.001)
φ_2	-24.677***	0.013***
	(2.919)	(0.0004)
ϖ_1		-0.009***
		(0.001)
λ_λ	-190.164***	-1.057***
	(44.281)	(0.230)
$\lambda_{KLC,0}$	-5.449***	-0.082***
	(0.876)	(0.005)
$\lambda_{o,0}$	-3.270***	-0.011*
	(1.172)	(0.006)
ν	-36.287***	-0.636***
	(11.772)	(0.061)
τ_{Tob}	3.102***	0.017***
	(0.472)	(0.002)
ω_p	-1.362***	-0.007***
	(0.317)	(0.002)
$\nu_{w_1}^2$	19.641***	0.085***
	(2.708)	(0.014)
ξ_{NBFI}^2	25.598***	0.088***
	(5.825)	(0.030)
ν_u^2	-168.770***	-0.928***

Continued on next page

	<i>Dependent variable:</i>	
	Credit risk ρ_C	Market Risk ρ_M
	(1)	(2)
	(28.317)	(0.147)
$\xi_{Funds_B}^2$	-250.901***	-0.338***
	(58.681)	(0.024)
r_D^2	30,823.490***	-89.023***
	(1,829.100)	(9.491)
σ_{CH}^2	1,072.470***	3.427***
	(149.370)	(0.775)
σ_{NPL}^2	282.390*	2.090***
	(148.643)	(0.119)
$\bar{\mu}^2$	5,044.750***	
	(1,254.243)	
$\bar{l}ev^2$	55.439***	0.334***
	(14.596)	(0.076)
φ_1^2	-6.933***	
	(1.320)	
φ_2^2	2.055***	
	(0.187)	
ϖ_2^2	-0.364***	
	(0.050)	
ϖ_1^2	0.077***	0.001***
	(0.012)	(0.0001)
λ_λ^2	1,640.859***	8.821***
	(368.492)	(1.913)
$\lambda_{KLC,0}^2$	0.680***	0.011***
	(0.146)	(0.001)
$\lambda_{\sigma,0}^2$	1.478**	0.005*
	(0.583)	(0.003)
ν^2	253.227***	2.296***
	(58.680)	(0.304)
τ_{Tob}^2	-2.119***	-0.013***

Continued on next page

	<i>Dependent variable:</i>	
	Credit risk ρ_C	Market Risk ρ_M
	(1)	(2)
	(0.372)	(0.002)
MP 2	-30.439***	-0.096***
	(0.169)	(0.001)
MP 3	-32.395***	-0.095***
	(0.169)	(0.001)
MP 4	-39.456***	-0.135***
	(0.169)	(0.001)
MP 5	-34.842***	-0.108***
	(0.169)	(0.001)
MP 6	-34.156***	-0.113***
	(0.169)	(0.001)
MP 7	-32.329***	-0.101***
	(0.169)	(0.001)
MP 8	-36.119***	-0.077***
	(0.169)	(0.001)
MP 9	-25.379***	-0.071***
	(0.169)	(0.001)
MP 10	-39.828***	-0.122***
	(0.169)	(0.001)
MP 11	-37.890***	-0.055***
	(0.169)	(0.001)
MP 12	-39.704***	-0.136***
	(0.169)	(0.001)
MP 13	-39.052***	-0.120***
	(0.169)	(0.001)
MP 14	-38.619***	-0.100***
	(0.169)	(0.001)
MP 15	-36.903***	-0.122***
	(0.169)	(0.001)
MP 16	-32.066***	-0.103***

Continued on next page

	<i>Dependent variable:</i>	
	Credit risk ρ_C	Market Risk ρ_M
	(1)	(2)
	(0.169)	(0.001)
MP 17	-38.099***	-0.123***
	(0.169)	(0.001)
MP 18	-36.745***	-0.107***
	(0.170)	(0.001)
MP 19	-29.052***	-0.056***
	(0.171)	(0.001)
MP 20	-39.976***	-0.140***
	(0.170)	(0.001)
MP 21	-39.970***	-0.140***
	(0.170)	(0.001)
MP 22	-39.966***	-0.097***
	(0.170)	(0.001)
MP 23	-39.883***	-0.126***
	(0.170)	(0.001)
MP 24	-39.983***	-0.145***
	(0.170)	(0.001)
MP 25	-40.091***	-0.148***
	(0.170)	(0.001)
MP 26	-39.856***	-0.141***
	(0.170)	(0.001)
MP 27	-23.564***	-0.027***
	(0.170)	(0.001)
MP 28	-39.041***	-0.127***
	(0.170)	(0.001)
MP 29	-35.755***	-0.092***
	(0.171)	(0.001)
MP 30	-36.776***	-0.038***
	(0.170)	(0.001)
MP 31	-39.725***	-0.116***

Continued on next page

	<i>Dependent variable:</i>	
	Credit risk ρ_C	Market Risk ρ_M
	(1)	(2)
	(0.170)	(0.001)
MP 32	-39.993***	-0.137***
	(0.170)	(0.001)
MP 33	-39.812***	-0.131***
	(0.170)	(0.001)
MP 34	-39.772***	-0.108***
	(0.170)	(0.001)
MP 35	4.352***	0.070***
	(0.284)	(0.001)
MP 36	-21.888***	-0.030***
	(0.170)	(0.001)
MP 37	-9.383***	0.061***
	(0.170)	(0.001)
MP 38	-39.203***	-0.102***
	(0.170)	(0.001)
MP 39	-34.629***	-0.074***
	(0.170)	(0.001)
MP 40	-35.719***	-0.096***
	(0.170)	(0.001)
MP 41	-36.998***	-0.100***
	(0.170)	(0.001)
MP 42	-15.439***	0.018***
	(0.218)	(0.001)
MP 43	-39.772***	-0.142***
	(0.170)	(0.001)
MP 44	-39.606***	-0.135***
	(0.170)	(0.001)
MP 45	-37.434***	-0.121***
	(0.169)	(0.001)
MP 46	-39.838***	-0.144***

Continued on next page

	<i>Dependent variable:</i>	
	Credit risk ρ_C	Market Risk ρ_M
	(1)	(2)
	(0.170)	(0.001)
MP 47	-39.777***	-0.139***
	(0.170)	(0.001)
MP 48	-39.574***	-0.081***
	(0.170)	(0.001)
MP 49	-39.615***	-0.133***
	(0.170)	(0.001)
MP 50	-39.796***	-0.127***
	(0.170)	(0.001)
SSP 2	-0.226***	-0.001**
	(0.053)	(0.0003)
SSP 3	0.181*	0.002***
	(0.103)	(0.001)
SSP 4	0.215***	0.002***
	(0.064)	(0.0004)
SSP 5	-1.380***	-0.002***
	(0.142)	(0.001)
Constant	-194.737**	0.455***
	(84.707)	(0.029)
Observations	120,350	120,350
R ²	0.694	0.719
Adjusted R ²	0.694	0.719
Residual Std. Error	5.432 (df = 120259)	0.028 (df = 120262)
F Statistic	3,026.870*** (df = 90; 120259)	3,536.040*** (df = 87; 120262)

Note:

*p<0.1; **p<0.05; ***p<0.01

For SSPs, the reference value is SSP1. For Scenarios, the reference value is Scenario indexed 1.

As can be seen, results are globally aligned with those found in Chapter 2, with nonetheless lower R^2 metrics due to the increased variance across our results. Most

parameter values have similar signs and levels of significance, which comforts us in the stability of our model even across many scenarios. However, some differences emerge due to the larger sample on which the OLS is run and the slight change in specification. We focus here on the most meaningful ones. In particular, some effects become linear, like inflation ($\nu_{w,1}$), while retaining the same overall negative sign. Some other variables gain significance, like the NBF1 payout ratio ξ_{NBF1} , which exhibits a positive linear effect. It implies that a higher payout ratio may increase the resilience of the system through growth effects but that too high payouts create fragility for the agents. Finally, φ_2 exhibits a non-linear positive effect, which contrasts with the results in Chapter 2. This difference likely emerges due to a larger sample size and a laxer tolerance in the selection of our sensitivity calibration, which may allow us to explore a wider breadth of parameter sets with high φ_2 than in Chapter 2. Similarly, interest rate variables exhibit non-linear positive effects on both indicators. For market risks, the effect is fully positive, highlighting the destabilising effect of interest rate hikes on NBFIs – which we also found in Chapter 2. For credit risk, the linear effect is negative, suggesting that, while incremental interest rate increases may temper credit risks, too high interest rate hikes may endanger the viability of borrowers in a classical Minskian way (Nikolaidi 2017). However, despite these differences, the general picture remains the same as in Chapter 2, increasing the confidence in our tool.

We follow, as in Chapter 2, with an ANOVA decomposition. We only display the outcomes of the 20 most important parameters for brevity. Figure D.2.2 displays our results.

Overall, the variables of interest are the same as in Chapter 2, with slight variations due to the higher number of scenarios we consider and changes in the outcome of interest. We find again the importance of $\lambda_{KLC,0}$ for market risk and the crucial role of interest rate variables in explaining the variance.

Following the results in Table D.2.1, some variables of Table D.2.2 in Chapter 2 are missing from the Top 20 influential variables. Notably, some squared effects become

Table D.2.2: ANOVA Analysis

Credit Risk (ρ_C)			Market Risk (ρ_M)		
Variable	Explained Variance (%)	Significance	Variable	Explained Variance (%)	Significance
Scenarios	64.595	***	Scenarios	66.3797	***
φ_2	2.3424	***	ν_{w_1}	1.5231	***
ν_{w_1}	0.8417	***	$\lambda_{KLC,0}$	1.4929	***
$\bar{\mu}$	0.5477	***	σ_{CH}	0.4392	***
$\lambda_{KLC,0}$	0.2827	***	$\bar{\mu}$	0.4207	***
σ_{CH}	0.18	***	ν	0.3969	***
σ_{NPL}	0.095	***	γ_C	0.3519	***
r_D^2	0.0692	***	φ_2	0.174	***
ξ_{FundsB}	0.0448	***	ξ_{NBFI}	0.0821	***
σ_{IN}	0.0393	***	γ_C^2	0.0815	***
SSPs	0.0374	***	φ_1	0.0778	***
σ_{NBFI}	0.0352	***	σ_{NPL}^2	0.0726	***
φ_2^2	0.0328	***	σ_{NBFI}	0.0672	***
ν	0.0306	***	ϖ_2^2	0.0561	***
lev	0.0286	***	$\lambda_{KLC,0}^2$	0.0548	***
φ_1	0.0284	***	ξ_{FundsB}^2	0.0438	***
r_{BG}	0.0171	***	σ_{IN}	0.0331	***
ν_u	0.0145	***	lev	0.0274	***
τ_{Tob}	0.0133	***	r_D^2	0.0216	***
σ_{CH}^2	0.0127	***	SSPs	0.0207	***
Total	69.2884		Total	71.8171	

Note : Only the twenty parameters explaining most variance are displayed.

linear, suggesting that outcome variability across scenarios with different patterns is less non-linear than with fewer scenarios. Note also that, due to changes in SSP calibrations, we explore a larger range of crucial parameters governing growth γ_C , and inflation, ν_1 and ν_2 , which may result in a different ranking from the one shown in Chapter 2.

Overall, however, changes in our macroeconomic worlds and scenarios explain an overwhelming share of the variance, confirming the importance of considering a wide array of scenarios and hypotheses on macroeconomic conditions. However, only looking at these results should not lead to the conclusion that our parameters are unimportant. Instead, it remains to study how much of the variance in the results of a given outcome for a single Scenario-SSP couple.

D.3. Sensitivity analysis for individual SSP-MP pairs

To do so, we again display in Figure D.3.1 the distribution of explained variances across our Scenario-SSP couples by selecting the best fit with an AIC criterion.

Our analysis shows that most of our parameters have a minimal impact on outcomes,

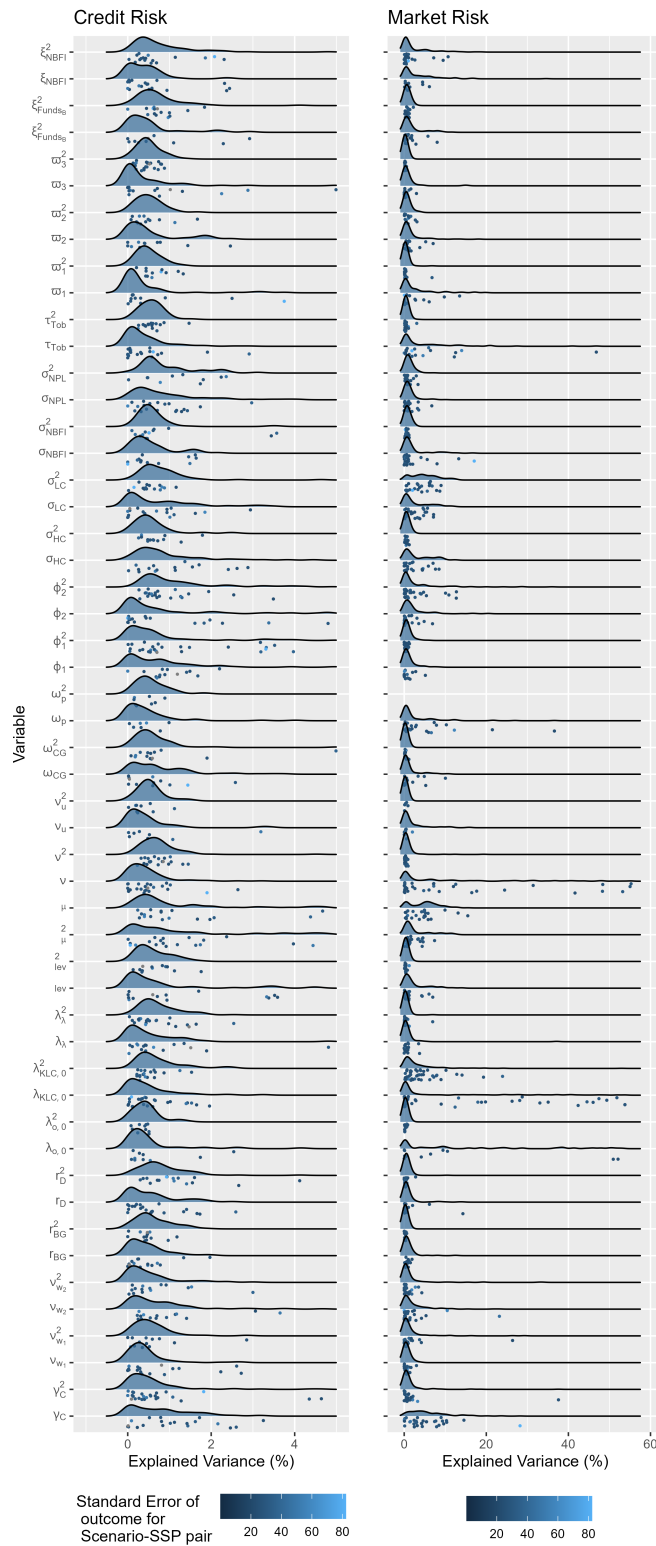


Figure D.3.1: Distribution of explained variance for sensitivity parameters across SSP-Scenario pairs. Bubbles are observations, with colors corresponding to the standard variation of outcome for the corresponding SSP-Scenario pair. Only observations in top-20% of standard error for the outcome are displayed. For instance, a bubble showing on the $x_{NBFI,s,q}$ in Panel (a) gives the share of the variance explained by this parameter in a scenario whose credit risk outcome is within the top-20% of standard errors across SSP-Scenario pairs.

explaining only a share of variance slightly above zero on average. Results are broadly in line with the ANOVA analysis of Table D.2.2, showing a minor dependence on scenarios. For credit risks, explained variance is relatively low across our parameters, ranging between 1 and 2% on average and globally homogeneous. Indeed, outliers, if any, lie relatively close to the distribution mode, as do most values of interest. For market risk, a more significant share of outliers lies far from the mode, with some scenarios driven by one or two parameters. It highlights the higher sensitivity of NBF1 default probability to parametrisation already highlighted in Chapter 2. These parameters are the NBF1 leverage parameter ν and the cost parameters $\lambda_{KLC,0}$ and $\lambda_{o,0}$, and, to a lesser extent, the passthrough rate and the Tobin coefficient. In contrast to the ANOVA analysis, the passthrough rate seems more critical in some high-variant scenarios, highlighting that some scenario profiles are more sensitive to some parameters. We rely on our parallel coordinate template to link the explained variance to scenario characteristics to disentangle which scenarios exhibit such sensitivity patterns. For brevity, we only perform this analysis for the two parameters with the most significant outliers: ν and $\lambda_{KLC,0}$.

For ν , scenarios are those with low climate-policy efficiency, for mid to mid-high carbon price stringency and steepness. It highlights again the destabilising role of inefficient climate policy. The scenario highly driven by $\lambda_{KLC,0}$ is the low-ambition, slow decarbonisation dynamics and low climate policy pressure. It is fair to assume that, with such an “easy” transition, the cost of low-carbon technology will play a major role in determining outcomes, other scenario hypotheses being relatively innocuous for financial agents. Otherwise, high-stringency scenarios are also driven by $\lambda_{KLC,0}$, which is reasonable, given that less expensive low-carbon technologies may make sharp adjustments less disruptive. Finally, in both cases, we find, again, the higher variability in SSP5 scenarios, highlighting these projections’ greater sensitivity to parameter values.

Despite some outliers, the model behaves consistently across scenarios, confirming that a disproportionate source of variance for our results flows from different scenario

assumptions. It confirms the need to assess better scenario and model uncertainty in assessing long-run transition risks.

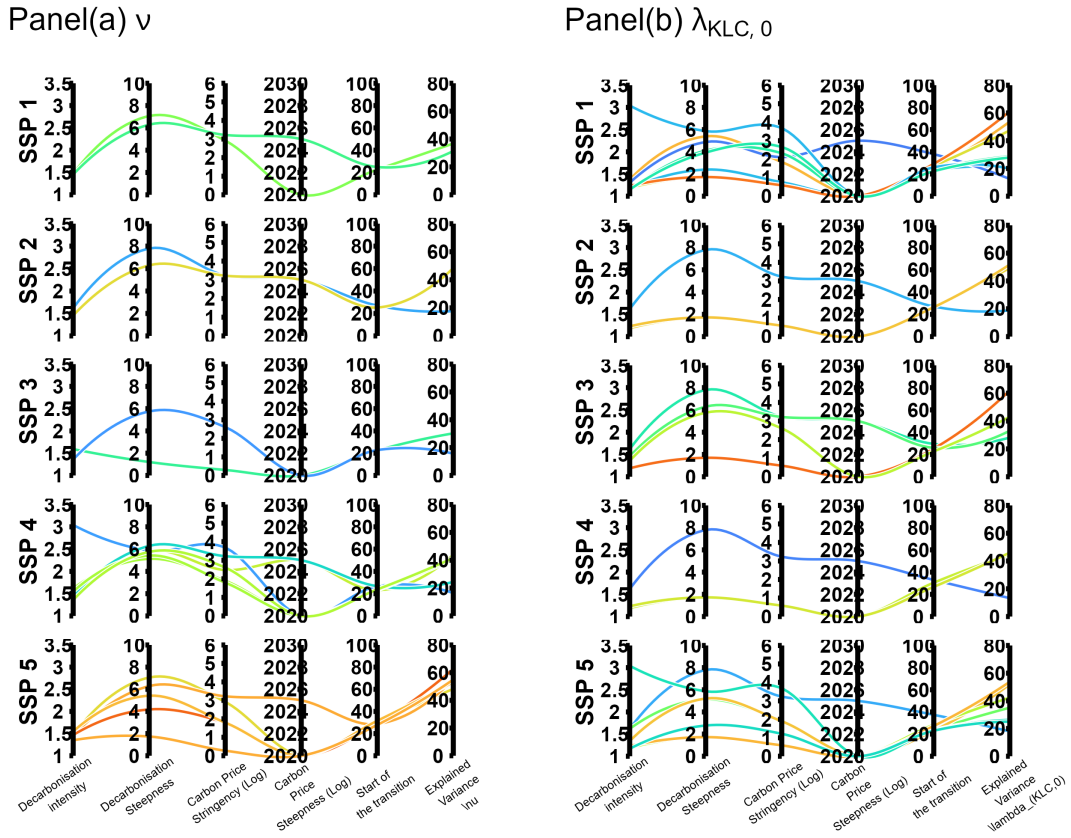


Figure D.3.2: Matching between scenario characteristics and outliers in explaining variance. Color shades correspond to the explained variance. Panel (a) displays results for variable ν (NBFi leverage) and Panel (b) displays those for $\lambda_{KLC,0}$ the starting value of the productivity of low-carbon capital production, which influences the cost of low-carbon technology. Only observations explaining a high share of the variance are displayed, and only scenarios in the top-75% of outcome variance are displayed.

Chapter 4

Stranding Ahoy?

Heterogeneous Transition

Beliefs and Capital

Investment Choices

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Abstract

Individuals have heterogeneous beliefs regarding the future speed and shape of the low-carbon transition. In this paper, we study to what extent opinion diversity matters for aggregate capital investment decisions. We develop a model where firms formulate heterogeneous expectations around a dominant narrative, or ‘market norm’, with their dispersion increasing over a finite planning horizon. Our analytical and numerical results suggest that belief heterogeneity can significantly affect the share of low-carbon investments, with the strength of its effects non-linearly correlated to market norms. We show that investment behaviour tends to be more sensitive to shocks to short-term, rather than long-term, belief heterogeneity, highlighting the importance of setting credible short-term targets. Finally, we find beliefs to interact strongly and in non-trivial ways with measures of short-termism, with increasing agents’ farsightedness not necessarily leading to less carbon-intensive investments under high heterogeneity.

Acknowledgements

We would like to thank Giorgos Galanis, Francesco Lamperti, Hubert Massoni, Esther Marie Shears, Alessandro Spiganti, Marko Stojanovic and Roberta Terranova, as well as participants to the 2021 EAERE and the 2022 ESEE conferences. The research leading to these results has received funding from the Oesterreichische Nationalbank (Jubiläumsfonds projects 17641 and 18651). E.C. and L.D. gratefully acknowledge funding from the European Research Council (ERC) under the European Union’s Horizon 2020 Research and Innovation Programme (Grant agreement No 853050 - SMOOTH). All remaining errors are ours.

Introduction

How do you expect the low-carbon transition to unroll? This question is likely to be answered in radically different ways by different individuals, depending on their information set, their degree of trust in policymakers, their beliefs on future technological advancements, and a number of other behavioural factors. Some might expect the transition to take place rapidly and in line with limiting global warming to 1.5°C or 2°C (IPCC 2022b; IEA 2021a). Others might expect more gradual dynamics, allowing carbon-intensive assets to exit the economic system in an orderly fashion or to remain in some proportion in the long term. Others might not even have well-formulated answers, as the transition timeline goes beyond the span of their planning horizon.

Disagreement over what lies in the future is common and found to be significant in several spheres of economic behaviour (Coibion, Gorodnichenko, and Kumar 2018; Hommes 2021; Mankiw, Reis, and Wolfers 2003; Xiong and Yan 2010). Some recent contributions have shown evidence of heterogeneous expectations also for what concerns transition-related beliefs (*e.g.* Giglio, Maggiori, et al. 2023; Nordeng et al. 2021), but these insights have yet to be incorporated in suitable modelling frameworks. Does expectation heterogeneity matter for the low-carbon transition dynamics?

In this paper, we address this research question by developing a model of capital investment choices with heterogeneous beliefs.¹ In our model, firms choose how to allocate investments between a high- and a low-carbon technology based on their relative expected profits, discounted over a finite planning horizon. Profit expectations are affected by how decision-makers perceive the future speed and shape of the low-carbon. We proxy transition-related beliefs by focusing on the expected degree of ‘stranding’ of the high-carbon technology, *i.e.* its expected utilisation rate. If the firm imagines a rapid low-carbon transition in the near future, it will expect the high-carbon technology to be used less than fully and, hence, generate lower revenues

¹In what follows, we use the word ‘beliefs’ interchangeably with ‘expectations’ to insist on the idea that beliefs about the future are not model-consistent, following Acemoglu and Jensen (2018).

and profits. If it expects instead a slow transition, it will anticipate full or close to full utilisation of carbon-intensive capital stocks. We then use a discrete choice model to aggregate the multiple decentralised individual investment choices and compute the overall share of low-carbon investments.

We introduce three main features of expectations in an attempt to capture relevant real-world dimensions.

First, a central transition projection exists, representing the dominant wisdom, or “market norm”, within the community of investors. Agents take this as a focal point when formulating their expectations and investment decisions (Beckert and Bronk 2018; Schelling 1960).

This ‘common wisdom’ can take the form of a general narrative that most agents believe to be true and that guides their investment decisions, which might be more or less close to the government’s stated policy objectives (Boyer 2018; Campiglio, Lamperti, and Terranova 2023). While we refrain from simulating co-existing conflicting narratives, we explore the implications of two distinct possible central projections: (i) a low-stranding scenario, roughly aligned with current policies and the expectation of a gradual transition; and (ii) a high-stranding scenario, entailing a more rapid transition and achieving net-zero emissions by mid-century.

Second, individual agents might drift from this dominant opinion, following their own beliefs. As exemplified by the wide range of possible decarbonisation pathways given by IPCC (2022b) and other institutions (*e.g.* IEA 2020d), the precise pace and shape of decarbonisation is far from being well-established.

Different combinations of production technologies, energy-efficiency measures and societal changes may leave investors undecided as to what kind of business will be most adequate for the future. Further uncertainties around the implementation of mitigation policies and technological developments cast doubt on the pace and steadiness of the low-carbon transition and force agents to formulate their own expectations around the market norm (Nemet et al. 2017). Hence, today’s assessment of the profit prospects of available technological options is a distribution rather than a point value,

with its shape depending on the strength of transition-related belief diversity. Heterogeneity in beliefs may make aggregate investment decisions uncoordinated, possibly contradictory, ultimately hampering the good course of the transition (Acemoglu and Jensen 2018; Fais et al. 2016).

Third, the degree of heterogeneity varies with the length of the time horizon considered. As shown by the literature on the term structure of expectations for key macroeconomic variables, diversity in expectations depends crucially on how far away in time agents are projecting (Patton and Timmermann 2010; El Ouadghiri and Uctum 2020; Binder, McElroy, and Sheng 2022). Figure 1 confirms this evidence by showing how the dispersion of expectations concerning future carbon price levels increases if individuals are asked to provide estimates for periods further in time. We capture this stylised fact by letting the variance of expectation distribution increase along the planning horizon. We propose a novel logistic characterisation of this feature, building on the IPCC 6th Assessment Report decarbonisation scenarios (IPCC 2022b).

We then calibrate our model on 2019 data for the European Union and derive both analytical and numerical results. We illustrate our findings with a sensitivity analysis based on sensible value ranges of our behavioural parameters. Our main results can be summarised as follows.

First, heterogeneity of transition expectations does matter, as it significantly affects firms' investment allocation decisions. We find the direction and strength of this effect to depend on the underlying market norm and its associated capital-stranding dynamics. In general, stronger belief heterogeneity will decrease the share of low-carbon investment in the presence of high-stranding central expectations and increase it when central expectations forecast low stranding. However, we also find this relationship to be strongly non-linear. Market norms centred around expectations of either very low or very high stranding (*i.e.* very slow or very rapid transition) will lock in investment behaviours, while more balanced stranding expectations are exposed to large investment swings if belief dispersion moves.

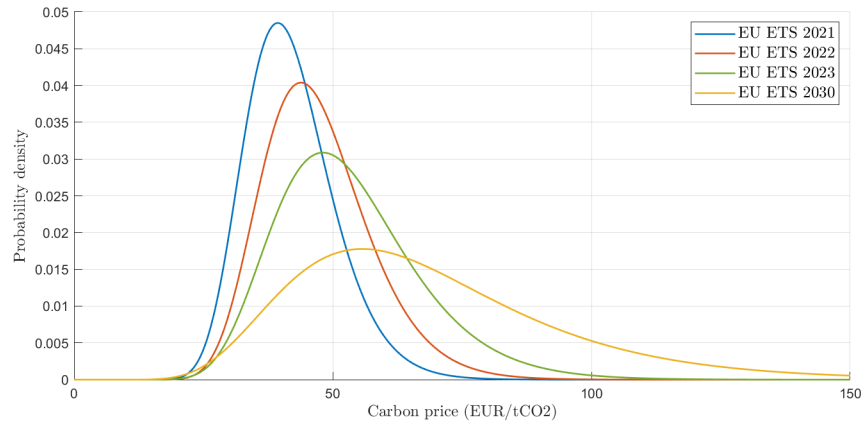


Figure 1: Distribution of expected carbon price in the EU Emission Trading Scheme for different time horizons. Adapted from Nemet et al. (2017), using data from Nordeng et al. (2021)

Second, we show how, for our benchmark calibration and for a sizeable proportion of the parameter constellation we explore, investment behaviours are more sensitive to shocks to short-term, rather than long-term, belief heterogeneity. This situation only reverses if agents are strongly far-sighted. This result suggests that policymakers should prioritise anchoring expectations for the earliest periods of the transition, even if there is no clear consensus about long-term outcomes. The introduction of credible *short-term* targets hence appears crucial. In addition, policymakers risk misinterpreting the drivers of investment allocation changes (*e.g.* an increase in low-carbon investment share might be due to shocks to short-run belief heterogeneity rather than a change in market norms), which recommends a thorough measurement and analysis of transition-related expectations, currently missing.

Third, we find belief heterogeneity to interact strongly with measures of short-termism (high discount rate or short planning horizon).² This tendency can be exacerbated by cognitive limitations, biases or norms, creating sets of incentives favouring myopia. While it has been shown that short-termist behaviour can slow down the development of relevant technologies and the pace of decarbonisation (Souder, Reilly, et al. 2016; Nerini, Keppo, and Strachan 2017; Löffler et al. 2019), it is yet unclear

²Many companies extend the time horizon considered to adopt business decisions, including investments, only up to a few years into the future (Souder, Badwaik, et al. 2021; Spiro 2014).

how different time preferences could interact with heterogeneous transition expectations in determining individual and aggregate capital investment choices. The effect of a higher discount rate on low-carbon investment share is exacerbated (mitigated) by higher heterogeneity if central expectations imply high (low) stranding. Belief heterogeneity can also negatively affect the impact of longer planning horizons, which generally increases low-carbon investment shares, by further widening the range of projections and expanding the diversity of opinions.

Our article contributes to a better understanding of the role of expectations/beliefs and time preferences in defining the carbon intensity of capital investment choices.

Several contributions rooted in neoclassical economic theory have investigated *optimal* investment decision-making in the context of the low-carbon transition, with or without uncertainty (among others Cai and Lontzek 2018; Campiglio, Dietz, and Venmans 2022; van den Bremer and van der Ploeg 2021; Vogt-Schilb, Meunier, and Hallegatte 2018).

Expectations in these models are usually homogeneous and model-consistent. Other contributions in the field of behavioural macroeconomics have studied transition dynamics, allowing for belief/preference heterogeneity and stronger complexity in individual and systemic behaviours (Dunz, Naqvi, and Monasterolo 2021; Knobloch and Mercure 2016; Geisendorf 2016). A particularly relevant stream of work in this field for us is the one studying the process of technological diffusion (Mercure 2012; Mercure, Pollitt, Bassi, et al. 2016), which adopts a similar modelling approach rooted in discrete choice theory. However, these models tend to be governed by backward-looking (adaptive) expectations, making it difficult to analyse the effect of changes in the longer-term thinking of economic agents.

We opt for an in-between modelling strategy, able to capture expectations that are both forward-looking and (dynamically) heterogeneous. Our approach is similar in spirit to the literature developing logit or probit models of switching beliefs, usually applied to issues linked to inflation expectations and monetary policy (De Grauwe and Macchiarelli 2015; Franke and Westerhoff 2018; Galanis et al. 2022; Hommes 2021),

but with some recent applications also to climate- and transition-related matters (Campiglio, Lamperti, and Terranova 2023; Cafferata, Dávila-Fernández, and Sordi 2021; Dávila-Fernández and Sordi 2020; di Guilmi, Galanis, and Proaño 2022; Zeppini 2015).

Our treatment of transition expectations positions us close to the literature studying the ‘stranding’ of physical or financial assets along a low-carbon transition (van der Ploeg and Rezai 2020a; Campiglio, Daumas, et al. 2023; Daumas 2023). To our knowledge, this paper is the first to incorporate capital stranding into a model with heterogeneous expectations, with most other contributions assuming homogeneity (see, for instance, Baldwin, Cai, and Kuralbayeva 2020; Campiglio, Dietz, and Venmans 2022; Rozenberg, Vogt-Schilb, and Hallegatte 2020).

We also partly connect to the extended research field tackling the role of time preferences, discounting and planning horizons, in climate-related economic dynamics (see Groom et al. (2022) for a review).

Finally, our joint representation of idiosyncratic beliefs and market norms calls out an emerging literature in economic sociology (Beckert and Bronk 2018; Bronk 2009) and macroeconomics (Andre et al. 2022; Barrero 2022) that has emphasised the role of beliefs and narratives in driving economic outcomes.

The remainder of the article is structured as follows. Section 1 presents our modelling framework. Section 2 explains our calibration strategy. Section 3 discusses some analytical results and illustrates them numerically. Section 4 concludes and discusses future research avenues.

1 The Model

The model is populated by a continuum of firms producing electricity e in response to an exogenous level of electricity demand e^d , growing at a constant rate g_E . Electricity can be produced by two technologies: i) a stock of capital K_L running on renewable resources and producing low-carbon electricity, and ii) a stock of capital K_H run-

ning on fossil fuels and producing high-carbon electricity. The subscript $i \in \{H, L\}$ denotes the technology type. The electricity produced by the two technologies, e_i , $i \in \{H, L\}$, is identical. However, capital stocks have different productivities ξ_H and ξ_L .³ Capacity utilisation $u_i = \frac{e_i}{\xi_i K_i} \in [0, 1]$, defines the extent to which capital stocks are used. We also define a full capacity utilisation level u_i^f , which can differ from one.

1.1 Technological return rates

We assume a continuum of small firms index by $j \in \mathbb{R}$. Firms compare the two available technologies $i \in \{L, H\}$ by calculating their unitary return rate r_i , *i.e.*, the sum of the discounted stream of expected profits $\pi_{i,j,s}$ that can be obtained from a unit of technology (in our case, a unit of installed generation capacity). Firms discount profit expectations over this planning horizon with the same discount factor $\beta = \frac{1}{1+\rho}$, with ρ the corporate discount rate our measure of ‘rational’ short-termism. For firm j , it writes:

$$\mathbb{E}_j(r_i) = \sum_{s=0}^S \beta^s \mathbb{E}(\pi_{i,j,s}), \quad (1)$$

Three components determine the unitary profit rate π_i : i) revenues; ii) capital costs; and iii) variable costs.

Revenues come from producing and selling electricity e_i . Electricity is sold on a wholesale market with a merit order structure. The energy produced by renewable sources usually comes first in the merit order, as these incur lower marginal costs than fossil-based technologies (Figueiredo and Silva 2019). It means that low-carbon electricity will be sold first and, assuming it is not enough by itself to satisfy the entire demand (*i.e.* $e^d > \xi_L K_L$), capacity utilisation u_L will be equal to u_L^f . The high-

³Since capital is the only production input in our model, productivities ξ_H and ξ_L can also be interpreted as Leontief production function coefficients.

carbon capital stock will instead be used to the extent necessary to satisfy demand not already met by low-carbon electricity. That is,

$$u_H = \frac{e^d - e_L}{\xi_H K_H}. \quad (2)$$

The price of electricity p_E is also determined on the merit order, as the price offered by the marginal technology producing (the high-carbon one, typically). Hence, per-period revenues stemming from a unit of capital K_i can be calculated as $p_E u_i \xi_i$.

Capital costs are incurred when installing a new capital unit. The cost of installing a unit of capital i is c_i . Firms require external finance to perform new investments. We define ψ_i as the debt-to-investment ratio, *i.e.* the proportion of investment expenditure funded via borrowed credit. Companies must pay back the debt over the course of the loan tenure LT , together with accrued interests. Firms spread repayment tranches equally throughout the loan tenure period. We thus calculate a capital recovery factor $\alpha_i = \frac{\iota_i(1+\iota_i)^{LT_i}}{1-(1+\iota_i)^{LT_i}}$, where ι is the fixed interest rate applied on the loan. α represents the ratio between the period repayments (inclusive of principal and interests) and the loan stock. Per-period capital costs for technology i can thus be computed as $\alpha_i \psi_i c_i$.

Variable costs in the model only arise from purchasing fossil fuels as intermediate inputs necessary to operate K_H (we abstract for simplicity from other variable costs such as labour). We name the price of fossil fuels p_F and the productivity of fossil fuels in producing electricity ξ_F . Variable costs can thus be computed as $\frac{p_F \xi_H u_H}{\xi_F}$.

At time t , we can treat most of the parameters above as constant in the expected future. The price of electricity p_E is more and more determined by long-term power purchase agreements and is, therefore, less subjected to uncertainty over long horizons. Capital productivity parameters ξ_i are embodied in the specific vintage of capital available today. While productivity is likely to change in the future in more advanced capital vintages, we explicitly place ourselves in the context of an investor

comparing current technologies and anticipating their payoffs. Sidestepping from simple productivity losses due to ageing and related maintenance costs, we assume investors consider productivity parameters to be constant over their planning horizon. Finally, we treat the price of fossil fuels p_F as exogenous, as this allows us to disentangle the effect of stranding expectations.⁴

The proportion of investments covered by debt ψ_i is decided today and remains the same. Loan duration LT and interest rate ι are negotiated with the bank today and remain constant. In other words, firms choose a fixed interest rate and do not renegotiate financing conditions.

We can now define the expected unitary retained profit rates⁵ for the two technologies as:

$$\mathbb{E}_j(\pi_{L,j,s}) = p_E \xi_L u_L^f - \alpha_L \psi_L c_L, \quad (3)$$

$$\mathbb{E}_j(\pi_{H,j,s}) = \left(p_E - \frac{p_F}{\xi_F} \right) \xi_H \mathbb{E}_j(u_{H,s}) - \alpha_H \psi_H c_H, \quad (4)$$

where the only variable subject to firms' expectations is the capacity utilisation rate of the high-carbon capital stock, u_H . We denote by \mathbb{E}_j the fact that expectations are firm-specific.

After discounting and summing the stream of expected profits over the planning horizon S as shown in equation (1) and given a specific vector of expected high-carbon capacity utilisation rates $\{u_s\}_t^S$, an individual firm obtains values for the expected return rates of its two technological options, $\mathbb{E}_j(r_H)$ and $\mathbb{E}_j(r_L)$. Defining:

$$\mathbb{E}_j(\varphi) = \mathbb{E}_j(r_L) - \mathbb{E}_j(r_H) \quad (5)$$

as the difference between the two expected return rates, firm j invests in a unit of

⁴In Appendix B, we extend the model by allowing for beliefs on the future profitability of both technologies.

⁵For the sake of brevity, we conflate in what follows the profit rate and the retained profit rate.

K_L if $\mathbb{E}_j(\varphi) > 0$ or in a unit of K_H if $\mathbb{E}_j(\varphi) < 0$.

1.2 Stranding Expectations

At the aggregate level, we assume stranding expectations to be heterogeneous across firms, normally distributed around a central expectation path and serially uncorrelated. This choice is motivated by the additive stability of independent normal distributions and the easy interpretation of parameters.⁶

Formally, this writes:

$$\mathbb{E}_j(u_{H,s}) = u_{H,s}^* + \varepsilon_{u,j,s}, \quad (6)$$

where $u_{i,s}^*$ identifies a benchmark “central stranding” expected path and the error term $\varepsilon_{u,j,s}$ represents the idiosyncratic expectation of firm j . Its distribution $\varepsilon_{u,s}$ represents the diversity of expectations. It follows a normal distribution with mean 0 and variance σ^2 , *i.e.* $\varepsilon_{u,s} \sim \mathcal{N}(0, \sigma_{u,s})$. We call this schedule “central stranding” in that it would be the path expected if agents did not have idiosyncratic beliefs. This path can be considered the ongoing “common wisdom” on the market that serves as a focal point for agents (Schelling 1960). This “common wisdom” can take the form of a general narrative that most agents believe to be true and that guides their investment decisions (Boyer 2018). It can also be construed as the government’s policy objective that agents use as an anchor for their beliefs. However, we refrain from adopting this definition since we do not model the interactions between regulator credibility and investment behaviours, which may have critical implications (see Campiglio, Lamperti, and Terranova 2023, on this topic). For instance, a very ambitious policy plan may be seen as non-credible and increase belief heterogeneity. As a result, we interpret central expectations only as market norms.

⁶We also implement the model with another family of addition-stable distributions, Stable laws, whose skewness and kurtosis can be parameterised and of which the Normal distribution is a special case. The qualitative insights are similar. However, as Appendix A. discusses, the properties of non-normal Stable distributions render the interpretation of results more uncertain. More general results could be found numerically using convolution products; however, we prefer to opt for addition-stable distributions for analytical clarity. See also Appendix B, where we extend the model by allowing for beliefs on the future profitability of both technologies.

1.3 Central stranding expectation

Three crucial factors contribute to determining firms' transition expectations: i) expected growth of demand; ii) expected speed of development of new technologies; iii) expected long-term share of the new technology in the mix. We analyse each of them in turn.

First, firms expect a constant and positive growth rate g_E of electricity demand within their planning horizon. This assumption is supported by energy demand forecasts, which argue that the increase in global population and the economic development of emerging economies will require an expanding supply of electricity (Enerdata 2021). An expansion of electricity production is also commonly perceived as a crucial component of decarbonisation strategies.

Second, firms expect the transition to follow an S-shaped curve, as technological transitions typically exhibit this pattern (Fouquet 2010; Grubb, Drummond, and Hughes 2020). New technologies often first emerge as niches within a technological paradigm dominated by the incumbent technology (in this case, fossil-based capital stocks). After some early adoption, expansion can accelerate due to a number of factors, including the decline in production costs, the diffusion of information and the growing social legitimisation of the technology (Geroski 2000). In the electricity sector, network effects also play a role in facilitating adoption, as complementary infrastructure and policy develop to better integrate renewable technology. This growth is, however, limited by factors such as market saturation and physical capacity and slows down as we approach the "carrying capacity" of the system. Expectations of low-carbon energy share $\ell_E = \frac{e_L}{e_L + e_H}$ thus move logistically in psychological time s :

$$\mathbb{E}(\ell_{E,s+1}) = \mathbb{E}(\ell_{E,s}) \left[1 + b_\ell \left(1 - \frac{\mathbb{E}(\ell_{E,s})}{\mathbb{E}(\bar{\ell})} \right) \right], \quad (7)$$

where b_ℓ represents the unconstrained expected speed of transition, *i.e.* the growth rate of ℓ_E when close to its lower asymptote and $\bar{\ell}$ represents the maximum expected

share of low-carbon technologies.

Third, firms expect a less-than-full energy transition. Mainly due to the current lack of reliable large-scale energy storage technologies, some non-renewable generation capacities - able to adjust their output more rapidly than renewable technologies - will likely still be needed to deal with demand peaks. In addition, firms might also include radical technological breakthroughs in their mental scenarios (*e.g.* carbon capture and storage, direct air capture, geoengineering), which might result in an early deceleration of ℓ_E . Hence, $\mathbb{E}(\bar{\ell})$ is lower than 1.

Hence, given a set of expectation parameters g_E , b_ℓ and $\bar{\ell}$, the rational stranding path $\{u_s^*\}_t^S$ identifies the succession of expected capital utilisation rates for which i) positive high-carbon investments I_H are expected to the amount necessary to provide the exact amount of K_H needed to satisfy demand $e_s^d - e_{L,s}$ at a full capacity utilisation rate u_H^f , which we call K_H^d ; ii) no premature decommissioning or technological re-conversion of capital stocks is desired by firms; *i.e.* firms do not expect negative investments. We can thus define central stranding expectations of high-carbon investments $I_{H,s}^*$ as:

$$I_{H,s}^* = \text{Max} \left[K_{H,s}^d - (1 - \delta)K_{H,s}^*; 0 \right], \quad (8)$$

Given (7) and the definition of u_H given in section 1.1, we can thus write the resulting rational stranding capacity utilisation u_H^* as:

$$u_{H,s+1}^* = \frac{(1 + g_E) \left(e_s^d - e_{L,s} \left[1 + b_\ell \left(1 - \frac{e_{L,s}}{\bar{\ell} e_s^d} \right) \right] \right)}{\xi_H [(1 - \delta)K_{H,s} + I_{H,s}^*]}. \quad (9)$$

Figure 2 portrays how the expected share of low-carbon energy ℓ_E and the benchmark expected high-carbon capital utilisation rate u_H^* move in psychological time s for different values of expected intrinsic speed of renewable development b_ℓ .

It is worth noting that these expectations concern the whole of the high-carbon sector.

⁷The logistic function defined in equation (5) has a lower asymptote of zero. In the chart, we only show the portion of the curve to the right of our starting calibration value for the share of low-carbon energy, $\ell_{E,0} = 0.22$.

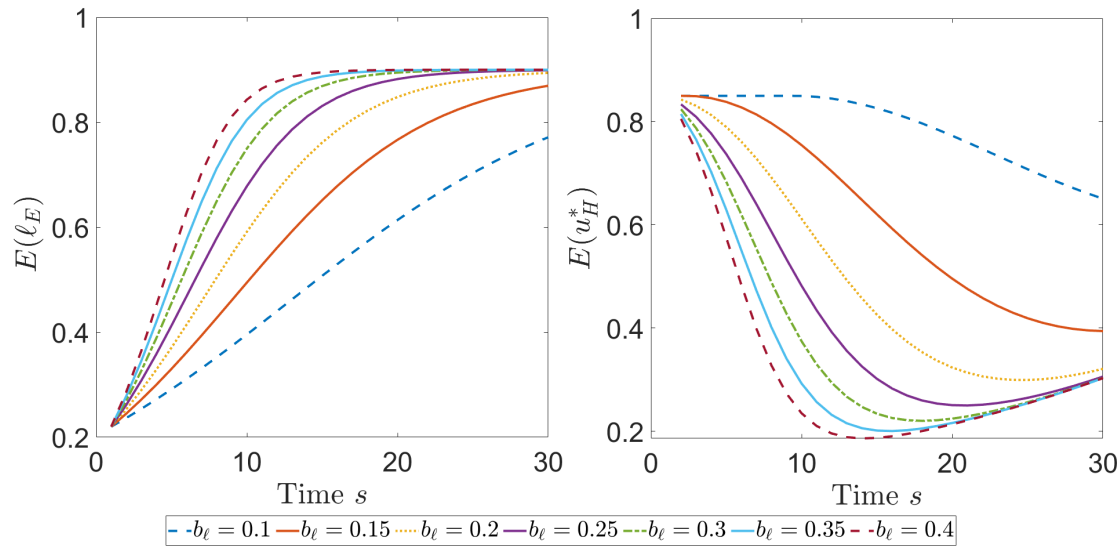


Figure 2: Illustration of central expectations on future diffusion of low-carbon energy and the associated high-carbon capital utilisation rate ⁷

We make the assumption that utilisation is homogeneous across high-carbon capital vintages, such that any future decrease in utilisation rates at the sector level will translate one-to-one to individual capital units to be installed today. Hence, if agents expect a lower utilisation rate at the sector level, they will expect a lower utilisation rate for their prospective new capacity.⁸

Stranding expectations are key in determining investment behaviours, as per Proposition 4.1 below:

Proposition 4.1. *For large enough values of b_ℓ , there exists an interval $T \subset [0, S]$ such that, $\forall s \in T$, $\pi_{L,s} - \pi_{H,s} > 0$.*

Proof. Demonstration given in Appendix F.1.

In other words, if they suppose that the development of low-carbon energy will be fast, agents expect at least a period of psychological time over their planning horizon

⁸This simplifying assumption could be challenged on the ground that older units will be underutilised first. However, as noted by prospective studies N. Grant et al. (2021), high-carbon capital installed today will anyways have to suffer significant underutilisation or premature decommissioning, even if older units stopped in priority.

over which, in the future, low-carbon technologies will be more profitable than high-carbon technology, which could induce them to change their investment behaviour.

1.4 Heterogeneity of stranding expectations

Heterogeneity in expectations is represented by the error term $\varepsilon_{u,s} \sim \mathcal{N}(0, \sigma_{u,s}^2)$ of Equation (6), where $\sigma_{u,s}$ is a parameter indicating the strength of expectation diversity. The lower $\sigma_{u,s}$, the more stranding expectations are homogeneous and close to $u_{H,s}^*$. The higher $\sigma_{u,s}$, the more stranding expectations are diverse and possibly far away from $u_{H,s}^*$.

An important question is how this dispersion should change in time s . The literature on projection disagreements amongst economic forecasters provides inconclusive insights into the term structure of opinion diversity. Binder, McElroy, and Sheng (2022) show that disagreements largely depend on the variable at stake.

The term structure for some variables (growth rate, inflation) shows higher (lower) disagreement over short-run (long-run) forecasts. For other variables (unemployment, base rates), the disagreement's term structure is strictly increasing. Patton and Timmermann (2010) show a logistically increasing uncertainty disagreement for all the variables they consider. However, these studies focus on macroeconomic, short-run macroeconomic variables. Inter-model comparison exercises using Integrated Assessment Models (IAMs) focus instead on more relevant variables for our purposes, such as energy capacity shares. Kriegler, Weyant, et al. (2014) show that technology deployment schedules can vary importantly across models, which can be taken as a measure of disagreement along the term structure.

To build on this insight, we consider projections of the share of renewables in total electricity production across all IPCC (2022b) scenarios⁹ and compute their variance at each available simulation step over the 2020-2060 period.¹⁰ We consider IPCC scenarios as a good proxy for expectations in that they provide long-run projections

⁹IPCC scenarios are available at <https://data.ece.iiasa.ac.at/ar6>.

¹⁰The picture over 2020-2100 is similar, with the variance of projection oscillating around a carrying capacity.

that policymakers and economic agents can take as a benchmark in forming their own expectations. We assume further that the cross-scenario variance in the share of renewables reasonably proxies disagreement across agents, who can give more or less credence to one or the other IPCC projection. The result of this exercise is displayed in Figure 3.

As can be seen, the variance follows a near-perfect sigmoid pattern, on which we fit a logistic function with an intrinsic growth rate of 0.28. Hence, we let σ increase in psychological time s following a logistic pattern:

$$\sigma_{u,s+1} = \sigma_{u,s} \left[b_\sigma \left(1 - \frac{\sigma_{u,s}}{\bar{\sigma}_u} \right) \right], \quad (10)$$

where b_σ is the unconstrained growth rate of $\sigma_{u,s}$, $\bar{\sigma}_u$ represents the maximum heterogeneity in the long-run and $\sigma_u = \sigma_0$ at time t . Short-term views regarding the transition are roughly aligned as agents observe the current state of things and recent trends. In other words, given the past evolution of low-carbon energy production shares up to time t , the expected low-carbon energy share for $t+1$ will be rather homogeneous across firms. However, transition expectations then diverge rapidly over the medium term, capturing the heterogeneity of opinions concerning technological and policy prospects. While some might be expecting decarbonisation to unravel rapidly in the course of the next decade, others might expect fossil fuels to remain the backbone of the global economy in the decades to come. In the longer run, the marginal divergence of expectations weakens, approaching a fixed maximum level $\bar{\sigma}_u$. In other words, the diversity of long-term opinions remains roughly constant once a certain beyond a certain threshold in psychological time.

1.5 Aggregate investment decisions

We now want to calculate the share of aggregate investments flowing into each technology. We define $\ell_I = \frac{I_L}{I_H + I_L}$ as the share of total investments allocated to low-carbon capital stocks. In our setting, this is equivalent to the probability for an individual

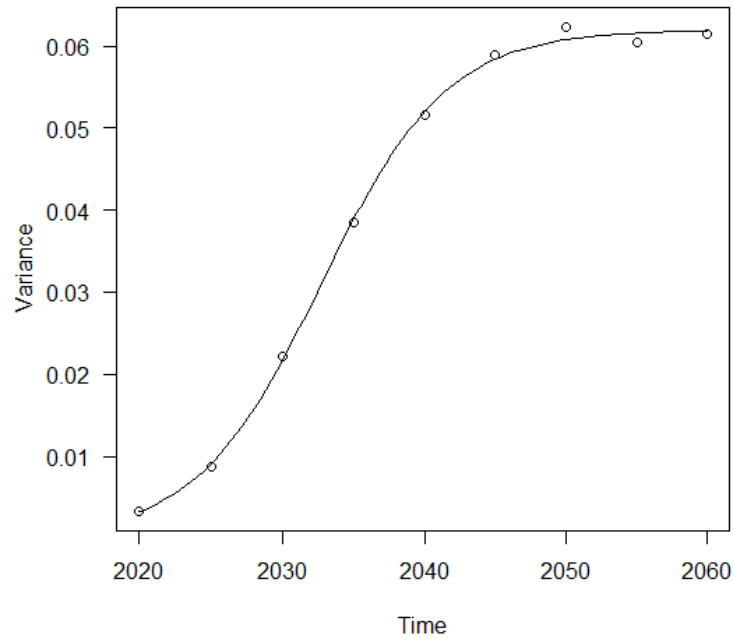


Figure 3: Evolution of disagreement in psychological time - Source: AR6 Scenario Explorer and own calculations. Each point is the variance of the share of renewable energy across all scenarios provided by the AR6.

firm to obtain a positive φ ; that is, to expect the low-carbon return rate r_L to be higher than the high-carbon return rate r_H .

Given our assumption of a normal distribution of the error term ε_u in equation (6) and considering that linear transformations maintain the normal distribution pattern, we can rewrite φ as the sum of a deterministic ‘rational stranding’ component φ^* and an error term $\varepsilon_\varphi \sim \mathcal{N}(0, 1)$:

$$\varphi^* = \frac{R^*}{\Gamma}, \quad (11)$$

with:

$$R^* = \sum_{s=0}^S \beta^s \left\{ p_E \xi_L - \alpha_L \psi_L c_L - \left[\left(p_E - \frac{p_F}{\xi_F} \right) \xi_H u_{H,s}^* - \alpha_H \psi_H c_H \right] \right\} \quad (12)$$

$$\Gamma = \sqrt{\sum_{s=0}^S \beta^{2s} \left(p_E - \frac{p_F}{\xi_F} \right)^2 \sigma_{u,s}^2}. \quad (13)$$

All details of the transformation are discussed in Appendix D. Figure 4 schematises our representation of belief heterogeneity as a set of normal distributions with varying means and variances.

R^* can be thought of as a “benchmark return rate”, which would prevail in the absence of idiosyncratic beliefs ε , i.e., when agents’ expectations are aligned on the central projection. In the presence of belief dispersion, it represents the average return expectation. Γ is a measure of the extent of belief dispersion across the planning horizon. In the definition of φ^* , Γ can be taken as a belief-correction term used on R^* to account for the extent of belief dispersion. A high Γ implies that agents form beliefs that can be significantly different from the average expectations, making R^* less important for aggregate behaviour.

We can then derive ℓ_I , our main variable of interest, as the value of the cumulative distribution function $\Phi(\cdot)$ of the standard normal distribution at φ^* . That is,

$$\ell_I = \Pr(\varepsilon_\varphi < \varphi^*) = \Pr(r_L > r_H) = \Phi(\varphi^*). \quad (14)$$

To allow ourselves to explore large $\sigma_{u,s}$ values while keeping heterogeneous beliefs realistic, we censor the $\varepsilon_{u,s}$ distributions above 1 and below zero. After some transformations (see Appendix E.), the final definition of ℓ_I is:

$$\ell_I = \frac{\delta_{\varphi_0 \varphi^*} (\Phi(\varphi^*) - \Phi(\varphi_0^*)) - \delta_{\varphi_1 \varphi^*} (\Phi(\varphi_1^*) - \Phi(\varphi^*))}{\Phi(\varphi_1^*) - \Phi(\varphi_1)}, \quad (15)$$

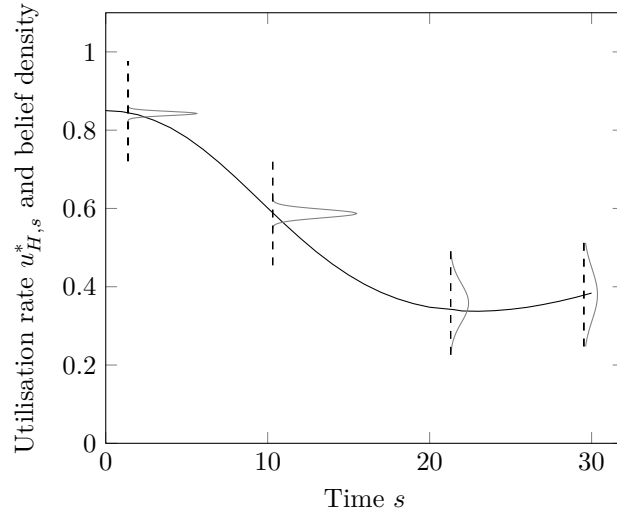


Figure 4: Stylised representation of our approach to belief heterogeneity. To each time $s \in [1, S]$ corresponds a central utilisation expectation. Each bell curve represents the actual distribution of expectations (rotated 90°), with time-varying variances and means. Here displayed an example for $\bar{\ell} = 0.9$, $b_\ell = 0.2$, $\sigma_0 = 0.01$ and $\bar{\sigma} = 0.5$

$$\text{where } \delta_{uv} = \begin{cases} 1 & u < v \\ 0 & u \geq v. \end{cases},$$

and φ_0^* and φ_1^* are the values φ would take if $\mu_{H,s}^* = 0 \forall s$ or $\mu_{H,s}^* = 1 \forall s$ respectively.

For the values of φ^* we are exploring, we are always in a case in which $\varphi_0 \leq \varphi^* \leq \varphi_1$, such that the equation reduces to:

$$\ell_I = \frac{\Phi(\varphi^*) - \Phi(\varphi_0)}{\Phi(\varphi_1) - \Phi(\varphi_0)}. \quad (16)$$

2 Calibration

This section presents our calibration strategy.

The model's time step in s -time is explicitly yearly. All monetary values are expressed in billion 2019\$US; electricity production in terawatt-hours (TWh); electricity generation in gigawatts (GW); fossil energy in British thermal units (Btu).

We use the EU27 region in 2019 as our model economy. We can distinguish two

categories of parameters. First, a set of technological or financial parameters calibrated to replicate empirical evidence and summarised in Table 1. Second, a set of behavioural parameters for which, in the absence of solid empirical foundations, we perform a sensitivity analysis along reasonable value ranges in Section 3.

2.1 Technological and financial parameters

We include solar, wind and other minor renewable energy technologies in our low-carbon category and all other technologies in the high-carbon category. While hydropower and nuclear can be considered to be low-carbon considering their low emission intensity, additional environment-related issues (*e.g.* land use, waste treatment) usually lead them to be treated separately from wind, solar, geothermal and other renewable technologies. In addition, we take into consideration the fact that installing large hydro plants is now mostly infeasible in Europe, where the generation of electricity from hydro has been stationary since 2000 and not strongly desired by policymakers due to its environmental footprint. Furthermore, across scenarios, uncertainty revolves mostly around the share of “modern” renewables compared to other energy sources (Tsiropoulos et al. 2021). We thus focus on them and include nuclear and hydro in our “high-carbon” category. We investigate alternative categorisations, with hydro and nuclear included as part of the low-carbon technology, in Appendix C.

We set the initial values of capital stocks following Keramidas et al. (2020), which reports a total installed capacity of approximately 947GW in 2019 for the EU-27 region, of which around 30% is made of solar, wind or geothermal plants. We thus set $K_{L,0} = 288\text{GW}$ and $K_{H,0} = 659\text{GW}$, which implies that the share of low-carbon capital $\ell_{K,0} = \frac{288}{947} \approx 30\%$.

We further make a difference between utilisation rates and capacity factors. Utilisation rates are demand-driven and depend on economic factors. They refer to the degree to which the capital stock is used and are measured as the ratio between production and potential production at the best of technical possibilities. It is common

for firms to maintain their available capital stocks operating on average at a rate lower than 100%, to be able to accommodate for peaks in demand. The normal capacity utilisation rate u^f is equal to 0.85 for both technologies, which is roughly in line with utilisation rates at the macro level in the European Union in 2019 given by Eurostat. We assume that the economy starts from a situation where both technologies operate at normal capacity and that firms expect the current-period utilisation to be equal to normal, *i.e.*, we set $u_{L,0} = u_{H,0} = 0.85$.

On the other hand, capacity factors represent the technical limitations preventing an electricity-generation technology from operating at 100%. We assume them to be encapsulated in our productivity factors ξ_H and ξ_L , in the sense that they are purely defined by technology. Given our assumptions on utilisation rates, we calibrate our productivity parameters ξ_H and ξ_L to match energy production from high- and low-carbon technology in Europe. The share of wind, solar and geothermal technologies in total gross electricity production in Europe was around 22% in 2019. With a utilisation rate of 85% and a total energy demand equal to 3243TWh this yields $\xi_L = \frac{0.22*3243}{0.85*288} = 2.9145$ and $\xi_L = \frac{0.78*3243}{0.85*659} = 4.5158$. Given that a GW of capacity would produce 8.76TWh in a year at full capacity, this yields implicit capacity factors of $\frac{2.9145}{8.76} \approx 33\%$ and $\frac{4.5158}{8.76} \approx 51\%$, which are both roughly in line with 2018 capacity factors (*i.e.* uncorrected for utilisation rates, in Europe, IEA (2019)).

The data on electricity prices for both households and non-household consumers is provided by Eurostat.¹¹ It shows values ranging from 0.005 to 0.27 €/KWh in 2019 for the EU27 region. We adopt a middle value by setting $p_E = 0.2\text{bn}\$/\text{TWh}$.

Fossil productivity parameter ξ_F transforms fossil fuels, expressed in trillion British thermal units (Btu), into electricity, expressed in TWh. One TWh physically corresponds to approximately 3.5 trillion British thermal units (Btu). We then need to adjust this number for the efficiency of thermal plants (heat rate) to account for energy losses arising from the conversion process. According to EIA (2020), the efficiency of thermal plants is around 0.33-0.45. Taking an intermediate value of 0.4,

¹¹See series nrg_pc_204 and nrg_pc_205 available at <https://ec.europa.eu/eurostat/data/database.%7D>

Table 1: Technological and financial parameters

Symbol	Variable	Value	Source
<i>Production</i>			
e_d	Initial energy production	3243GWh	European Commission (2019)
$K_{H,0}; K_{L,0}$	Initial capital stock	659GW; 288GW	European Commission (2019)
$\xi_H; \xi_L$	Capital productivity	4.5158; 2.9145	Eurostat (2022)
u_H^f	Full capacity utilisation rate	0.85	Eurostat (2022)
$u_H; u_L$	Initial utilisation rate	0.85	Eurostat (2022)
p_e	Price of electricity	0.2bn\$/TWh	Eurostat (2022)
ξ_f	Productivity of fossil fuels	0.114	EIA (2020)
p_f	Price of fossil fuels	0.0022bn\$/TWh	Eurostat (2022)
$\delta_H^k; \delta_L^k$	Capital depreciation rate	0.03; 0.04	IEA (2020b)
$c_H^k; c_L^k$	Capital cost	3.5bn\$/GW; 2.9bn\$/GW	IEA (2020b)
g_e	Energy demand growth	0.012	Enerdata (2021)
<i>Finance</i>			
$\psi_H; \psi_L$	Debt-to-investment ratio	0.7; 0.75	Baruya (2017); IRENA (2020a)
$\iota_H; \iota_L$	Interest rate on loans	0.045; 0.0394	Kempa, Moslener, and Schenker (2021)
$LT_H; LT_L$	Loan tenor	15 years	Refinitiv (2022)
<i>Belief heterogeneity</i>			
b_σ	Intrinsic growth rate for $\sigma_{u,s}$	0.28	IPCC (2022b)

we calculate EU thermal plants to require 8.75 ($=3.5/0.4$) trillion Btu to produce one TWh of electricity. The ξ_F coefficient is then computed as the inverse of this number, that is $\frac{1}{8.75} \approx 0.114$.

The price of natural gas in 2019 for non-household consumers in the EU27 region was around 0.03€/KWh.¹² Rescaling to Btu and taking into consideration that the price of coal is usually lower than the one of gas, we set $p_F = 0.0025$ bn\$/tnBtu.

We set depreciation rates δ_H and δ_L as the inverse of technology-specific asset lifetimes. IEA (2020a) reports expected lifetimes of 25 years for solar and wind plants and 30-40 years for fossil-fuelled plants. We thus set $\delta_H = 0.03 \approx 100/33$ and $\delta_L = 0.04 = 100/25$.

Capacity installation cost parameters c_i represent the cost of installing a unit of generating capacity (the ‘overnight constructions costs’). IEA (2020a) describes the overnight cost for various technologies hypotheses made by the IEA in its projection exercises.¹³ By taking a weighted average based on the European energy mix, we retain $c_H^k = 3.5$ bn\$/GW and $c_L^k = 2.9$ bn\$/GW.

¹²See series nrg_pc_203_c available at https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_203/default/table?lang=fr

¹³For hydro, the IEA does not provide data specific to Europe; we thus relied on a weighted average of costs across countries (IEA 2020c)

Financing costs depend on the loan interest rate ι_i . Recent findings from Kempa, Moslener, and Schenker (2021) show an average 3.5% spread to Libor for high-carbon projects and that renewable projects face a 16% lesser markup. We then assume, for Europe, a 1% risk-free interest rate, resulting in $\iota_H = 0.01 + 0.035 = 0.045$ and $\iota_L = 0.01 + 0.035 * 0.84 \approx 0.0394$. Debt-to-investment ratios (ψ_H, ψ_L) for renewable projects are taken from IRENA (2020a), which reports a 75% rate. For high-carbon energy sources, sources are more conflicted (Baruya 2017), with numbers ranging between 60 and 80% debt-financing. We thus adopt a middle-range assumption of a 70% rate. Regarding the loan term of debt financing, we rely on the Refinitiv project database. Albeit scarce, data shows a rough average of a 15-year loan term for all technologies ($LT = 15$).

Finally, we take energy demand growth from the EnerData Enerblue scenario (Enerdata 2021), which projects a 43% increase in final electricity consumption demand between 2020 and 2050. Assuming a constant growth rate over this period yields a yearly 1.2% growth.¹⁴

2.2 Behavioural parameters

Our model includes several parameters capturing the expectations and behavioural features of investment decision-makers. Despite the recent emergence of a stream of research contributions trying to assess climate-related expectations via surveys or financial econometrics (Krueger, Sautner, and Starks 2020; Bolton and Kacperczyk 2020), we currently do not have reliable data on which to calibrate these parameters. An exception is b_σ , which we calibrate to 0.28 based on our analysis of IPCC scenarios (see Section 1.4). However, since uncertainty acts on a different compact, we keep σ_0 and $\bar{\sigma}$ free.

For this reason, we illustrate our analytical results with sensitivity analyses on pairs of parameters while keeping the rest of the behavioural parameters fixed. We thus

¹⁴We follow most of the energy modelling literature in assuming that, while electricity demand can be affected by energy efficiency and other demand-side measures, the composition of its supply does not significantly affect the amount of power demanded by economic agents.

choose a reference value (to be kept constant while the parameter is not part of the sensitivity analysis) and a sensitivity range for each parameter. Since we are interested in exploring how these behavioural parameters could affect investment choices, we keep the sensitivity ranges large enough to capture all possible dynamics. In particular, we choose the sensitivity range for the maximum expected share of low-carbon technologies $\bar{\ell}$ and the intrinsic growth rate of the expected low-carbon energy share b_σ to match scenarios for the European Green New Deal (Tsiropoulos et al. 2021). Table 2 offers a summary of our choices.

2.3 High- and low-stranding projections

We conclude our calibration by specifying two representative central projection paths. In both of them, the long-run share of low-carbon energy is left fixed at 90%, in the upper distribution of the European Commission's scenarios (Tsiropoulos et al. 2021), so to leave the intrinsic growth rate as the only degree of freedom. In formal terms, low-stranding projections can be defined as the set of b_ℓ such that $R^* < 0$ for our benchmark S and ρ . Reciprocally, high-stranding projections can be seen as the set of b_ℓ such that the benchmark return rate R^* is strictly positive. We choose $b_\ell = 0.15$ for a low-stranding central projection and $b_\ell = 0.25$ for a high-stranding central projection. We summarise this choice in Table 3.

Whenever relevant, we will compare results from these two central projections.

We characterise a low-stranding scenario as a gradual transition, with a slow development of low-carbon technologies that does not result in much stranding. High-carbon energy sources remain operational for relatively long and are decommissioned gradually. By contrast, a high-stranding central expectation would feature a quicker deployment of low-carbon technology, resulting in larger stranding. This narrative implies a more disruptive transition in which high-carbon technology is quickly replaced in the short run (Grubb, Drummond, and Hughes 2020). Our 'low-stranding' scenario can be roughly compared to the IEA's 'Announced Pledges' scenario (IEA 2022a), in which fossil fuels are slowly replaced by alternative technologies. The

Table 2: Behavioural parameters

Variable	Meaning	Reference value(s)	Sensitivity range
S	Length of planning horizon	20	[2, 40]
\underline{b}_ℓ	Expected intrinsic growth rate for ℓ	0.15 ; 0.25	[0, 0.5]
$\bar{\ell}$	Maximum expected ℓ	0.85	[0.5, 0.95]
σ_0	Opinion diversity at time t	0.01	[0, 0.1]
$\bar{\sigma}$	Maximum opinion diversity	0.5	[0.01, 2]
ρ	Corporate discount rate	0.05	[0.01, 0.1]

IEA’s ‘Net Zero by 2050’ scenario (IEA 2022b), entailing a more rapid and intense low-carbon transition, could instead be compared to our “high-stranding” path.

3 Results

This section expounds our main takeaways. We start by studying how belief heterogeneity affects aggregate investment decisions. To do so, we begin in Section 3.1 with a polar case without belief heterogeneity, corresponding to a benchmark in which agents’ expectations are fully coordinated around the central expectation. We then lift the no-heterogeneity assumption to explore how our modelling proposal influences results compared to the benchmark. Subsequently, in Section 3.2, we explore how aggregate investment behaviours change with various levels of belief heterogeneity. We notably characterise the relative effect of short (σ_0) and long-run ($\bar{\sigma}$) belief heterogeneity and derive some properties in the case of hyperbolic heterogeneity. Sections 3.3 and 3.4 explore instead the interactions between belief heterogeneity and preference for the present: the discount rate ρ and the length of the planning horizon S .

3.1 Introducing belief heterogeneity

We start by assuming $\sigma_{u,s} = 0 \forall s \in [1, S]$, *i.e.*, we describe a situation in which all agents believe in the central projection. Being this a limit condition on our model, we can prove Proposition 4.2:

Table 3: Intrinsic growth rate values for low and high-stranding central expectations

Scenario type	b_ℓ
Low stranding	0.15
High ambition	0.25

Proposition 4.2. For $\sigma_{u,s} = 0 \forall s \in [1, S]$, ℓ_I tends towards a degenerate probability distribution function, whereby:

$$\ell_I = \begin{cases} 0 & \text{if } R^* < 0 \\ 0.5 & \text{if } R^* = 0 \\ 1 & \text{if } R^* > 0 \end{cases} \quad (17)$$

Proof. Demonstration is given in Appendix F.2.

In other words, without belief heterogeneity the system can only achieve three outcomes: i) the whole population invests in low-carbon energy ($\ell_I = 1$); ii) none of it does ($\ell_I = 0$); or iii) exactly half of the population does ($\ell_I = 0.5$). The interpretation is straightforward: absent belief heterogeneity, only the central projection, which rules the sign of R^* , matters. If this implies that low-carbon sources will be more profitable over the planning horizon according to this central projection ($R^* > 0$), then it is rational for all investors to invest in low-carbon energy. The intermediate case $R^* = 0$ would denote a ‘total indecision’ situation, in which agents are indifferent between the two technologies and therefore exhibit a 50-50 dispatch in aggregate. We illustrate these findings in Figure 5, Panel (a).¹⁵

The value of R^* depends on the discount rate ρ , the planning horizon S and the variables linked to the central expectations, *i.e.* the maximum expected share of low-carbon technologies $\bar{\ell}$ and the intrinsic growth rate b_ℓ . More precisely, we rewrite :

$$R^* = R^*(\rho, S, (u_{H,s})_{s \in [1, S]}) \quad (18)$$

¹⁵Note that the case $\ell_I = 0.5$ does not show because of the numerical simulation steps used for the chart.

Based on the definition of Equation (12), it can be shown $\frac{\partial R^*}{\partial \rho} < 0$. This is a standard effect of increasing the discount rate. It leads agents to weigh less later periods over which stranding is expected to be strong enough to give an edge to low-carbon sources. For a high ρ , R^* can be negative.

Further, the lower the $(u_{H,s})_{s \in [1,S]}$ schedule, the lower R^* . The position of the $(u_{H,s})_{s \in [1,S]}$ schedule depends directly on the $(\ell_{E,s})_{s \in [1,S]}$ schedule, governed by $\bar{\ell}$ and b_ℓ , as per Proposition 4.3 below:

Proposition 4.3. *Consider a logistic sequence $x_n = x_{n-1} (1 + b(1 - \frac{x_{n-1}}{K}))$ where K is a carrying capacity and b an intrinsic growth rate. Consider then x_0 the first term of this sequence. It follows that, $\forall n$ such that $x_n < K$ and $b \leq 1$:*

$$\frac{\partial x_n}{\partial K} \geq 0 \quad (19)$$

$$\frac{\partial x_n}{\partial b} \geq 0 \quad (20)$$

$$\frac{\partial x_n}{\partial x_0} \geq 0 \quad (21)$$

With the last proposition holding for $x_0 < K$.

Proof. Demonstration is given in Appendix F.3.

For what concerns the expected low-carbon share of energy, this implies that $\forall s$:

$$\frac{\partial \ell_{E,s}}{\partial \bar{\ell}} \geq 0 \quad (22)$$

$$\frac{\partial \ell_{E,s}}{\partial b_\ell} \geq 0 \quad (23)$$

The intrinsic growth rate b_ℓ rules the number of periods in time s needed to reach the maximum share $\bar{\ell}$ in expectations. If $\bar{\ell}$ is increased with b_ℓ held constant, agents will expect that a higher maximum share will be reached within the same amount of time. It requires ℓ_s to be higher or equal $\forall s$. Conversely, given a certain $\bar{\ell}$, a higher b_ℓ

means that less time is required to reach $\bar{\ell}$. This entails a steeper growth and higher $\ell_s \forall s$. Hence, a path with higher $\bar{\ell}$ or b_ℓ entails more stranding expectations due to a speedier increase of the share of low-carbon energy, which will result in higher low-carbon investment.

In economic terms, this proposition demonstrates that, under reasonable assumptions, if agents expect a higher long-term share of renewables $\bar{\ell}$ or a speedier transition b_ℓ , they will expect a higher share of renewables for all periods within their planning horizon. Given that stranding expectations are directly governed by the expected share of low-carbon investment, this implies that a higher ℓ or b_ℓ will imply higher stranding for all periods within the agents' planning horizon.

Finally, as per the definition of R^* , a minimum planning horizon is required for low-carbon investment to emerge. Indeed, if agents are so short-sighted to only account for early periods, over which stranding is low, they will expect a negative R^* . However, very long planning horizons are not necessarily improving. Given that stranding is transitory in our model – as high-carbon capital naturally depreciates – the period over which low-carbon capital becomes more profitable is finite. Once it is over, agents will expect an edge for high-carbon technologies again over subsequent periods, which may compensate for the positive payoff over the stranding period. Hence the following Proposition:

Proposition 4.4. *It is possible to define an interval $\mathcal{S} = [|\underline{S}; \bar{S}|] \subset [1, S]$ such that, for a given ρ , b_ℓ and $\bar{\ell}$, $R^* > 0 \forall s \in \mathcal{S}$ and $R^* \leq 0$ otherwise. \mathcal{S} can be empty.*

Proof. Demonstration is given in Appendix F.4.

This proposition states that, over their planning horizon, agents will expect low-carbon energy sources to be more profitable than high-carbon technologies over a sub-period \mathcal{S} , typically the period over which the stock of high-carbon capital will suffer most from stranding.

We now introduce belief heterogeneity by assuming the shape for the $\sigma_{u,s}$ schedule presented in Equation (10). Results are illustrated in Figure 5, Panel (b).

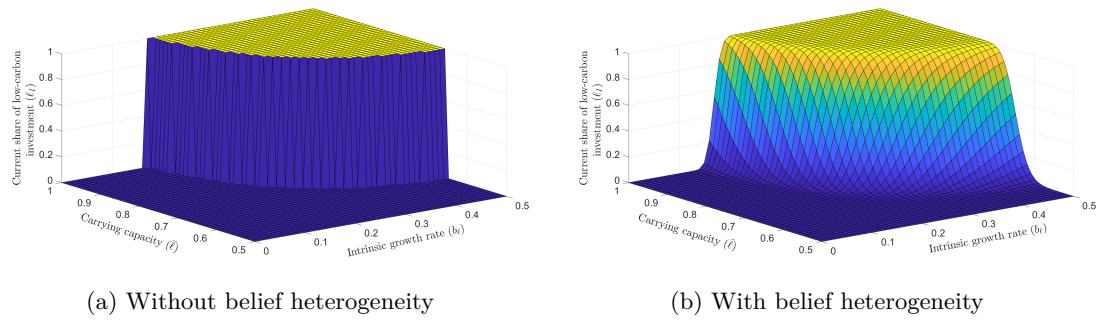


Figure 5: Effect of belief heterogeneity

As can be seen, the bang-bang solution disappears to give rise to a whole gradient of interior solutions ranging between 0 and 1 depending on the value of parameters b_ℓ and $\bar{\ell}$. The smoothness of the corresponding surface depends positively on belief heterogeneity.

Lifting the limit condition implies that the variables linked to relative return rates, φ^* , φ_0 and φ_1 , take a finite value and that the ℓ_I function takes value over the whole $[0, 1]$ interval.

Intuitively, introducing belief heterogeneity allows for the existence of investors whose behaviour will drift from the central projection. Hence, for a projection entailing zero investment in the no-heterogeneity case, introducing idiosyncratic beliefs is equivalent to assuming that a part of the population will expect sufficient stranding to invest in low-carbon energy.¹⁶ Reciprocally, for a high-stranding central projection, entailing 100% low-carbon investment in the absence of heterogeneity, allowing for a population of norm-contrarians will entail less low-carbon investment than in a no-heterogeneity case since this share of the population will expect insufficient stranding.

Including a degree of belief, heterogeneity significantly increases the indeterminacy of the model. This result is of important policy relevance, as the results implied by different degrees of belief heterogeneity can be very different from those flowing from an assumption of perfectly aligned expectations. We explore the impact of various

¹⁶Due to the symmetry of belief heterogeneity, belief heterogeneity also entails that a population expects *less* stranding than with expectations aligned on the central projection. However, expecting even less stranding than on the central projection does not change the investment choice of these agents. As a result, only the population expecting more stranding has an impact on aggregate investment decisions.

levels of belief heterogeneity in the following and their policy consequences.

3.2 Belief heterogeneity, investment decisions and the central projection

To explore the role of belief heterogeneity, we let our parameters σ_0 (short-run belief dispersion) and $\bar{\sigma}$ (long-run belief dispersion) vary. Proposition 4.3 implies that:

$$\frac{\partial \sigma_{u,s}}{\partial \sigma_0} \geq 0 \quad (24)$$

$$\frac{\partial \sigma_{u,s}}{\partial \bar{\sigma}} \geq 0 \quad (25)$$

As a result, any increase in these two parameters will result in a higher $(\sigma_{u,s})_{s \in \{1, S\}}$ schedule, which will increase the belief-correction factor Γ defined in Equation (12).

It is possible to demonstrate the following proposition:

Proposition 4.5. *The effect of a higher σ_0 or $\bar{\sigma}$ will depend on the sign of R^* . If $R^* < 0$, then $\frac{\partial \ell_I}{\partial \sigma_0} \geq 0$, $\frac{\partial \ell_I}{\partial \bar{\sigma}} \geq 0$. Furthermore, ℓ_I is concave in σ_0 and $\bar{\sigma}$. If $R^* > 0$, then $\frac{\partial \ell_I}{\partial \sigma_0} \leq 0$ and $\frac{\partial \ell_I}{\partial \bar{\sigma}} \leq 0$. Plus, ℓ_I is convex in σ_0 and $\bar{\sigma}$. Plus, there exists an $R' \in [R_0; R_1]$ such that $\frac{\partial \ell_I}{\partial \sigma_0}(R')$ and $\frac{\partial \ell_I}{\partial \bar{\sigma}}(R')$ equal to zero.*

Proof. Demonstration is given in Appendix F.5.

We further illustrate the effect of belief heterogeneity on ℓ_I in Figure 6. As a contour plot, it shows isovalue lines, *i.e.*, all the combinations within the $(\bar{\sigma}, \sigma_0)$ space that yield the same ℓ_I value. The space between the lines gives indication on how the value of the outcome evolves when one of the two parameters is fixed. Typically, an increasing space across isovalue lines for increasing values of a parameter – like in Figure 6 – would denote a decreasing marginal effect of the moving parameter. In the high-stranding scenario, increasing belief heterogeneity, either in the short- or the long-run, unambiguously decreases the low-carbon investment share. By contrast, increasing

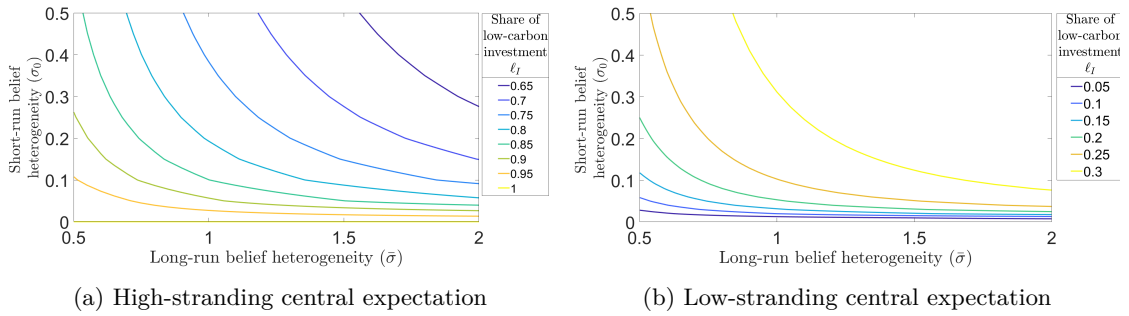


Figure 6: Long-run and short-run belief heterogeneity – The charts plot iso-value lines. For instance, the curve with legend “0.85” on Panel (a) corresponds to all $(\bar{\sigma}, \sigma_0)$ combinations for which the share of low-carbon investment ℓ_I is equal to 0.85 in the case of high stranding central expectation.

dispersion in the low-stranding case tends to increase low-carbon investment. In both cases, the effect of higher heterogeneity is bounded, as the low-carbon share tends towards a minimum (high stranding) or a maximum (low stranding) as dispersion increases. These results emerge because we define belief heterogeneity as deviations from the central projection or ‘market norm’. Hence, the effects of belief heterogeneity on investment decisions also depends on the existing central projection. In the case of low-stranding expectations, ‘transition believers’ investing in low-carbon projects will be the ‘norm contrarians’. Reciprocally, contrarians in the high-stranding case will be ‘transition sceptics’, who will invest more in high-carbon energy. As a result, belief heterogeneity will have a balancing effect on investment behaviour, the direction of which will depend on the existing norm.

We can also show that the (absolute) effect of more belief heterogeneity on investment allocation is higher when belief heterogeneity is lower. It shows on Figure 6 through the increasing distance across iso-value lines. This is due to the concavity (in the low-stranding case) or convexity (in the high-stranding case) property of ℓ_I in Γ . Increasing belief heterogeneity from a low-dispersion situation will open a range of stranding expectations close to the cut-off point from which agents switch behaviours. Hence, many switches will occur. Conversely, if belief heterogeneity is high, most beliefs relevant for behaviour switch will already have a sizeable mass in the distribution.

Hence a decreasing marginal (absolute) effect of belief heterogeneity.

The previous result, however, only holds for a fixed central projection. This begs studying how changes in belief heterogeneity will affect investment behaviours for various central expectation scenarios.

We first consider the expression of $\frac{\partial \ell_I}{\partial \Gamma}$ from the demonstration of Proposition 4.5 (see Appendix F.5., Equation F.15). Then, we fix the belief correction factor Γ (see 12) to match our benchmark values ($\sigma_0 = 0.01$ and $\bar{\sigma} = 0.5$). Reducing $\frac{\partial \ell_I}{\partial \Gamma}$ to a function of R^* , the function takes the shape displayed in Figure 7.

Figure 7 shows that the higher (lower) the curve, the more positive (negative) a change in investment behaviour following a shift in Γ and *vice-versa*. A value of zero would denote that, for the corresponding central projection, moving belief heterogeneity has no effect on investment behaviour, which would be a case of “perfect resilience”. However, norm resilience is non-monotonous. Sensitivity reaches two optima on each side of the y-axis. As can be seen in Figure 7, sensitivity is zero for $R^* = 0$, *i.e.*, a perfect balance between profit rates at the benchmark. Moving from this point, (absolute) sensitivity increases to a maximum and decreases to perfect resilience.

Policy-wise, this implies that medium-stranding projections are fragile to belief heterogeneity shocks (*e.g.* shocks to confidence; decrease in policy credibility). As a result, policymakers should strive to measure the state of the central expectation to anticipate its resilience to possible shocks in belief dispersion. With the caveat that it should also make sure to remain credible, the regulator could also try to influence this central expectation through policy announcements, in order to anchor expectations more towards higher stranding - if the penetration of renewable energy sources is indeed its goal.

Regarding low-stranding projections, if the market norm is close to business-as-usual (very low stranding), the share of the population expecting enough stranding is so little that marginally increasing it will only affect aggregate investment decisions negligibly. This kind of “low equilibrium” cannot be changed by a transition-believer minority but only by changing the ongoing market norm.

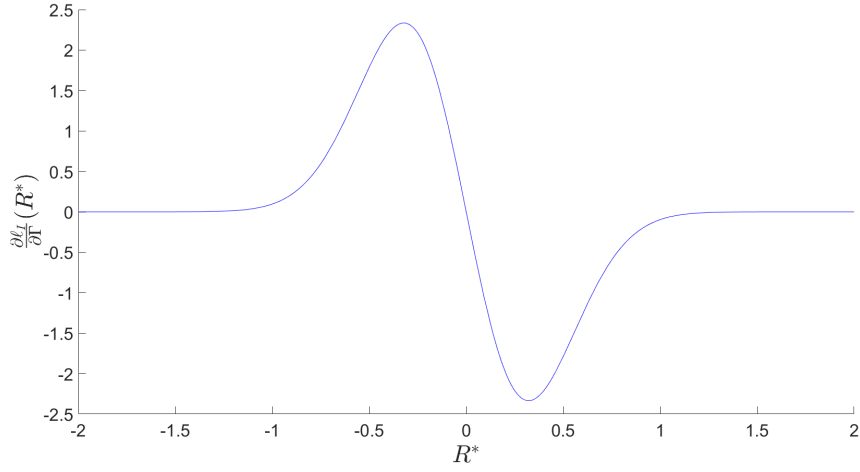


Figure 7: Evolution of the sensitivity of the share of low-carbon investment ℓ_I to the belief correction factor Γ as a function of the central expectation return spread R^*

Another feature emerging from Figure 6 is that the relative effects of short- (σ_0) and long-run heterogeneity ($\bar{\sigma}$) depend on the magnitude of one another:

Proposition 4.6. *For a given S and ρ , there exists a threshold ratio $\left(\frac{\bar{\sigma}}{\sigma_0}\right)^* = \sqrt{\frac{1-\exp(-b_\sigma S)}{\exp(-b_\sigma S)}}$ such that $\left|\frac{\partial \ell_I}{\partial \sigma_0}\right| > \left|\frac{\partial \ell_I}{\partial \bar{\sigma}}\right| \forall \frac{\bar{\sigma}}{\sigma_0} > \left(\frac{\bar{\sigma}}{\sigma_0}\right)^*$. In other words, the effect of increasing short-run belief dispersion σ_0 on investment behaviours is higher than that of increasing long-run dispersion $\bar{\sigma}$ if $\bar{\sigma}$ is sufficiently high relatively to σ_0 .*

Proof. Demonstration is given in Appendix F.6.

Whether the condition holds or not depends directly on the length of the planning horizon. Unsurprisingly, the more far-sighted agents are, the more the aggregate investment behaviour will be influenced by belief dispersion on long-run outcomes, unless belief dispersion on long-run developments is already very high.

It is possible to show that this condition holds true for a large proportion of the parameter space we explore. In particular, it holds for our benchmark calibration with $S = 20$ and $\sigma_0 = 0.01$ for $\bar{\sigma} > 0.16$. It accounts for the whole parameter space we explore in Figure 6. We therefore focus on this case.

Let us first notice that long-run belief heterogeneity $\bar{\sigma}$ does not need to be very high for the condition to be fulfilled in our benchmark calibration. Because investment shares are more sensitive to belief heterogeneity for low values of σ_0 and $\bar{\sigma}$, it entails that, for reasonable values of $\bar{\sigma}$, an increase in σ_0 can have sizeable effects on aggregate investment behaviours. For high $\bar{\sigma}$ values, however an increase in σ_0 , although it will bear larger effects than an increase in $\bar{\sigma}$, will have quantitatively small impacts on ℓ_I . It is due the concavity/convexity properties of ℓ_I in Γ (see above).

The policy implications are nonetheless clear. In the case of a high-stranding central expectation, the priority for policymakers should be to anchor expectations firmly for the earliest periods of the transition, if there is no clear consensus about long-run outcomes. If short-run belief heterogeneity is very low and long-run dispersion even moderately high, slightly higher short-run belief dispersion can have sizeable effects. Anchoring short-term expectations is all the more crucial considering that long-run belief dispersion is to some extent inevitable due to the many uncertainties surrounding the long-run future. Comparatively, aligning expectations on short-term outcomes seems more feasible. In the case of a low-stranding expectations, policymakers should be cautious in interpreting positively a large tilt of investment behaviours towards low-carbon investment, as it may represent only a shock to short-run belief heterogeneity. These insights confirm the need for policymakers to carefully measure the state of expectations, in mean and in dispersion.

Figure 6 further shows that the effect of higher belief heterogeneity dies down as σ_0 or $\bar{\sigma}$ increases, until seemingly reaching a finite value. What happens when the belief-dispersion term Γ tends towards infinity, describing a state of “full dispersion” of beliefs?

Proposition 4.7. *As belief heterogeneity approaches infinity, ℓ_I will tend towards a finite value $\tilde{\ell}_I = \frac{R^* - R_0}{R_1 - R_0}$, where R^* , R_0 and R_1 are the numerators of φ^* , φ_0 and φ_1 respectively. It defines a uniform distribution on R^* over $[R_0, R_1]$. We call $\tilde{\ell}_I$ ‘full dispersion’ equilibrium and it is a function of b_ℓ , \bar{b} for a given S and ρ . Note that if we do not censor our distribution, the “full-dispersion” equilibrium $\tilde{\ell}_I$ is always equal*

to 0.5.

Proof. Demonstration is given in Appendix F.7.

This result means that if we ensure that expected utilisation rates remain between 0 and 1 (*i.e.*, agents have “reasonable” beliefs), only the position of the central expectation within the realm of acceptable beliefs matters for aggregate investment behaviour when belief dispersion is very high. Because the distribution of beliefs converges towards a uniform distribution, so does the distribution of expected return rates. As a result, all expectations have the same weight in determining investment decisions as long as they remain within the boundaries of acceptable beliefs. It implies that the only determinant of investment shares will be the position of the central expectation relative to the boundaries defining acceptable beliefs.

This feature has several policy implications. First, it implies that, with high belief heterogeneity, 100% low-carbon investment can only be achieved if the central expectation entails maximum stranding ($u_{H,s} = 0 \forall s \in [1, S]$), *i.e.* $R^* = R_1$. However, stranding the entire stock of high-carbon capital overnight is a hardly credible scenario. Hence, in the case of a full-dispersion equilibrium, low-carbon investment will always represent less than 100% of the total.

Second, low- and high-stranding projections are asymmetric. High belief heterogeneity for low-stranding projections will always yield *less* low-carbon investment than high belief heterogeneity with high-stranding expectations. This implies that a strong minority of ‘high-stranding believers’ will never be able to turn the tide of low-carbon investments and reach investment shares that would prevail for a high-stranding projection.

Finally, for a benchmark return rate R^* equal to zero, the limit is not equal to 0.5, unlike for the case $\Gamma = 0$. This is because, for Γ very high or close to infinity, the censoring of opinions becomes more relevant for aggregate investment behaviour. As a result, unless $-R_0 = 2(R_1 - R_0) \iff R_0 = -R_1$, *i.e.* a case of perfect symmetry in censoring, high belief heterogeneity will introduce a distortion if beliefs are censored.

Even in a situation of indifference ($R_0 = 0$), the aggregate investment behaviour will be biased. For our calibration, $\frac{-R_0}{R_1 - R_0} \approx \frac{3.43}{6.59 + 3.43} = 0.3426$, which denotes a bias in disfavour of low-carbon technology.

3.3 The discount rate and belief heterogeneity

We now explore the effects of the discount rate ρ on investment behaviours and how it interacts with belief heterogeneity.¹⁷ While the strong dependence on other parameters does not allow us to derive analytical results for the effect of discount rate ρ on aggregate investments, it is possible to draw some insights from numerical simulations.

As Figure 8 shows, for high-stranding plans (Panel (a)), ρ and $\bar{\sigma}$ interact non-linearly. For sufficiently low levels of belief heterogeneity, the effect of the discount rate is negligible. In other words, when $\bar{\sigma}$ is low, an increase in ρ requires only a marginal change in $\bar{\sigma}$ to remain on the same isovalue curve. For higher levels of belief heterogeneity, instead, the relationship becomes strongly non-linear. When discount rate ρ is low, remaining on the same isovalue line requires a higher belief heterogeneity, i.e. an equal level of belief uncertainty would yield a higher low-carbon investment share. When ρ becomes higher, its effect on low-carbon investments becomes unambiguously negative, as lower belief heterogeneity is now necessary to compensate for the increase in ρ and remain on the same isovalue line. This pattern emerges because of two opposite effects of the discount rate. On the one hand, the discount rate decreases the weight of periods over which agents expect a higher payoff for low-carbon energy in the central expectation. On the other hand, because longer-run beliefs are also discounted, agents tend to give less weight to opinions relevant for later periods. This suggests that the belief-discounting effect of ρ dominates the discounting of the central expectation for low values of ρ . The opposite is true for higher values of ρ . It also explains why belief heterogeneity and ρ should interact positively for high values of ρ . In the presence of high belief heterogeneity, discounting more those beliefs

¹⁷For the sake of brevity, we only allow $\bar{\sigma}$ to vary in modulating belief heterogeneity in our illustrations. Effects would be qualitatively similar if we changed the level of σ_0 , as long as we keep $\sigma_0 < \bar{\sigma}$.

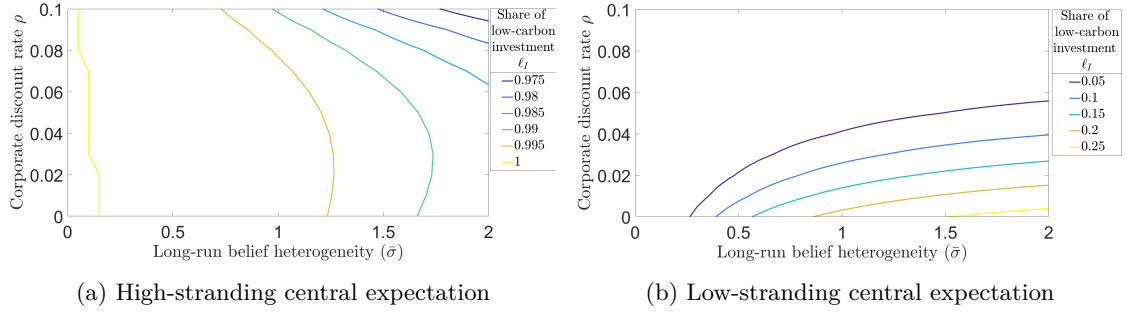


Figure 8: Interaction between long-run belief heterogeneity $\bar{\sigma}$ and the discount rate ρ – The charts plot isovalue lines. For instance, the curve with legend “0.995” on Panel (a) corresponds to all $(\bar{\sigma}, \rho)$ combinations for which the share of low-carbon investment ℓ_I is equal to 0.995 in the case of high stranding central expectation.

straying from the central expectation will tend to give even more weight to the central expectation, which yields less low-carbon investment due to higher discounting.

The low-stranding projection (Panel (b)), by contrast, entails an unambiguously negative impact of the discount rate on low-carbon investment shares. We can see that the interaction between belief heterogeneity and discounting is reversed compared to the high-stranding case. The mechanism is the same as in the above: discounting heterogeneity decreases the weight of norm-contrarian beliefs for investor behaviours which, with a low-stranding central expectation, will reduce low-carbon investment.

This interaction between belief heterogeneity and the discount rate shows that, regardless of their beliefs, agents exhibiting a higher discount rate will invest less in low-carbon technology. It suggests that anchoring expectations and striving to decrease socially inadequate preferences for the present (Steffen 2020) should go hand in hand. For low-stranding projections, an optimal discount rate is zero. For high-stranding ones, our results show that a non-zero discount rate maximises low-carbon investment through the lower weighting of heterogeneous beliefs over later periods.

3.4 Farsightedness and belief heterogeneity

We now turn to the interactions between belief heterogeneity and farsightedness, denoted by the length of the planning horizon S . The general impact of increasing

the planning horizon by one period is given by Proposition 4.8.

Proposition 4.8. *Let us define R_S^* the value of the benchmark return rate for a given length for the planning horizon S . An increase in the planning horizon S has a positive effect if $R_{S-1}^* + \pi_{L,S} - \pi_{H,S} > 0$. Based on Proposition 4.1, there exists an $s_1 \in [1, S]$ sufficiently large such that this condition holds (if $\pi_{L,1} - \pi_{H,1} > 0$, $s_1 = 1$). Still based on Proposition 4.1, there exists an $s_2 > s_1$ such that the condition reverses if $\pi_{L,1} - \pi_{H,1}$ is negative and low enough. s_2 increase with $\bar{\ell}$ and b_ℓ .*

Proof. Demonstration is given in Appendix F.8.

Intuitively, agents with a longer planning horizon tend to include more periods s where low-carbon tech is expected to be more profitable. However, as shown in Proposition 4.8, this effect is compensated for by negative $\pi_{L,s} - \pi_{H,s}$ emerging once the stranding period ends. This latter effect is exacerbated by low discounting.

These figures illustrate the fact that a minimum planning horizon is required for low-carbon investment to emerge in the current period. This minimum planning horizon corresponds to the expectation horizon necessary for agents to account for enough s -time intervals so as to tilt the expected profit rate in favour of low-carbon technologies.

Starting with the high-stranding central expectation (Panel a), increasing belief heterogeneity has two opposite effects. It increases low-carbon investment for low planning horizons, consistent with the discussion above. It can also decrease by a moderate amount ($\approx 10\%$) the share of low-carbon investment if the horizon of expectation is long and belief heterogeneity is high.¹⁸ This feature is due to our assumption of time s -increasing opinion diversity. As the planning horizon increases, expectations will diverge more for later periods. Hence, agents will tend to exhibit a more balanced investment portfolio as their planning horizon increases. This highlights a trade-off between sufficient long-termism and the uncertainty linked to very late periods.

¹⁸This feature shows in Panel (a) through the upward-sloping shape of the “0.9” line.

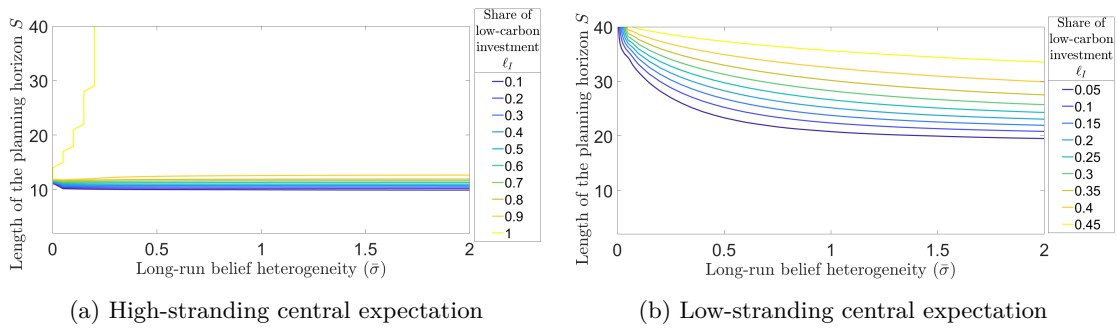


Figure 9: Interaction between long-run belief heterogeneity $\bar{\sigma}$ and the planning horizon S – The charts plot iso-value lines. For instance, the curve with legend “0.5” on Panel (a) corresponds to all $(\bar{\sigma}, S)$ combinations for which the share of low-carbon investment ℓ_I is equal to 0.5 in the case of high stranding central expectation.

Finally, an increase in belief heterogeneity decreases the cutoff point from which the effect of a longer planning horizon entails lower low-carbon investment. This is because higher heterogeneity will tend to decrease the expected value of positive $\pi_{L,s} - \pi_{H,s}$ over $[|s_1, s_2|]$ in aggregate, resulting in negative φ^* if the planning horizon is sufficiently longer to include periods over which agents expect low-carbon technologies to be less profitable.

The low-stranding case (Panel (b)) shows a synergy between the length of the planning horizon and belief heterogeneity. It is because, with higher belief dispersion, including more periods into the planning horizon will lead a greater part of the investors’ population to believe that low-carbon investments will be profitable and for longer. Conversely, if belief heterogeneity is low, increasing the planning horizon has only a very moderate impact on low-carbon investment. It is because agents expect that the period of stranding over which low-carbon investments will be more profitable is only transitory. Because the central projection features low stranding, the stranding period will be short and too transitory to outweigh subsequent periods, over which the edge of the low-carbon technology is reduced. Quantitative implications are greater than in the high-stranding case and function of the length of the planning horizon. Intuitively, for a planning horizon maximising stranding expectation, allowing for greater belief heterogeneity pushes even farther the range of transition-prone expectations. Hence, the share of low-carbon investors will increase.

These results also show that a relatively high share of low-carbon investment (40-50%) can emerge for some planning horizons in the event of important belief heterogeneity, regardless of the underlying central expectation. As sketched in Sections 3.2 and 3.3, introducing belief heterogeneity introduces a whole gradient of interior solutions between 0 and 1. The same share of low-carbon investment can correspond to many parameter constellations. As a result, considering observed shares of low-carbon investment alone as an indicator of the good health of the transition can be misleading.

For instance, the share of renewable investment in Europe revolves around 40%, which may be seen as encouraging. Yet, policymakers should be cautious, in that this figure may correspond equally to a state of high central expectation but short planning horizon (Figure 9 Panel (a) or, conversely, to a state of long planning horizon, but high belief dispersion (Panel (b)). Given that both possibilities lead to different policy implications, regulators should consider surveying investors to gauge as much as possible the state of the market wisdom, how dispersed beliefs are, and how short-sighted agents are.

4 Conclusion

Transitioning to a carbon-free economy requires convincing a sufficiently relevant proportion of private decision-makers that investing in low-carbon technology is the most profitable strategy. High-carbon technologies still often represent the most convenient investment alternative due to higher productivity, better financing conditions, and other factors. However, firms might decide to invest in low-carbon technologies if they expect them to diffuse rapidly and, consequently, high-carbon capital units to become underutilised (“stranded”) and deliver lower profits in the future.

Firms have diverse beliefs about what will happen in the future. We introduce heterogeneity by representing firms’ opinions as normally distributed around a central expectation, which we take as an announced policy pathway or a common market

norm, and increasing logistically in the length of their planning horizon. Our model allows us to explore the role of opinion diversity on investment behaviours, relaxing the hypothesis of coordinated expectations usually encountered in macroeconomic modelling.

Our analytical framework is not immune to limitations, paving the way for future research. The assumption of homogeneous time preferences could be relaxed by representing populations with heterogeneous planning horizons and discount rates. Including expectations for other variables than the utilisation rate, as we start exploring in Appendix B., would be equally relevant, possibly down to the conception of a full “mental model” of the economy for the agents, close to Gabaix’s (2014) endeavour. Our work could also include different and more complex distributions for opinion diversity, as suggested by Appendix A. Finally, exploring the dynamic implications of the model is likely to offer valuable insights. For instance, competing market norms across which agents could switch (in a way similar to Franke and Westerhoff 2018; Hommes 2021, among others) could be included; or climate policies and their implications could be explicitly represented. However, despite its limitations, we believe our paper offers a novel perspective on the low-carbon transition dynamics, with a framework that is close enough to reality to capture several key behavioural dimensions for the first time while maintaining analytical tractability.

We find that the effects of belief heterogeneity on investment shares depend significantly on the existing market norm. If central market expectations entail a rapid transition and large high-carbon stranding, stronger belief heterogeneity reduces low-carbon investment. The opposite is true for central expectations, implying low stranding expectations. The strength of this effect is strongly non-linear: in a context of both very polarised or fully balanced market expectations, investment shares will not react much to changes in belief heterogeneity; by contrast, milder central expectations in favour of either technology will be very sensitive to changes in heterogeneity. Another key finding is that high-stranding market norms will deliver higher low-carbon investment shares, even with high belief dispersion. Our main policy takeaway is that

policymakers should strive to estimate the state of existing central expectations and belief heterogeneity in the marketplace in order to best anticipate possible market reactions to real-world developments. They could also try to infuse high-stranding market norms within the business community if their goal is to increase the share of low-carbon energy, with the caveat that such policy move should not endanger their credibility.

We also find that under our benchmark calibration, and for a sizeable proportion of the parameter constellation we explore, low-carbon investment shares are more sensitive to shocks to short-run belief heterogeneity than to long-run belief heterogeneity. For moderate overall belief dispersion, this implies that shocks to short-run belief dispersion can have disproportionate effects. In this respect, we suggest that policymakers should make sure that agents' expectations are aligned as much as possible regarding short-run outcomes. This could be done, for instance, by adopting short-term planning involving all stakeholders to reach a consensus, with regular evaluation from an independent authority. These findings finally suggest that policymakers should assess investors' views about the low-carbon transition – *e.g.* through surveys or expert auditions – to fully grasp whether the dynamics of today will keep going in the future.

Finally, we study how heterogeneous beliefs interact with agents' time preferences along two dimensions. Belief heterogeneity interacts with the discount rate in various ways. If the central expectation has high stranding content, higher belief heterogeneity exacerbates the effects of the discount rate. Reciprocally, higher belief heterogeneity tones down the impact of the discount rate if the central expectation has low stranding content. In that case, transition believers tend to expect more stranding in the early periods of their planning horizon. More importantly, we show that belief heterogeneity can thwart the positive effects of longer planning horizons. Indeed, while increasing the planning horizon augments expected stranding, it also increases the impact of opinion diversity by widening the range of projections. Again, the final result depends on the underlying central expectations. In particular, belief

heterogeneity can have a highly detrimental effect if the central expectation has low stranding content by keeping low-carbon investment close to a 50-50 dispatch. Finally, we find that, in the presence of belief heterogeneity, simply looking at the share of low-carbon investment to assess the state of investor expectations is misleading, as the same share of low-carbon investment can correspond to many different states of investor opinion, lengths of the planning horizon, or levels of the market norm.

This way of modelling expectations could, in principle, be applied to other variables than capacity utilisation rates (See Appendix B.), and implemented within a broader modelling framework like FASM-ID. Furthermore, although this expectation structure was applied to non-financial companies, it could be expanded to financial agents, who also have their own beliefs about the transition. It could help in coming up with a finer-grained picture of real-financial expectations, notably through the provision of credit, the setting of interest rates, and portfolio choice. The next chapter will precisely expand on portfolio allocation, albeit with a more empirical and disaggregated lens. More precisely, it proposes a first step towards mapping how assets change hands across financial agents in order to better understand how financial exposures to transition risks could evolve along transition paths.

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Appendices

A. Using a Stable Distribution for belief heterogeneity

We present here some insights into the use of alternative distributions to depict belief heterogeneity. The normal distribution has the important drawback of being symmetric, which does not make well for skewed distributions. It also puts great emphasis on values around the mean. The normal distribution, however, is a special case of a broader family of distributions, Stable laws. They are stable by addition and whose skewness and kurtosis can be parameterised.

Stable laws are not directly depicted by a density, but can be derived from their characteristic function. With $X \sim \text{Stable}(\alpha, \gamma, \beta, \delta)$, the characteristic function writes, with i the imaginary number and $\forall t \in \mathbb{R}$:

$$\mathbb{E}(e^{itX}) = \begin{cases} \exp(-\gamma^\alpha |t|^\alpha [1 + i\beta \text{sign}(t) \tan(\frac{\pi\alpha}{2}) (|\gamma|^{1-\alpha} - 1)] + i\delta t) & \text{if } \alpha \neq 1 \\ \exp(-\gamma |t| [1 + i\beta \text{sign}(t) \frac{2}{\pi} \ln(\gamma |t|) + i\delta t]) & \text{if } \alpha = 1 \end{cases}.$$

This function is parameterised by :

- $\alpha \in]0; 2]$, named “stability parameter”, which is a proxy for kurtosis. $\alpha = 2$ is a normal distribution.
- $\gamma \in \mathbb{R}^+$ is the scale parameter, which rules the range on which the distribution will take most of its values and is therefore a proxy for the variance.
- $\beta \in [-1; 1]$ is the skewness parameter. $\beta = 1$ indicates rightward skewness and vice-versa.
- $\delta \in \mathbb{R}$ is a position parameter, which is an approximation for the mode for high α 's.

The stable distribution is called α -stable, in the sense that the sum of stable distributions with the same α 's is a stable distribution. More precisely, with $X_1 \sim \text{Stable}(\alpha, \gamma_1, \beta_1, \delta_1)$ and $X_2 \sim \text{Stable}(\alpha, \gamma_2, \beta_2, \delta_2)$, the sum $X_1 + X_2 \sim \text{Stable}(\alpha, \gamma, \beta, \delta)$, with:

$$\begin{aligned}\gamma &= (\gamma_1^\alpha + \gamma_2^\alpha)^{\frac{1}{\alpha}}, \\ \beta &= \frac{\beta_1 \gamma_1^\alpha + \beta_2 \gamma_2^\alpha}{\gamma_1^\alpha + \gamma_2^\alpha}, \\ \delta &= \delta_1 + \delta_2.\end{aligned}$$

This can be easily generalised to the sum of n stable distributions, which allows us to define our $\varepsilon_{u,s}$ much more generally than with a normal distribution while still being able to compute our aggregate profitability metric R^* .

However, worth emphasising is that stable distributions are in general not as readily interpretable as the Gaussian special case. Typically, the variance is undefined for $\alpha < 2$ (*i.e.* any case that is not a normal distribution) and the mean value is undefined for $\alpha < 1$. As a result, the two parameters γ and δ are only proxies for respectively the variance and the mode of the distribution in the general case. Any result should therefore be taken with precaution given their lesser interpretability.

We nonetheless parameterise our $\varepsilon_{u,s}$, such that $\delta_{u,s} = 0$ and $\gamma_{u,s} = \sigma_{u,s}$, leaving β and α free. To keep an interpretable 0-mean, we modulate α to keep it within the $]1, 2[$ interval. To study the impact of leftward-skewed beliefs (*i.e.*, a greater mass of agents believing in stranding), we set to start with $\beta = -1$. We illustrate how this constellation of parameters changes the distribution with respect to a Normal benchmark in Figure A.1, for the same scale ($\sigma_{u,s}$) schedule and various α 's.

As can be seen, distributions are obviously more skewed leftward. Plus, the mode tends to shift away from the zero mean to make for the skewness. Finally, non-normal distributions tend to de-emphasise values around the mode and focus on “rarer” events to the left. However, as can be seen, they also tend to include more events to the right of the zero-mean. As a result, especially for low α 's, Stable distributions are useful in representing populations that are more polarised. We display results in Figures A.2 for the σ_0 and $\bar{\sigma}$, over a smaller compact than in Section 4 to make it more tractable and for various values of α .

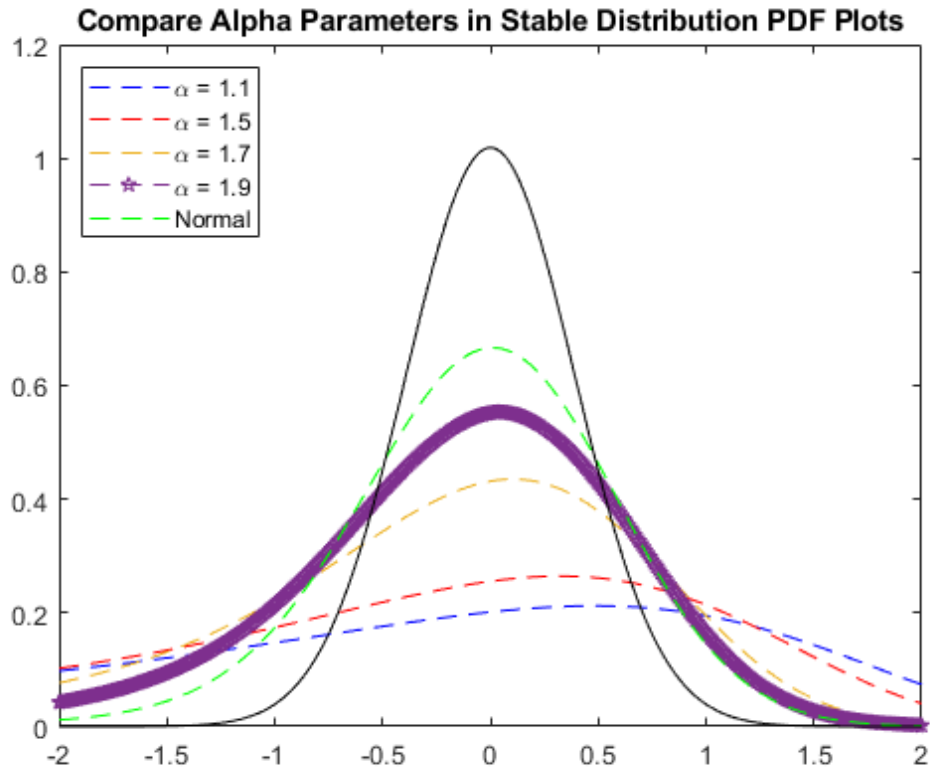


Figure A.1: Comparison of the Normal distribution benchmark to various Stable laws for the same $\sigma_{u,s}$ schedule

As can be seen, changing the distribution has both qualitative and quantitative implications. Interestingly, more skewness leads most often to lower low-carbon investment, even if it makes a greater part of the population believing in high stranding. This is entirely attributable to the fact that skewness is compensated by a greater share of the population believing in higher stranding. Because of our censoring process, this share of the population will become more relevant as the central stranding projection hits lower values, resulting in lower low-carbon investment values. Interestingly, however, this logic gets reversed for low α 's and high $\sigma_{u,s}$ schedules, as the population believing in high stranding is more important. These results suggest that a greater polarisation of beliefs acts in disfavour of the low-carbon transition, unless it is characterised by a very “strong minority”. Note nonetheless that, within our

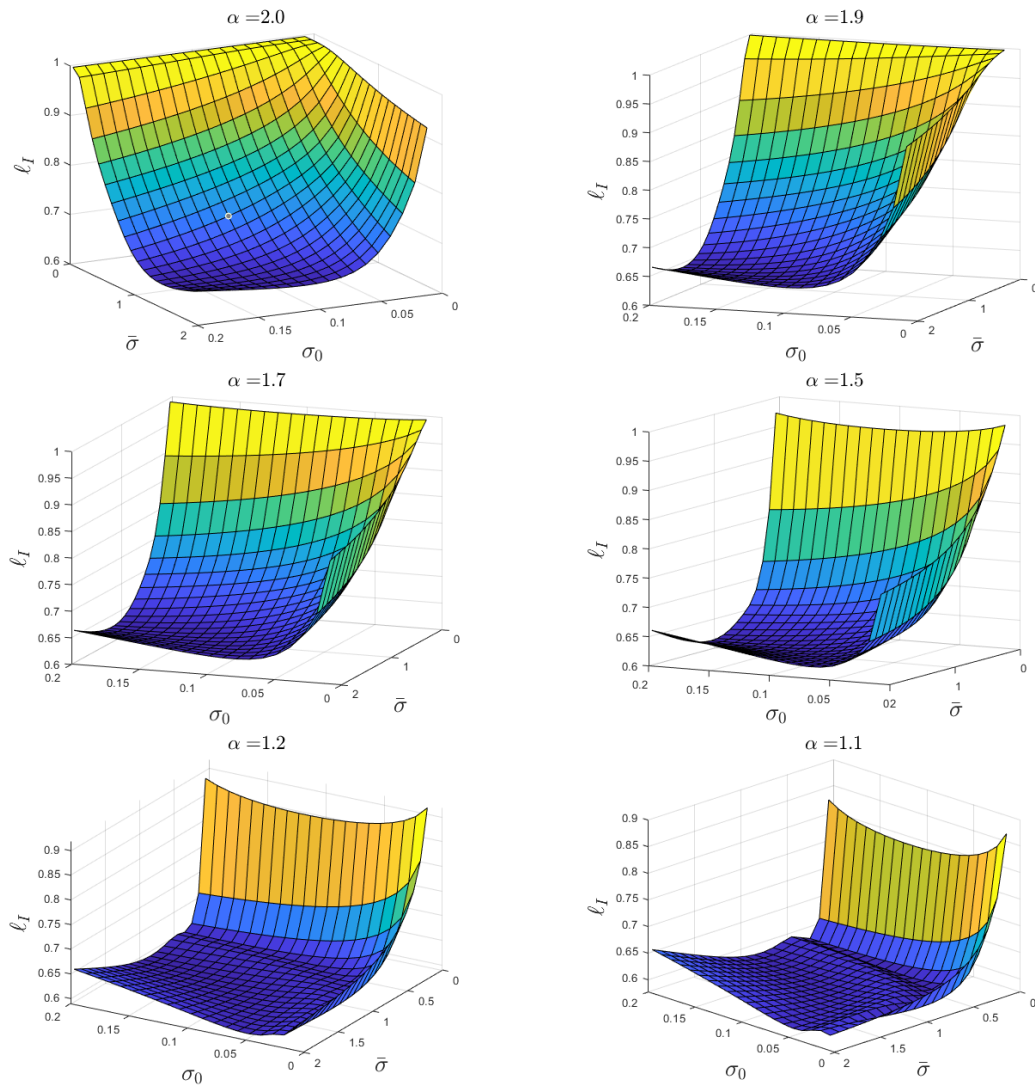


Figure A.2: Sensitivity figures on dissent parameters σ_0 and $\bar{\sigma}$

parameter range, the impact of this strong minority seems reduced.

B. Expanding the realm of uncertainty

In this Appendix, we offer some insights into how our results would change if belief heterogeneity went beyond the utilisation rate of high-carbon capital to also affect the prices of both electricity and fossil fuels. We redefine the return rates for the two technologies as:

$$r_H = \sum_{s=t}^S \beta^s \left[\left(p_E - \frac{p_F}{\xi_F} + \varepsilon_{\pi,s}^H \right) \xi_H (u_{H,s}^* + \varepsilon_{u,s}) - \alpha_H \psi_H c_H \right], \quad (\text{B.1})$$

$$r_L = \sum_{s=t}^S \beta^s \left[(p_E + \varepsilon_{\pi,s}^L) u_L^f \xi_L - \alpha_L c_L \right]. \quad (\text{B.2})$$

where $\varepsilon_{\pi,s}^{(H,L)} \sim \mathcal{N}(0, (\sigma_{\pi,s}^{(H,L)})^2)$ is now the dispersion of beliefs around the normal expected unit profitability for both technologies. These terms include movements in intermediate fossil input prices p_F (including taxes) and changes in electricity prices p_E .

By recalling our investment rule for which $\ell_I = \Pr(r_L - r_H > 0)$ and developing the expression, we can write:

$$\ell_I = P \left(\underbrace{\sum_{s=t}^S \beta^s \left[\left(p_E - \frac{p_F}{\xi_F} \right) \xi_H u_{H,s}^* - p_E \xi_L u_L^f - \alpha_H \psi_H c_H + \alpha_L c_L \right]}_{\text{"Mean belief" term}} + \underbrace{\sum_{s=t}^S \beta^s \left[\varepsilon_{u,s} \left(p_E - \frac{p_F}{\xi_F} \right) + \varepsilon_{\pi,s}^H \xi_H u_{H,s}^* - \varepsilon_{\pi,s}^L \xi_L \right]}_{\text{Normal distribution term}} + \underbrace{\sum_{s=t}^S \beta^s [\varepsilon_{u,s} \varepsilon_{\pi,s}^H \xi_H]}_{\text{Normal-Product Distribution Term}} \geq 0 \right). \quad (\text{B.3})$$

Equation (B.3) yields a product of Normal random variables (bottom term in the equation), which is known to be described by a Normal-Product distribution. The sum of such a distribution, which we need to derive our aggregate return rate, does not have a readily available functional form. However, if the random variables are assumed to be independent, the central-limit theorem allows us to approximate the whole distribution by a well-parametrised Normal distribution. Ware and Lad (2003) further show that for Normal-Product distribution, this approximation holds once we sum as few as five products of normal random variables. Hence, because we sum more than five random variables in our benchmark case with $S = 20$, all the random variables having a mean of zero, and since we assume independence between $\varepsilon_{u,s}$ and $\varepsilon_{\pi,s}^H$, products can be well approximated by a Normal distribution with mean zero and variance $(\varepsilon_{u,s}\varepsilon_{\pi,s}^H\xi_H)^2$.

As a result, waiving the censoring described in Appendix E. for simplicity, we can write:

$$\ell_I \sim \mathcal{N} \left(\underbrace{\sum_{s=t}^S \beta^s \left[\left(p_E - \frac{p_F}{\xi_F} \right) \xi_H u_{H,s}^* - p_E \xi_L u_L^f - \alpha_H \psi_H c_H + \alpha_L c_L \right]}_{\text{Mean}}, \underbrace{\sqrt{\sum_{s=t}^S \beta^{2s} \left(\sigma_{u,s}^2 \left(p_E - \frac{p_F}{\xi_F} \right)^2 + (\sigma_{\pi,s}^H \xi_H u_{H,s}^*)^2 + (\sigma_{\pi,s}^L \xi_L u_L^f)^2 + (\sigma_{u,s} \sigma_{\pi,s} \xi_H)^2 \right)}}_{\text{Standard-Error}} \right) \quad (\text{B.4})$$

Hence, the Normal distribution above allows us to maintain the same Probit approach we use in the main text. Equation (B.4) is a direct extension of our basic formula described in Equations (11)-(16) and with three additional terms:

- $(\sigma_{\pi,s}^H \xi_H u_{H,s}^*)^2$, the belief dispersion on the profitability of high-carbon technology;
- $(\sigma_{\pi,s}^L \xi_L)^2$, the belief dispersion on low-carbon profitability;
- $(\sigma_{u,s} \sigma_{\pi,s} \xi_H)^2$, the interaction between belief dispersion on the profitability of high-carbon

technology and on the utilisation rate.

Notice that expanding the realm of uncertainty has, quantitatively, the same implications as shifting the $\sigma_{u,s}$ schedule in the case when there is only belief dispersion around future utilisation rates (asset stranding). We therefore expect this augmented model to yield lower values of ℓ_J , all other things left equal. Furthermore, increasing any σ would yield the same qualitative results as in the benchmark case with beliefs only on future utilisation rates.

Without providing analytical proofs for brevity, we report some results along the line of Section 4 by supposing that belief dispersion on π_L and π_H (σ_{π_L} and σ_{π_H}) increases through time s following the same logistic behaviour identified for σ_{u_H} and with the same default minimum and maximum belief dispersion (*i.e.* $\sigma_{\pi_L,0} = \sigma_{\pi_H,0} = \sigma_{u_H,0} = 0.01$ and $\bar{\sigma}_{\pi_L,0} = \bar{\sigma}_{\pi_H,0} = \bar{\sigma}_{u_H,0} = 0.5$).

First, we study how the introduction of these new dimensions of belief uncertainty affects our results. For this purpose, we reproduce Figure 6, including our new hypotheses on σ_{π_L} and σ_{π_H} . Results are reported in Figure B.1. For the ambitious scenario (high stranding), results are close to those in Figure 6, qualitatively and quantitatively. However, effects are more in disfavour of low-carbon energy sources overall: a full low-carbon investment share is never reached, with a 95% maximum, and the lower values are reached for high belief dispersion. Furthermore, the effects of $\bar{\sigma}_{u_H}$ and $\sigma_{u_H,0}$ are much more non-linear, with sharper curvatures. This is attributable to: (i) belief dispersion on low-carbon energy profitability, which tends to decrease low-carbon investment; and (ii) the interaction term $(\sigma_{u_H,s}\sigma_{\pi_H,s}\xi_H)^2$, which exacerbates the effects of uncertainty on asset stranding. In the unambitious case (low stranding), we find again effects to be in disfavour of low-carbon energy sources compared to our default case due to the belief dispersion on low-carbon energy profitability. We also find a non-linear effect, with $\bar{\sigma}_{u_H}$ and $\sigma_{u_H,0}$ associated with *less* low-carbon investment than lower combinations, especially for high $\sigma_{u,0}$. This non-linearity emerges because of the interaction term $\sigma_{\pi_H}\sigma_{u_H}$, which amplifies the effect of high $\bar{\sigma}_{u_H}$ and $\sigma_{u_H,0}$ in late periods. In this context, agents hardly take

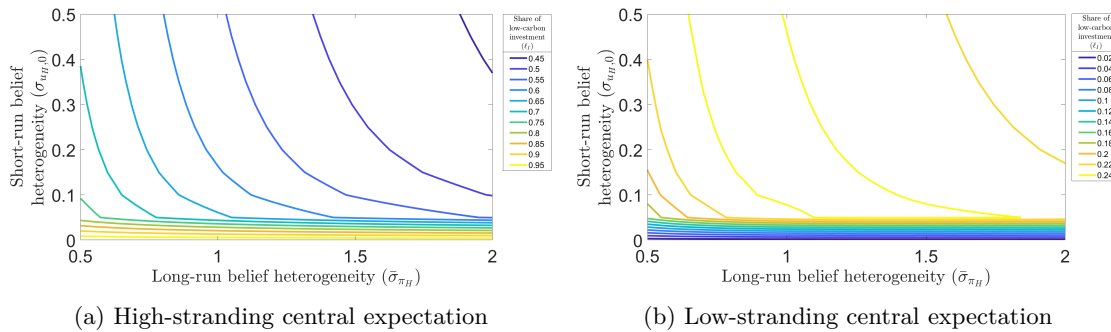


Figure B.1: Long-run and short-run belief heterogeneity (extended uncertainty). The charts plot isovalue lines. For instance, the curve with legend “0.85” on Panel (a) corresponds to all $(\bar{\sigma}_{u_H}, \sigma_{u_H,0})$ combinations for which the share of low-carbon investment ℓ_I is equal to 0.85 in the case of high stranding central expectation.

into account the slow progress of low-carbon energy in the long run prevailing under the central expectation and consider, in the aggregate, low-carbon energy to be overall less profitable than for lower levels of belief dispersion. Hence a lower share of low-carbon energy for high belief dispersion levels in the unambitious case. Otherwise, results are qualitatively similar, albeit sharper, due to the interaction between σ_{u_H} and $\sigma_{\pi_{H,s}}$.

Second, we fix belief dispersion parameters on the utilisation rate to their benchmark values and modulate the maximum value of σ_{π_L} and σ_{π_H} . As mentioned above, we differentiate between an ambitious and an unambitious central expectation. Results are displayed in Figure B.2. The effects of higher belief dispersion on profitability are less pronounced than the ones associated with capacity utilisation belief dispersion for both scenarios. This is because these beliefs apply to variables that do not move in time s while we assume a moving central projection for stranding. However, we never reach a full investment in low-carbon technologies, the highest achieved value being 95% in the ambitious scenarios. We also find that the effects of both types of belief dispersion are non-linear but not symmetrical. In the high-stranding scenarios, long-run belief heterogeneity on σ_{π_L} has a relatively low effect on investment behaviour for low values, as figured by the flatness of the upper part of the curves in the bottom-left corner. These magnitudes are very close to the effects of σ_{u_H} shown

in Figure 6. Conversely, σ_{π_H} exhibits much larger effects. This is explained by the multiplicative term including σ_{π_H} and σ_{u_H} , which exacerbates the effects of any increase in σ_{π_H} . This, however, only holds true until a certain point, after which effects become relatively linear. Results are qualitatively similar but reversed in the non-ambitious case.

All in all, extending the realm of uncertainty bears similar qualitative results to the analysis provided in the main text. Quantitatively, it tends to reduce low-carbon investment shares due to uncertainty on future profitability. Most importantly, the effects of belief dispersion are sharper and more non-linear due to interactions between different belief items. This *compound* effect of belief dispersion suggests that several types of uncertainties can exacerbate each other and that regulators should aim to tackle various types of uncertainties simultaneously as much as possible.

C. Alternative dispatch composition for low- and high-carbon technologies

In this Appendix, we consider alternative dispatch compositions for the definition of our “low-carbon” category to address potentially misleading results linked to our choice of including hydropower and nuclear technologies in the “high-carbon” category.

First, we include hydro in the low-carbon category. This brings the initial share of low-carbon energy production to 34%, and total low-carbon capacity to 438GW, *i.e.* around 45% of total installed capacity (Eurostat 2021). Productivity parameters are redefined accordingly to $\xi_H \approx 5.0221$ and $\xi_L \approx 2.8745$. To adjust for the change in the starting value of the low-carbon share, we recalibrate the intrinsic growth rate of our ambitious and unambitious scenarios to 0.2 and 0.1, respectively, while setting the long-term share to 95% after 30 years, consistently with the goals laid in the Fit for 55 Package (EC 2021). We reproduce here the results displayed in Figure 6 to compare the effect of short- and long-run belief heterogeneity. As shown in Figure C.1, results are qualitatively very close to the ones obtained with our default dispatch.

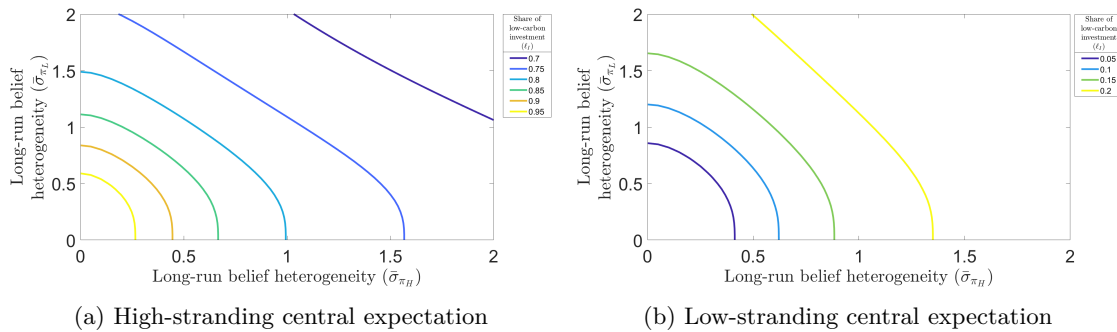


Figure B.2: Long-run belief heterogeneity on low- and high-carbon profitability (extended Uncertainty) – The charts plot iso-value lines. For instance, the curve with legend “0.86” on Panel (a) corresponds to all $(\bar{\sigma}_{\pi_L}, \bar{\sigma}_{\pi_H})$ combinations for which the share of low-carbon investment ℓ_I is equal to 0.85 in the case of high stranding central expectation.

The dichotomy between ambitious and unambitious scenarios remains, and we still find the decreasing marginal effect of increasing uncertainty in both cases. Our effects become slightly sharper than in the benchmark case due to the redefinition of our ambitious and unambitious scenarios, which tend to favour the incumbent.

Second, we also introduce nuclear power. Given the high weight of this energy source in the European mix, including nuclear brings the low-carbon share of energy to 53%, and total low-carbon capacity to around 550GW, *i.e.* around 55% of total installed capacity Eurostat 2021. Productivity parameters are redefined as $\xi_H = 4.4942$ and $\xi_L = 3.69$. Given the large change to our energy shares, we redefine our ambitious and unambitious scenarios. The intrinsic growth rate b_ℓ for the ambitious scenario is decreased from 0.25 to 0.1. The carrying capacity $\bar{\ell}$ is moved from 0.9 to 0.95 as in the above. For the unambitious scenario, while retaining the same carrying capacity of 0.95, we assume an intrinsic growth rate of 0.05. Results are displayed in Figure C.2.

In the ambitious scenario (high stranding), results are similar to the ones with the default dispatch composition, with similar gradients and effects. For the unambitious scenario (low stranding), the model yields a non-linearity in belief dispersion for low values, as shown by the outward orange line. Further, the overall pattern matches that of the ambitious scenario, with most cold-coloured lines corresponding to low

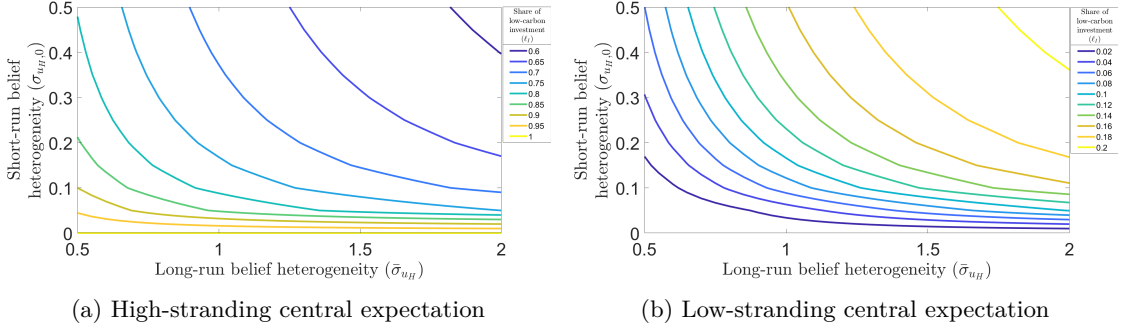


Figure C.1: Long-run and short-run belief heterogeneity (hydro in low-carbon category) – The charts plot iso-value lines. For instance, the curve with legend “0.85” on Panel (a) corresponds to all $(\bar{\sigma}, \sigma_0)$ combinations for which the share of low-carbon investment ℓ_I is equal to 0.85 in the case of high stranding central expectation.

levels of low-carbon investments. Results differ due to the redefinition of productivity parameters. Although they still give an edge to the high-carbon sector for low levels of belief heterogeneity, this edge is very small due to the high productivity of nuclear power plants. As a result, for high levels of belief dispersion, this edge is reversed (the spread between r_L and r_H becomes positive). This yields a behaviour similar to the ambitious scenario for high levels of belief dispersion. This result shows that, if the technologies are very close in terms of mean expected returns, non-linearities can emerge in the model. And, under certain conditions, such as those in the example above, belief uncertainty can diminish low-carbon investment even for otherwise unambitious scenarios.

D. Derivation of return rates

Heterogeneity in transition expectations creates heterogeneity in the the expected return rates for the two technologies. Given equations (4) and (6), we can rewrite equation (1) for the high-carbon sector as

$$r_{H,t} = \sum_{s=t}^S \beta^s \left[\left(p_E - \frac{p_F}{\xi_F} \right) \xi_H (u_{H,s}^* + \varepsilon_{u,s}) - \alpha_H \psi_H c_H \right]. \quad (\text{D.1})$$

Similarly to what was done with the expected capacity utilisation u_H , the expected re-

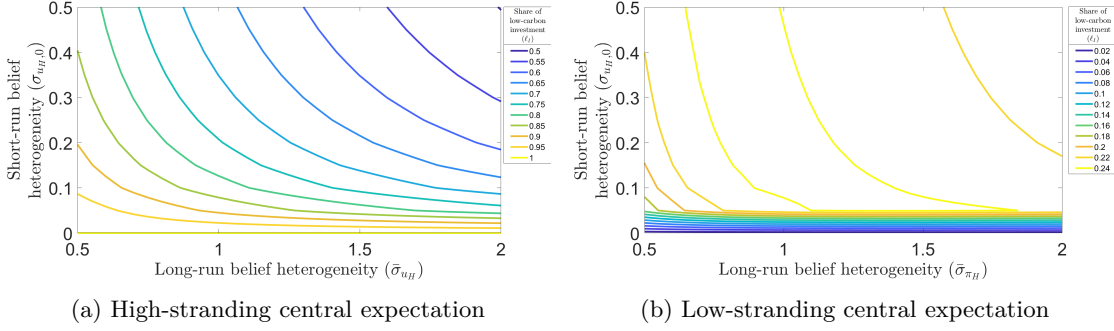


Figure C.2: Long-run and short-run belief heterogeneity (hydro and nuclear energy in low-carbon category) – The charts plot isovalue lines. For instance, the curve with legend “0.85” on Panel (a) corresponds to all $(\bar{\sigma}, \sigma_0)$ combinations for which the share of low-carbon investment l_I is equal to 0.85 in the case of high stranding central expectation.

turn rate on a unit of K_H can be disaggregated into a ‘rational stranding’ deterministic part and an error term. Defining for convenience a new variable $\gamma_H = (p_E - \frac{p_E}{\xi_F})\xi_H$, equation D.1 becomes $r_{H,t} = R_H^* + \varepsilon_r$, with $R_H^* = \sum_{s=t}^S \beta^s [\gamma_H u_H^* - \alpha_H \psi_H c_H]$ and $\varepsilon_r \sim \mathcal{N}(0, \sum_{s=t}^S \beta^{2s} \gamma^2 \sigma_{u,s}^2)$. The expected return rate on low-carbon capital r_H , on the other hand, lacks by assumption any random part. That is, $r_L = R_L^* = \sum_{s=t}^S \beta^s [p_E \xi_L - \alpha_L \psi_L c_L]$. This gives us the net present value of future technological investments but it now remains to find an expression ϑ such that Equation (14) is satisfied.

$$\Pr(r_L > r_H) = \Pr(r_L - r_H > 0) = \Pr(\vartheta > 0). \quad (\text{D.2})$$

From the above we see that $\vartheta = R_L^* - R_H^* - \varepsilon_r$, but this expression must be scaled so the error term has a standard normal distribution. We thus divide the expression by the variance of ε_r to get our final expression φ :

$$\varphi = \frac{R_L^* - R_H^*}{\sum_{s=t}^S \beta^{2s} \gamma^2 \sigma_{u,s}^2} - \frac{\varepsilon_r}{\sum_{s=t}^S \beta^{2s} \gamma^2 \sigma_{u,s}^2} = \varphi^* - \varepsilon_\varphi, \quad (\text{D.3})$$

where $\varepsilon_\varphi \sim \mathcal{N}(0, 1)$.

Furthermore, since the variance term $\sum_{s=t}^S \beta^{2s} \gamma^2 \sigma_{u,s}^2 > 0$,

$$\Pr(r_L > r_H) = \Pr(\vartheta > 0) = \Pr\left(\frac{\vartheta}{\sum_{s=t}^S \beta^{2s} \gamma^2 \sigma_{u,s}^2} > 0\right) = \Pr(\varphi > 0). \quad (\text{D.4})$$

As a final step, using the symmetry of the normal distribution,

$$\Pr(\varphi > 0) = \Pr(\varphi^* - \varepsilon_\varphi > 0) = \Pr(\varepsilon_\varphi - \varphi^* < 0) = \Pr(\varepsilon_\varphi < \varphi^*) = \Phi(\varphi^*). \quad (\text{D.5})$$

E. Censoring the bounds of the distribution

To deal with the caveat that the utilisation rate is clearly bounded, we have to find a way to factor in the clear technical constraints imposed on it. If u_H is between a and b we must find out what the bounds are for the error and associated latent variable and how we deal with it as a probability. By censoring the random part of u_H in the relevant bounds and shifting these bounds along with the variable, we get bounds for ε_φ . The final probability is then calculated conditionally on these bounds.

We begin by censoring the normal random variables in our given bounds. Given a utilisation rate constrained in the interval (a, b) , the error of $u_{H,s}$, $\varepsilon_{u,s}$, is constrained by the inequality in Equation (18). Pictured in Figure E.1, we may shift the distribution down to centre it on 0, simply by subtracting the central value μ_H from both bounds.

$$a - u_{H,s}^* < \varepsilon_{u,s} < b - u_{H,s}^*. \quad (\text{E.1})$$

Likewise, the random variable derived from φ , $\varepsilon_\varphi = \frac{\sum_{s=t}^S \beta^s \gamma_s \varepsilon_{u,s}}{\sum_{s=t}^S \beta^{2s} \gamma^2 \sigma_{u,s}^2}$, is hence constrained by the following bounds:

$$\frac{\sum_{s=t}^S \beta^s \gamma_s (a - u_{H,s}^*)}{\sum_{s=t}^S \beta^{2s} \gamma^2 \sigma_{u,s}^2} < \varepsilon_\varphi < \frac{\sum_{s=t}^S \beta^s \gamma_s (b - u_{H,s}^*)}{\sum_{s=t}^S \beta^{2s} \gamma^2 \sigma_{u,s}^2}. \quad (\text{E.2})$$

Let A and B be the lower and upper bounds of ε_φ in Equation (E.2), respectively and

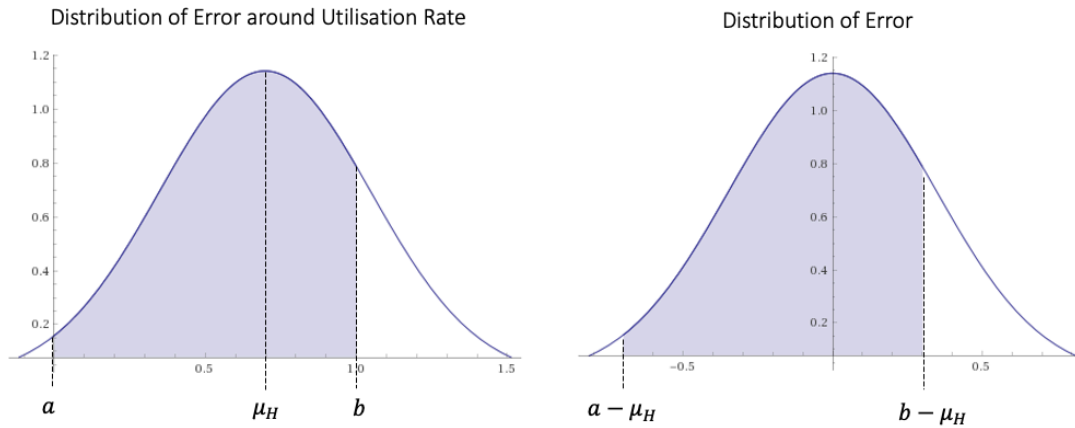


Figure E.1: Shifting bounds along with a change in variable

let $C = \mu_\varphi$. We proceed with the probability as in Equation 16, but this time it is calculated as a conditional probability using the censored standard normal variable that we have derived. The situation is pictured in Figure E.2, with the value of interest C between bounds A and B . The probability that ε_φ is less than C is the area left of the value C , $\Phi(C) - \Phi(A)$. We must account for the limited values of possibility, so divide by the shaded area representing all possible values, $\Phi(B) - \Phi(A)$, giving us Equation E.3.

$$\ell_I = \Pr(\varepsilon_\varphi < C \mid A < \varepsilon_\varphi < B) = \frac{\Phi(C) - \Phi(A)}{\Phi(B) - \Phi(A)}. \quad (\text{E.3})$$

Extending this process, we must account for the fact that the value C may be taken out of the realm of possibility. Thus we make a further extension to say that if the value is less than the possible range the probability is 0 and if higher then it is 1.

$$\ell_i = \Pr(\varepsilon_\varphi < C \mid A < \varepsilon_\varphi < B) = \frac{\delta_{AC}(\Phi(C) - \Phi(A)) - \delta_{BC}(\Phi(B) - \Phi(C))}{\Phi(B) - \Phi(A)} \quad (\text{E.4})$$

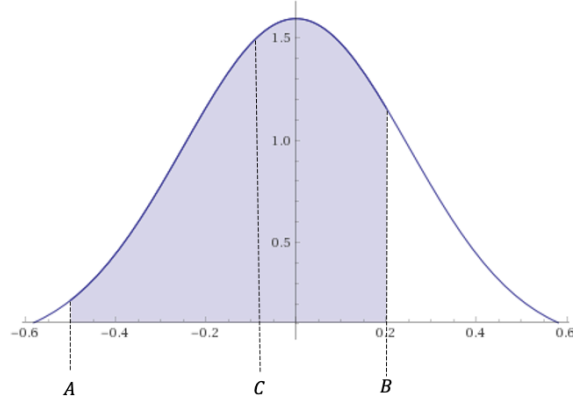


Figure E.2: Representation of possible values for bounds A and B and a value of interest C

$$\text{where } \delta_{ij} = \begin{cases} 1 & i < j \\ 0 & i \geq j. \end{cases}$$

F. Proofs

F.1. Proof of Proposition 1

Proposition. For b_ℓ large enough, $u_{H,s}^*$ is non-monotonous in $s \in [t+1, S]$ and reaches a minimum in $s_{min} \in [1, S]$

Proof. The proposition above is equivalent to showing that there exists an interval $[v, s_{min}] \subset [t+1, S]$ such that $\frac{u_{H,s+1}^*}{u_{H,s}^*} < 1 \forall s \in [t+1, s_{min}]$ and $\frac{u_{H,s+1}^*}{u_{H,s}^*} > 1 \forall s \notin [v, s_{min}]$. Let us first notice that $u_{H,s+1}^*$ is defined as:

$$u_{H,s+1}^* = \begin{cases} \frac{e_{H,s+1}}{(1-\delta)K_s \xi_H} & \text{if } I_{H,s}^* = 0 \\ \frac{e_{H,s+1}}{(1-\delta)K_{H,s}^d \xi_H} & \text{if } I_{H,s}^* > 0. \end{cases}$$

Hence that $\frac{u_{H,s+1}^*}{u_{H,s}^*}$ can take 4 possible values:

$$\frac{u_{H,s+1}^*}{u_{H,s}^*} = \begin{cases} \frac{e_{H,s+1}(1-\delta)K_{s-1}\xi_H}{(1-\delta)K_s\xi_H e_{H,s-1}} & \text{if } I_{H,s}^* = 0 \text{ and } I_{H,s-1}^* = 0 & (1) \\ \frac{e_{H,s+1}K_{H,s-1}^d\xi_H}{(1-\delta)K_s\xi_H e_{H,s-1}} & \text{if } I_{H,s}^* = 0 \text{ and } I_{H,s-1}^* > 0 & (2) \\ \frac{e_{H,s+1}(1-\delta)K_{s-1}\xi_H}{K_s^d\xi_H e_{H,s-1}} & \text{if } I_{H,s}^* > 0 \text{ and } I_{H,s-1}^* = 0 & (3) \\ \frac{e_{H,s+1}K_{s-1}^d\xi_H}{K_s^d\xi_H e_{H,s-1}} & \text{if } I_{H,s}^* > 0 \text{ and } I_{H,s-1}^* > 0 & (4). \end{cases}$$

We focus on cases (1) and (2), since cases (3) and (4) describe cases in which no stranding is expected and therefore on which $u_{H,s}$ is constant and equal to u^f .

Let us first notice that the condition for $I_{H,s}^* = 0 \forall s$ is:

$$\frac{u_{H,s-1}}{u^f} < \frac{(1-\delta)}{(1+g_{e_{H,s}})}. \quad (\text{F.1})$$

It is easy to show that:

$$(1-b_\ell)(1+g_e) < (1+g_{e_{H,s}}) < (1+g_e). \quad (\text{F.2})$$

And that the sequence $((1+g_{e_{H,s}}))_{s \in [t, S]}$ is increasing and converges towards $(1+g_e)$.

Hence, it is possible to find a b large enough such that Condition (1) is fulfilled at a given \bar{s} . For instance, the condition for $\bar{s} = t + 1$ supposing that $u_{H,t} = u^f$

$$1 < \frac{(1-\delta)}{(1+g_{e_{H,\bar{s}}})} \Leftrightarrow (1+g_e)(1-b(\frac{\bar{\ell}-\ell_{E,t}}{(1-\ell_{E,t})\ell})) < (1-\delta) \Leftrightarrow b > \frac{1-\frac{(1-\delta)}{(1+g_e)}}{(\frac{\bar{\ell}-\ell_{E,t}}{(1-\ell_{E,t})\ell})}. \quad (\text{F.3})$$

This condition can be generalised for any $s > t$ since, in expectations, as long as $I_{H,s}^* > 0$, $u_{H,s} = u^f$.

The condition for $I_{H,\bar{s}+1}^* = 0$ is:

$$\frac{u_{H,\bar{s}}}{u^f} < \frac{(1-\delta)}{(1+g_{e_{H,\bar{s}}})}. \quad (\text{F.4})$$

In that case, we can write $K_{H,\bar{s}+1} = (1 - \delta)K_{H,\bar{s}} = (1 - \delta)^2 K_{H,\bar{s}-1} = (1 - \delta)^2 \frac{e_{H,\bar{s}-1}}{u_{\bar{s}-1} \xi_H}$ and Condition (1) can be rewritten as:

$$\frac{u_{H,\bar{s}-1}}{u^f} < \frac{(1 - \delta)^2}{(1 + g_{e_{H,\bar{s}}})(1 + g_{e_{H,\bar{s}+1}})}. \quad (\text{F.5})$$

Which can again be fulfilled for b large enough. More generally, the condition for $I_{H,k}^* = 0, k > \bar{s}$ writes:

$$\frac{u_{H,\bar{s}}}{u^f} < \frac{(1 - \delta)^{k-\bar{s}}}{\prod_{i=\bar{s}}^k (1 + g_{e_{H,i}})}. \quad (\text{F.6})$$

As we saw above, the sequence $\left((1 + g_{e_{H,s}}) \right)_{s \in [t, S]}$ is increasing and converges towards $(1 + g_e) > (1 - \delta)$. Since g_e and δ are positive, based on the Intermediate value theorem, there exists a s^* for which:

$$(1 + g_{e_{H,s^*}}) < (1 - \delta) < (1 + g_{e_{H,s^*+1}}).$$

Hence that, for $k > s^*$, we can write $\frac{(1-\delta)^{k-\bar{s}}}{\prod_{i=\bar{s}}^k (1+g_{e_{H,i}})}$ as follows:

$$\frac{(1 - \delta)^{k-\bar{s}}}{\prod_{i=\bar{s}}^k (1 + g_{e_{H,i}})} = \frac{1}{\prod_{i=\bar{s}}^{s^*} (1 + g_{e_{H,i}})} \frac{(1 - \delta)^{k-\bar{s}}}{\prod_{i=s^*+1}^k (1 + g_{e_{H,i}})}.$$

For S large enough, $k^* < S$. This result shows that there exists an interval $U \subset [t, S]$ on which $I_{H,s}^* = 0$ and that, for S large enough, $k^* < S$. For $s > k^*$, $I_{H,s}^* > 0$

The right-hand term is decreasing in k and converges towards zero. As a result, there exists a k^* for which:

$$\frac{u_{H,\bar{s}}}{u^f} > \frac{(1 - \delta)^{k^*-\bar{s}}}{\prod_{i=\bar{s}}^{k^*} (1 + g_{e_{H,i}})}. \quad (\text{F.7})$$

Cases (1) and (2) $I_{H,k}^* = 0$ and $I_{H,k-1}^* = 0 \forall k \in U$ thus depict situations arising for b large enough.

Considering case (1) and simplifying the corresponding equation, we get:

$$\frac{u_{H,s+1}^*}{u_{H,s}^*} = \frac{e_{H,s+1}(1-\delta)K_{s-1}\xi_H}{(1-\delta)^2K_{s-1}\xi_H e_{H,s}} = \frac{e_{H,s+1}}{(1-\delta)e_{H,s}},$$

which is below 1 if and only $\frac{e_{H,s+1}}{e_{H,s}} = (1+g_{e_{H,s}}) < (1-\delta)$, that is, the decrease rate in high-carbon energy demand is superior to the depreciation rate. Using the fact that $\left((1+g_{e_{H,s}})\right)_{s \in [t, S]}$ is increasing and converges towards $(1+g_e) > (1-\delta)$ and using again the Intermediate value theorem, it follows that, for $s > s_{min} = s^*$, $\frac{e_{H,s+1}}{e_{H,s}} > 1$ and < 1 otherwise.

Considering now case (2) and noticing that in this instance $K_{H,s} = K_{H,s-1}^d$, we get:

$$\frac{u_{H,s+1}^*}{u_{H,s}^*} = \frac{e_{H,s+1}K_s^d \xi_H}{(1-\delta)2K_s^d \xi_H e_{H,s}} = \frac{e_{H,s+1}}{(1-\delta)e_{H,s}},$$

which yields the same condition as above : for b_ℓ large enough, the utilisation rate will decrease.

Lemma 4.1. *For b_ℓ large enough, there exists an interval $T \subset [t, S]$ such that, $\forall s \in T$, $\pi_{L,s} - \pi_{H,s} > 0$.*

Proof. The condition for $\pi_{L,s} - \pi_{H,s} > 0$ is:

$$u_{H,s} < \frac{1}{p_E - \frac{p_E}{f_F}} (p_E \xi_L - \alpha_K \psi_L c_L^k + \alpha_H \psi_H c_H^k).$$

As per Proposition 1, with b_ℓ large enough, it is possible to define a subset $U \subset [t, S]$ on which $u_{H,s}$ is decreasing, with the sequence $(u_{H,s})_{s \in [t+1, S]}$ hitting a minimum at the highest value of U : s_{min} . Now, we know that, $\forall s \in [t+1, S]$:

$$u_{H,s+1}^* = \frac{e_s^d(1+g_E) - e_{L,s}(1+g_E) \left[1 + b_\ell \left(1 - \frac{e_{L,s}}{\bar{l}e_s^d} \right) \right]}{\xi_H[(1-\delta)K_{H,s} + I_{H,s}^*]}. \quad (\text{F.8})$$

A fortiori,

$$u_{H,s_{min}}^* = \frac{e_{s_{min}-1}^d(1+g_E) - e_{L,s_{min}-1}(1+g_E) \left[1 + b_\ell \left(1 - \frac{e_{L,s_{min}-1}}{\ell e_{s_{min}-1}^d} \right) \right]}{\xi_H[(1-\delta)K_{H,s_{min}-1} + I_{H,s_{min}-1}^*]}, \quad (\text{F.9})$$

which is an obviously decreasing function of b_ℓ . Then, for b_ℓ large enough, $u_{H,s_{min}}^*$ will fulfil the condition above. It is further possible to define an interval $[[s_{min} - a; s_{min} + a]]$ on which this condition holds, again for b_ℓ large enough.

F.2. Proof of Proposition 2

Proposition. For $\sigma_{u,s} = 0 \forall s \in [[1, S]]$, ℓ_I tends towards a degenerate probability distribution function, whereby:

$$\ell_I = \begin{cases} 0 & \text{if } R^* < 0 \\ 0.5 & \text{if } R^* = 0 \\ 1 & \text{if } R^* > 0. \end{cases} \quad (\text{F.10})$$

Proof. Starting from $\ell_I = \frac{\Phi(\varphi^*) - \Phi(\varphi_0)}{\Phi(\varphi_1) - \Phi(\varphi_0)}$ and noticing that $\varphi_0 = \frac{R_0}{\Gamma} < 0$ and $\varphi_1 = \frac{R_1}{\Gamma} > 0$ within our parameter space, we have:

$$\begin{aligned} \lim_{\Gamma \rightarrow 0^+} \Phi(\varphi_0) &= \lim_{\Gamma \rightarrow 0^+} \Phi\left(\frac{R_0}{\Gamma}\right) = 0 \\ \lim_{\Gamma \rightarrow 0^+} \Phi(\varphi_1) &= \lim_{\Gamma \rightarrow 0^+} \Phi\left(\frac{R_1}{\Gamma}\right) = 1. \end{aligned}$$

For $R^* = 0$, the result flows from the definition of Φ . For any Γ , we have:

$$\begin{aligned} \ell_I &= \frac{\Phi(0) - \Phi(\varphi_0)}{\Phi(\varphi_1) - \Phi(\varphi_0)} \\ &= \frac{0.5 - \Phi(\varphi_0)}{\Phi(\varphi_1) - \Phi(\varphi_0)}, \end{aligned}$$

which, given the limits above, has $\Phi(0) = 0.5$ as limit for $\Gamma \rightarrow 0$.

All in all,

$$\lim_{\Gamma \rightarrow 0^+} \ell_I = \lim_{\Gamma \rightarrow 0^+} \Phi(\varphi^*) = \begin{cases} 0 & \text{if } R^* < 0 \\ 0.5 & \text{if } R^* = 0 \\ 1 & \text{if } R^* > 0. \end{cases} \quad (\text{F.11})$$

F.3. Proof of Proposition 3

Let us consider a logistic sequence $x_n = x_{n-1} (1 + b(1 - \frac{x_{n-1}}{K}))$ where K is a carrying capacity and b an intrinsic growth rate. Let us then consider x_0 the first term of this sequence. Then, $\forall n | x_n < K$:

$$\frac{\partial x_n}{\partial K} \geq 0 \quad (\text{F.12})$$

$$\frac{\partial x_n}{\partial b} \geq 0 \quad (\text{F.13})$$

$$\frac{\partial x_n}{\partial x_0} \geq 0, \quad (\text{F.14})$$

With the last proposition holding for $x_0 < K$.

Proof. The first property can be shown by recurrence. Considering $\frac{\partial x_n}{\partial K}$, it is obvious, with x_0 given that $\frac{\partial x_1}{\partial K} > 0$. Supposing that $\frac{\partial x_n}{\partial K} \geq 0$, we can show that $\frac{\partial x_{n+1}}{\partial K} \geq 0$.

$$\begin{aligned}
\frac{\partial x_{n+1}}{\partial K} &= \frac{\partial x_n}{\partial K} \left(1 + b \left(1 - \frac{x_n}{K}\right)\right) - x_n b \left(\frac{\frac{\partial x_n}{\partial K} K - x_n}{K^2}\right) \\
&= \frac{\partial x_n}{\partial K} \left(1 + b \left(1 - \frac{x_n}{K}\right)\right) - b \frac{x_n}{K} + \frac{x_n}{K^2} \\
&= \frac{\partial x_n}{\partial K} \left(1 + b \left(1 - 2b \frac{x_n}{K}\right)\right) + \frac{x_n}{K^2}.
\end{aligned}$$

The condition for this expression to be negative is:

$$1 + \frac{\partial x_n}{\partial K} \frac{K^2}{x_n^2} < b \left(\frac{x_n}{K} - 1\right).$$

$1 + \frac{K^2}{x_n^2} \frac{\partial K}{\partial x_n}$ is positive as per the assumption $\frac{\partial x_n}{\partial K} > 0$ and $\frac{x_n^2}{K^2} > 0$. Hence that the condition above cannot hold for $x_n \leq K$. We consider in the following only constellations of parameters for which $x_n \leq K$, without loss of generality for the purpose of the paper.

Regarding b , we can also proceed by recurrence. Defining:

$$\begin{aligned}
x_n &= x_{n-1} \left(1 + b \left(1 - \frac{x_{n-1}}{K}\right)\right) \\
x'_n &= x'_{n-1} \left(1 + (b + db) \left(1 - \frac{x'_{n-1}}{K}\right)\right) \\
&= x'_{n-1} \left(1 + (b') \left(1 - \frac{x'_{n-1}}{K}\right)\right) x_0 = x'_0.
\end{aligned}$$

It is easy to check that, for x_0 given, $x'_1 - x_1 \geq 0$. Supposing that $x'_n - x_n \geq 0$, we write:

$$\begin{aligned}
x'_{n+1} - x_{n+1} &= x'_n(1 + (b')(1 - \frac{x'_n}{K})) - x_n(1 + b(1 - \frac{x_n}{K})) \\
&= x'_n - x_n + b'(1 - \frac{x'_n}{K}) - b(1 - \frac{x_n}{K}) \\
&\geq x'_n - x_n + b'(1 - \frac{x'_n}{K}) - b'(1 - \frac{x_n}{K}) \\
&\geq x'_n - x_n + b'(\frac{x_n}{K} - \frac{x'_n}{K}) \\
&\geq (x'_n - x_n)\frac{(1-b)}{K}.
\end{aligned}$$

Given that $(1 - \frac{b}{K}) > 0$ for $b < 1$ and null when $b = 1$, we can consider this condition to hold for reasonable values of b .

For x_0 , we can use once again the same method. Defining:

$$\begin{aligned}
x_n &= x_{n-1}(1 + b(1 - \frac{x_{n-1}}{K})), \quad x_0 = x_0 \\
x'_n &= x'_{n-1}(1 + b)(1 - \frac{x'_{n-1}}{K}), \quad x'_0 = x'_0 \\
x_0 &\leq x'_0.
\end{aligned}$$

Showing that $x'_1 \geq x_1$ and supposing that $x'_n \geq x_n$, we get the similar condition :

$$\begin{aligned}
x'_{n+1} - x_{n+1} &= x'_n(1 + b)(1 - \frac{x'_n}{K}) - x_n(1 + b(1 - \frac{x_n}{K})) \\
&= x'_n - x_n + b'(1 - \frac{x'_n}{K}) - b(1 - \frac{x_n}{K}) \\
&= x'_n - x_n + b'(\frac{x_n}{K} - \frac{x'_n}{K}) \\
&= (x'_n - x_n)\frac{(1-b)}{K}.
\end{aligned}$$

Which again holds true for $b \leq 1$.

Lemma 4.2. *All else held equal, increasing $\bar{\ell}$ or b_ℓ will have a positive effect on low-carbon investment.*

Proof. This property follows from Proposition 2, Φ being a positive function of φ itself obviously a positive function of $\ell_{E,s}$.

Lemma 4.3. *All else held equal, increasing σ_0 , $\bar{\sigma}$, and b_σ will have a negative effect on low-carbon investment.*

Proof. This property follows from Proposition 2, $|\varphi_t^*|$ being a negative function of the $\sigma_{u,s}$ with a limit in zero.

F.4. Proof of Proposition 4

Proposition. *It is possible to define an interval $\mathcal{S} = [|\mathcal{S}; \bar{\mathcal{S}}|]$ such that, for a given ρ , b_ℓ and $\bar{\ell}$, $R^* > 0 \forall S \in \mathcal{S}$ and $R^* \leq 0$ otherwise. \mathcal{S} can be empty.*

Proof. As per Proposition 4.1, $u_{H,s}$ gets back closer to u^f , if the profit rate spread between high and low technologies $\pi_{L,1} - \pi_{H,1}$ is low enough, a longer planning horizon may have a negative effect on low-carbon investment, as agents account for more time periods during which $\pi_{L,s} - \pi_{H,s} < 0$.

F.5. Proof of Proposition 5

Proposition. *The effect of a higher σ_0 or $\bar{\sigma}$ will depend on the sign of R^* . If $R^* < 0$, $\frac{\partial \ell_I}{\partial \sigma_0} \geq 0$ and $\frac{\partial \ell_I}{\partial \bar{\sigma}} \geq 0$ and ℓ_I is concave in σ_0 and $\bar{\sigma}$. If $R^* > 0$, $\frac{\partial \ell_I}{\partial \sigma_0} \leq 0$ and $\frac{\partial \ell_I}{\partial \bar{\sigma}} \leq 0$ and ℓ_I is convex in σ_0 and $\bar{\sigma}$. Plus, there exists an $R' \in [R_0; R_1]$ such that $\frac{\partial \ell_I}{\partial \Gamma}(R')$ is equal to zero.*

Proof. Taking first the derivative of ℓ_I with respect to Γ , we find:

$$\frac{\partial \ell_I}{\partial \Gamma} = \frac{u_1 v^* - v_1 u^*}{2\Gamma^{\frac{3}{2}} v_1^2}, \quad (\text{F.15})$$

with:

$$\begin{aligned} u_1 &= R_1\phi(\varphi_1) - R_0\phi(\varphi_0) \\ u^* &= R^*\phi(\varphi^*) - R_0\phi(\varphi_0) \\ \phi(x) &= \frac{\partial\Phi}{\partial x} \quad \forall x \\ v_1 &= \Phi(\varphi_1) - \Phi(\varphi_0) \\ v^* &= \Phi(\varphi^*) - \Phi(\varphi_0). \end{aligned}$$

Considering the cross-derivative $\frac{\partial\ell_I}{\partial\Gamma\partial R^*}$, we obtain:

$$\frac{\partial\ell_I}{\partial\Gamma\partial R^*} = (v_1(\varphi^*)^2 - v_1 - \frac{u_1}{\Gamma}) \frac{e^{-\frac{x^2}{2}}}{2\pi}.$$

Since $u_1 > 0$ and $v_1 > 0$, the determinant of $(v_1\varphi^* - v_1 - \frac{u_1}{\Gamma})$ is always positive. Hence, this function admits two roots in R^* , R_- and R_+ and is strictly negative between the two corresponding local optima. Noticing that $\frac{\partial\ell_I}{\partial\Gamma}(R_0) > 0$ and $\frac{\partial\ell_I}{\partial\Gamma}(R_1) < 0$, it follows that $\frac{\partial\ell_I}{\partial\Gamma}(R_-) > 0$ and $\frac{\partial\ell_I}{\partial\Gamma}(R_+) < 0$. By the theorem of intermediate value, there exists a $R' \in [R_0; R_1]$ such that $\frac{\partial\ell_I}{\partial\Gamma}(R')$ is equal to zero. The concavity/convexity properties of ℓ_I follow from the definition of its second derivative.

F.6. Proof of Proposition 6

Proposition. *For a given S and ρ , there exists a $(\frac{\bar{\sigma}}{\sigma_0})^*$ ratio high enough such that*

$$\left| \frac{\partial\ell_I}{\partial\bar{\sigma}} \right| > \left| \frac{\partial\ell_I}{\partial\sigma} \right|.$$

Proof. Using the result of Proposition 4.3, suffices to prove that, for a $(\frac{\bar{\sigma}}{\sigma_0})^*$ high enough, $\frac{\partial\Gamma}{\partial\sigma_0} > \frac{\partial\Gamma}{\partial\bar{\sigma}}$.

Considering that the logistic sequence is well-approximated by a continuous counterpart, we write the following logistic function $l(x) \forall x \geq 0$, which includes a starting value σ_0 and a carrying capacity $\bar{\sigma}$

$$l(x) = \frac{\bar{\sigma}}{1 + \left(\frac{\bar{\sigma}}{\sigma_0} - 1\right)e^{-b_\sigma x}}.$$

Taking the corresponding derivatives:

$$\begin{aligned} \frac{\partial l}{\partial \bar{\sigma}} &= \frac{1 - e^{-b_\sigma x}}{\left(1 + \left(\frac{\bar{\sigma}}{\sigma_0} - 1\right)e^{-b_\sigma x}\right)^2} \geq 0 \\ \frac{\partial l}{\partial \sigma_0} &= \frac{\left(\frac{\sigma_0}{\bar{\sigma}}\right)^2 e^{-b_\sigma x}}{\left(1 + \left(\frac{\bar{\sigma}}{\sigma_0} - 1\right)e^{-b_\sigma x}\right)^2} \geq 0 \end{aligned}$$

We consider the ratio $\frac{\frac{\partial l}{\partial \sigma_0}}{\frac{\partial l}{\partial \bar{\sigma}}}$ to determine the condition under which $\frac{\partial l}{\partial \sigma_0} > \frac{\partial l}{\partial \bar{\sigma}}$, which is a sufficient condition for $\frac{\partial \Gamma}{\partial \sigma_0} > \frac{\partial \Gamma}{\partial \bar{\sigma}}$:

$$\frac{\bar{\sigma}}{\sigma_0} > \sqrt{\frac{1 - e^{-b_\sigma x}}{e^{-b_\sigma x}}}.$$

Given that we only consider S -long logistic sequences and because $\frac{(1 - \exp(-x))}{\exp(-x)}$ is a strictly increasing function of x , a sufficient condition is that:

$$\frac{\bar{\sigma}}{\sigma_0} > \max_x \sqrt{\frac{1 - e^{-b_\sigma x}}{e^{-b_\sigma x}}} = \sqrt{\frac{1 - e^{-b_\sigma S}}{e^{-b_\sigma S}}}. \quad (\text{F.16})$$

Given Proposition 4.3, this defines a $\frac{\bar{\sigma}}{\sigma_0}$ high enough for $\left|\frac{\partial \ell_I}{\partial \bar{\sigma}}\right| > \left|\frac{\partial \ell_I}{\partial \sigma_0}\right|$.

Let us fix σ_0 to its benchmark value of 0.01. The value of the threshold for $S = 30$ is around 66, which implies that the condition would hold for this planning horizon for $\bar{\sigma} \geq 0.6$;, that is, for a sizeable range of our parameter constellation. The condition

would hold for $\bar{\sigma} \geq 1$ with a planning horizon equal to 32, and $\bar{\sigma} \geq 1.5$ for a planning horizon of 35. Figure F.6.1 below gives the range of $\bar{\sigma}$ values for which the condition holds true for each length of the planning horizon.

F.7. Proof of Proposition 7

Proposition. *As belief heterogeneity approaches infinity, ℓ_I will tend towards a finite value $\tilde{\ell}_I = \frac{R^* - R_0}{R_1 - R_0}$, where R^* , R_0 and R_1 are the numerators of φ^* , φ_0 and φ_1 respectively. We call $\tilde{\ell}_I$ “full dispersion” equilibrium and it is a function of b_ℓ , \bar{b} for a given S and ρ .*

Proof. Using l'Hôpital's Rule, we have:

$$\lim_{\Gamma \rightarrow +\infty} \ell_I = \lim_{\Gamma \rightarrow +\infty} \frac{\Phi(\varphi^*) - \Phi(\varphi_0)}{\Phi(\varphi_1) - \Phi(\varphi_0)} = \lim_{\Gamma \rightarrow +\infty} \frac{\frac{\partial \Phi(\varphi^*) - \Phi(\varphi_0)}{\partial \Gamma}}{\frac{\partial \Phi(\varphi_1) - \Phi(\varphi_0)}{\partial \Gamma}}.$$

Differentiating, we obtain:

$$\frac{\frac{\partial \Phi(\varphi^*) - \Phi(\varphi_0)}{\partial \Gamma}}{\frac{\partial \Phi(\varphi_1) - \Phi(\varphi_0)}{\partial \Gamma}} = \frac{\frac{-R^*}{2\Gamma^{\frac{3}{2}}} \phi(\varphi^*) - \frac{-R_0}{2\Gamma^{\frac{3}{2}}} \phi(\varphi_0)}{\frac{-R_1}{2\Gamma^{\frac{3}{2}}} \phi(\varphi_1) - \frac{-R_0}{2\Gamma^{\frac{3}{2}}} \phi(\varphi_0)}.$$

Where $\phi(x) = \frac{\partial \Phi}{\partial x} \forall x$ the probability density function of a $\mathcal{N}(0, 1)$. Simplifying, we get:

$$\frac{\frac{\partial \Phi(\varphi^*) - \Phi(\varphi_0)}{\partial \Gamma}}{\frac{\partial \Phi(\varphi_1) - \Phi(\varphi_0)}{\partial \Gamma}} = \frac{R^* \phi(\varphi^*) - R_0 \phi(\varphi_0)}{R_1 \phi(\varphi_1) - R_0 \phi(\varphi_0)}.$$

Since $\phi(x) = \frac{1}{2\sqrt{\pi}} \exp(-\frac{x^2}{2})$, it is easy to see that, for any R , $\lim_{\Gamma \rightarrow +\infty} \phi(\frac{R}{\Gamma}) = \lim_{x \rightarrow 0^+} \phi(x)$ for $x = \Gamma$, which is equal to 1. Hence, we get the results:

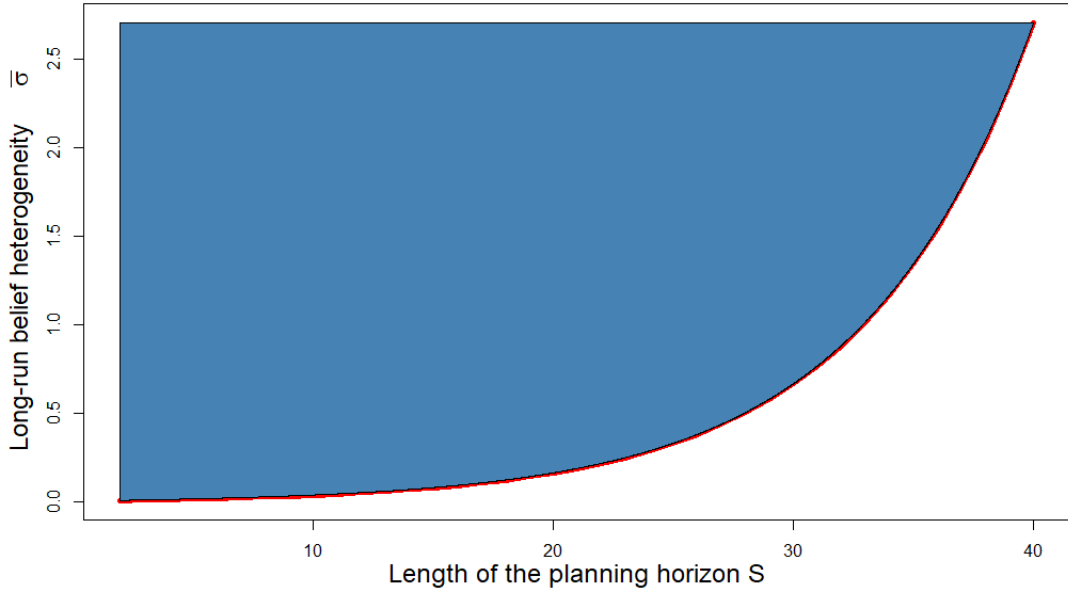


Figure F.6.1: Range of $\bar{\sigma}$ values for which Condition F.16 holds true for each length of the planning horizon. The shaded area gives the range of acceptable value, while the red line gives the value of the threshold as defined in Equation F.16.

$$\lim_{\Gamma \rightarrow +\infty} \ell_I = \frac{R^* - R_0}{R_1 - R_0}$$

Which indeed belongs to $[0, 1]$ for $R_0 \leq R^* \leq R_1$.

If $\ell_I = \Phi(\varphi^*)$, (*i.e.* the distribution is not censored), it is straightforward that, the limit of φ^* being zero, that of $\Phi(\varphi^*)$ is $\Phi(0) = 0.5$.

F.8. Proof of Proposition 8

Proposition. *An increase in the planning horizon S will have a positive effect if $R_{S-1}^* + \pi_{L,S} - \pi_{H,S} > 0$. For b_ℓ There exists an $s_1 \in [1, S]$ sufficiently large such that this condition holds. If $\pi_{L,t} - \pi_{H,t} > 0$, $S = 1$. There also there exists an*

$s_2 > s_1$ such that the condition reverses if $\pi_{L,S_2} - \pi_{H,S_2}$ is negative and low enough. s_2 increase with $\bar{\ell}$ and b_ℓ .

Proof. Let us assume that agents have a sufficiently large planning horizon S . In all generality, from Proposition 4.1, it is possible to decompose $\sum_1^S \beta^s (\pi_{L,s} - \pi_{H,s})$ as follows:

$$\sum_s^S (\pi_{L,s} - \pi_{H,s}) = \underbrace{\sum_1^{s_1} \beta^s (\pi_{L,s} - \pi_{H,s})}_{<0} + \underbrace{\sum_{s_1+1}^{s_2} \beta^s (\pi_{L,s} - \pi_{H,s})}_{>0} + \underbrace{\sum_{s_2+1}^S \beta^s (\pi_{L,s} - \pi_{H,s})}_{<0},$$

where s_1 and s_2 are the thresholds derived from Proposition 4.1. It is obvious from this decomposition that, because from $s_2 + 1$, only negative terms are added, a sufficiently large S will yield $\sum_0^{S-1} \beta^s (\pi_{L,s} - \pi_{H,s}) + \beta^s (\pi_{L,S} - \pi_{H,S})$ if $(\pi_{L,S} - \pi_{H,S})$ sufficiently negative.

Let us now assume that the planning horizon is equal to $s_1 \leq S' \leq s_2$. From Proposition 4.1, increasing the planning horizon to $S' + 1$ will have a positive effect on φ_t^* if $(\pi_{L,S'} - \pi_{H,S'})$ sufficiently high, which is true for b_ℓ (or $\bar{\ell}$) high enough. It follows immediately that S_2 is a positive function of b_ℓ and $\bar{\ell}$, the term $\underbrace{\sum_{s_1+1}^{s_2} \beta^s (\pi_{L,s} - \pi_{H,s})}_{>0}$ increasing in b_ℓ and $\bar{\ell}$.

Chapter 5

Climate shuffle? Tracking the evolution of financial agents' equity exposures to greenhouse-gas intensive companies

Abstract

This article performs a descriptive analysis of the changes in investors' high-carbon equity exposure between 2015 (Paris Agreement) and 2020 (Covid crisis). With a rich dataset on the ownership structure of around 3,000 companies reporting emissions, the paper starts by depicting sectoral trends in the evolution of exposures to quantiles of emitters over the period by differentiating across countries, investor categories and portfolio sizes. It then focuses on the portfolio weights of around 30,000 investors and examines how exposures to the 100 most greenhouse gas (GHG) intensive companies have changed. Investor types, countries and portfolio sizes are associated with the probability of increasing exposure (measured as portfolio weights) to investor characteristics through a logit model. While, on average, investors are relatively split on their portfolio allocation, some agent categories exhibit positive biases in favour of the Top 100. This pattern characterises mostly emerging economies in Asia and Africa and Pension Funds in Global North financial systems. Finally, investors who withdrew from the Top 100 did so with a lag with respect to the Paris Agreement and were replaced by a population of investors seemingly insensitive to climate-related matters. This pattern implies the emergence of pocket of agents with higher exposure on average than in the past, suggesting an increase in exposure concentration. This polarisation of the financial system calls for careful regulatory monitoring of concerned entities and a closer scrutiny of investors' motivations to increase exposure to the Top 100.

Acknowledgements

The author is grateful to Emanuele Campiglio and Céline Guivarch for helpful suggestions and comments. All possible remaining errors are mine.

Introduction

The Paris Agreement acted as a wake-up call for the financial sector regarding the relevance of climate change and the necessity to decarbonise economic systems. In this respect, finance has been growingly seen as a critical enabler of the low-carbon transition, with numerous initiatives launched in a bid to channel funds towards sustainability projects and prominent figures, like Blackrock CEO Larry Fink, championing themselves as pioneers of green and climate finance (Fink 2022).

That finance should go low-carbon is not only crucial concerning the good course of the low-carbon transition. It also has regulatory implications. As former Bank of England Governor Mark Carney (2015) put, the low-carbon transition carries risks for the financial sector. Decarbonisation will entail sweeping changes across the board, affecting numerous industries and possibly turning previously sanctioned investments into “stranded assets” (Caldecott, Kruitwagen, et al. 2016). These real-economy developments may affect the financial sector through unexpected portfolio losses. The latter would be considerable in the event of a “disorderly transition”, with briskly introduced climate policy and rampant technological change. If strong enough, such shocks may prompt what Mark Carney dubbed a “Climate-Minsky” moment. In such a course of events, insufficiently prepared investors would suffer losses that may endanger the financial system’s stability.

This possibility requires gauging how the financial sector currently deals with transition risks. A dynamic literature has intended to check whether investors priced transition risks in the marketplace (Delis, Greiff, and Ongena 2019; Bolton and Kacperczyk 2021). Reviews on the matter (Daumas 2023, Chapter 1) conclude that transition risks are likely priced but insufficiently and only when attention to climate-related issues is high. Nonetheless, such a “carbon premium” indicates that some financial agents consider transition risks sufficiently material to ask for a risk premium (Delis, Greiff, and Ongena 2019) and that some agents are relinquishing assets linked to high-carbon activity. This observation invites us to go beyond market prices and investigate how agents change their exposures to high-carbon assets.

Quantifying and mapping financial exposures to high-carbon activities has been a critical focus for financial regulators to provide insights on how much financiers would lose in a disorderly transition. Despite substantial heterogeneity across jurisdictions, investor types and asset classes, this literature finds potentially significant exposures in absolute and as fractions of portfolios. Climate stress tests built based on these mappings typically exhibit sizeable potential losses, primarily if network effects across financial agents are accounted for (Battiston, Mandel, et al. 2017). Nevertheless, this literature suffers from two limits. First, dynamic pictures of how exposures have changed since the emergence of discussions on climate-related risks are scarce and often focused on a subset of investors (IMF 2021; Gourdel and Sydow 2022). As a result, the literature lacks insights into how the distribution across agents has evolved through time and, therefore, how it could change in the future. Such insights could be particularly relevant for the precise modelling of the financial sector, one of the main weaknesses of the study of climate-related risks (Daumas 2023, Chapter 1). Second, a systematic mapping of investors' exposures across key characteristics still needs to be included. At the same time, it is crucial to precisely explore what kinds of agents have been more prone to increase their exposure to high-carbon companies.

To fill these gaps, this paper will offer a quantitative assessment of the changes in equity exposures to high-carbon companies between the first quarter of 2015 and the last quarter of 2020. It will provide a macroscopic picture, showing general trends since 2015 and more microeconomic insights by looking at investment behaviour at the financial agent level.

To do so, I take advantage of a rich dataset on ownership structures and corporate emissions. This database allows me to reconstruct portfolio sizes and investment shares for various percentiles of absolute emission levels. I start by ranking listed companies by their declared emissions as provided by the Refinitiv Database. It amounts to around 3,000 companies worldwide. I then focus on the one hundred most GHG-intensive companies and compile their ownership, also drawn from Refinitiv. Since the dataset features the share of each equity holding in the investors' total

portfolio, I can reconstruct total portfolio values for around 30,000 immediate owners worldwide. From this, I can estimate each portfolio's share dedicated to a given quantile of emitter for each quarter between 2015 and 2020. After matching this data with available investor characteristics, I provide several descriptive statistics and deploy a logit model linking investor characteristics to the probability of strictly increasing exposures to the Top 100. These characteristics include a precise nomenclature of investor types, a geographical disaggregation and a division of investors by portfolio size.

I notably find that, at the macroscopic level, North American investors have increased their absolute exposures to the Top 100 GHG-intensive companies at the expense of Asian investors. Other regions of the world have conserved relatively stable absolute exposures, except for a marginal withdrawal from Europe. Regarding investor types, I show that funds have represented a growing share of the market capitalisation of the Top 100. I further show that the ownership of the Top 100 GHG-intensive companies is increasingly sticky.

At the microeconomic level, I document that investors' behaviour is very split, with, overall, a slightly less than 50% chance to increase exposures across investors. However, this tendency must be qualified since exposure-increasing investors have overcompensated the other investors' exposure reduction. I further highlight a positive bias of some emerging countries, notably China, South Asia and Sub-Saharan Africa and a near-systematic negative bias of European investors. I also show that Pension Funds have the most significant and systematic tendency to increase exposure to the Top 100 amongst financial agents, especially in Global North countries. I further document a negative relationship between portfolio size and the probability of increasing exposure. I also show that this divide is due mainly to investors that have reduced their exposures late over the period of interest. This rebalancing of the market is a relatively recent phenomenon. I finally document the emergence of a population of investors not reacting to transition risk discussions, which have significantly increased their exposures through time despite the withdrawal of a sizeable part of

the investor community. Overall, these results hint at the emergence of a pocket of higher exposures to transition risks over 2015-2020, mainly composed of small and risky institutions, more often than not located in emerging economies. This feature suggests an increase in the concentration of equity exposures to the Top 100.

The remainder of the article is as follows. Section 1 starts by reviewing the literature and motivating the study further. Section 2 details the paper's goal and its methods. Section 3 presents the data. Section 4 provides general trends at the macroeconomic level. Section 5 uses individual investor share series to depict investment behaviour distributions and run an econometric analysis. Section 6 concludes.

1 Literature review, motivation and goal of the paper

The literature on low-carbon transition risks became rapidly interested in the extent of financial agents' exposure to high-carbon companies. Building on increasing access to company-level data on emissions (Alogoskoufis et al. 2021) or relying on adequate industry classifications (Battiston, Monasterolo, van Ruijven, et al. 2022), studies usually quantify exposures as the value of assets backing high-carbon activities held by financial agents relative to the size of their portfolios. Financial agents are often grouped into broad categories (pension funds, banks) and studied within a particular jurisdiction. Finally, the literature has tackled a wide array of financial asset types, ranging from loans for banks (Delis, Greiff, and Ongena 2019) to bonds (Baer 2021) through equity and other tradeable assets (Ilhan, Krueger, et al. 2020). This strand of research still needs to bridge some gaps.

First, beyond the focus on particular jurisdictions, exposures across regions of the globe are not compared and contrasted systematically (see Daumas (2023), Chapter 1 for a step in that direction). Such an assessment would thus be crucial in studying transition risks. Bos and Gupta (2019) suggested that, given their focus on growth and a lesser emphasis on sustainability, investors in developing countries could become

the ultimate owners of financial stranded assets, before they lose economic value. As a result, they may come at the frontline of possible transition risk shocks. These shocks may be all the more severe given the higher sensitivity of peripheral financial systems to financial disturbances compared to the Global North, which benefits from powerful central banks, sustained foreign financial inflows or better regulations. Furthermore, financial disturbances in the Global South could propagate to other financial systems, as happened during the Mexican and Russian crises of the 1980s. There is, therefore, an interest in precisely mapping the geography of financial exposures to transition risks.

Moreover, even if the Global North did not relinquish high-carbon assets to the Global South, some financial agents, even within well-protected financial systems, can harm financial stability like hedge funds or banks. While some studies within the exposure-mapping literature compare different agent types (Weyzig et al. 2014), most of them focus on one kind of financial institution or only contrast very few groups [Chapter 1; Daumas (2023)]. A sufficiently disaggregated picture is nonetheless crucial given the minute but non-trivial differences that can exist across different financial agent types, which may have very different implications *vis-à-vis* the resilience of the broader financial system. This paper aims at bridging that gap by offering a more disaggregated depiction of financial agents across business models, world regions and size.

Furthermore, these assessments only measure exposures at a certain point in time. They do not provide a dynamic picture of how exposures have evolved since climate change became a topic of interest for financiers. Such a picture would be informative in several respects.

Policy-wise, it would be helpful to gauge the efficacy of current initiatives to favour climate risk disclosures and sustainable investments. Such initiatives were launched based on the notion that climate-related risks cannot be dealt with efficiently if agents cannot reliably assess the risk content of assets. Closing this information gap would thus help reorient investments and provide incentives to support sustainable

investments by divesting (TCFD 2017) or engaging directly with the firm's strategy to make it low-carbon shareholder activism (Azar et al. 2021). Checking which kinds of investors have "walked the talk" so far would help discriminate which entities to supervise or incentivise away from high-carbon activity in priority.

From a financial-stability standpoint, it is crucial to map how assets have changed hands. As highlighted by the financial network literature, how assets are distributed across the population of investors matters (Battiston, Delli Gatti, et al. 2012). In other words, if an agent efficiently reduces her risk exposure and becomes more resilient to transition-related shocks, this agent has likely the risk to another agent, increasing the latter's exposure. If transition risks were adequately priced in, the risk premium demanded by the buyer would make for possible shocks. However, since current premiums are likely too low (Delis, Greiff, and Ongena 2019) and because many agents, especially outside Europe (Bos and Gupta 2019), still need to account for climate-related risks, risk shifting within the financial sector may decrease the resilience of the whole system. It would especially be the case if the riskiest assets are eventually possessed by less regulated, less solid or less transition-aware institutions, for instance, in the Global South (Bos and Gupta 2019).

Finally, from a heuristic perspective, there still needs to be insights into how agents concretely change their exposures through time. As a result, most current climate stress-test exercises rely on "static balance sheet" approaches, assuming that financial agents do not shift their exposures over time. If this assumption holds over short periods, longer-run exercises on transition risks (NGFS 2021b; ECB 2021) still need robust approaches to model dynamic balance sheets beyond *ad hoc* modelling. Some methods have been proposed, such as issuing questionnaires to supervised institutions (Clerc, Bontemps-Chanel, et al. 2021). However, because it relies on stated behaviour, the use of questionnaires suffers from agency and information asymmetry issues (Kalinowski and Chenet 2020). Observing dynamic balance sheet behaviours would complement existing approaches and provide elements to model changes in exposures.

Some exceptions exist in the literature that partially fill these gaps. Gourdel and Sydow (2022) offers a dynamic picture of the carbon intensity of European investment fund portfolios (measured as a ton of CO₂ per dollar invested). It suggests that funds have decreased their exposures between 2017 and 2020 through portfolio reallocation. The IMF (2021) shows a similar picture for developed countries in general but suggests that the magnitude is too low given the needs of the transition. They also show that developing countries's funds lag slightly behind but tend to converge towards their core counterparts. Beyene, Delis, and Ongena (2022) focuses on syndicated loans in Europe and shows the global stability of syndicated loans. Finally, Benz et al. (2021) determines what kind of investor type prefers carbon-intensive firms and offers a dynamic picture of changes in exposures between 2000 and 2015.

This paper intends to build on and expand the endeavours of these papers in several ways. Compared to Gourdel and Sydow (2022) and Beyene, Delis, and Ongena (2022), it expands the focus outside of Europe and, also relative to IMF (2021), it includes a wider variety of financial agents. The paper comes very close to Benz et al. (2021) in methodological terms and breadth but covers a period closer to the current time by covering the 2015-2020 period. However, this paper only focuses on one kind of financial asset. Due to data limitation, only data on equity holdings, through the study of ownership data (see below), could be gathered with sufficient coverage. Although it implies a lesser precision than studies encompassing other types of assets, like loans and corporate bonds (Gourdel and Sydow 2022; Beyene, Delis, and Ongena 2022), this paper intends to compensate it by more precise geographical and institutional coverage.

This study further diverges to some extent from existing studies in several respects.

2 Reach and method of the paper

Similarly to Benz et al. (2021), this paper aims to characterise how and what kind of financial agents worldwide have shifted their exposure to high-carbon companies

between 2015 and 2020. This period was chosen because it represented a shift in how financial agents generally dealt with climate-related risks. From the Paris Agreement and Mark Carney's epoch-making speech in late 2015, many initiatives have emerged to bring finance to the low-carbon transition and manage subsequent risks (see, amongst others, J. H. Nguyen, Truong, and B. Zhang 2020; Bolton and Kacperczyk 2021, for empirical evidence). This paper thus also provides a sense of the impact of these measures in the medium to long run.¹

2.1 Defining high-carbon companies

This endeavour first requires disentangling which companies can be considered “high-carbon”. Studies above rely on industry classifications or the carbon intensity of financial investments, measured as CO_2 emission per dollar held in the portfolio. This paper adopts a different approach by relying on a ranking of non-financial companies based on their greenhouse gas (GHG) intensity, defined as the sales-to-emission ratio, and by focusing on relevant quantiles of the GHG intensity distribution. This complementary metric offers a more precise picture than industry classification by overcoming intra-sectoral variance in carbon performances. It also complements carbon intensity measures by explicitly segmenting the portfolio of investors. More precisely, aggregate carbon intensity at the scale of their investor's portfolio does not allow to disentangle whether financial agents merely re-balance their portfolios, for instance, keeping their commitment to the most polluting companies constant and increasing holdings of less GHG-intensive ones or outright disengage from the transition-riskiest companies. Focusing on a particular quantile of the GHG intensity distribution offers a complementary view by effectively segmenting investors' portfolios.

It also allows, with a single indicator, to study the evolution of GHG-intensive holding from the two faces of equity investment. As Benz et al. (2021) put forward, equity holders are both partial owners of non-financial companies and agents exposed

¹However, the results of these papers are not meant to provide actual causality estimates of these policies or events' impact. Rather, they should be taken as broad indications of efficiency at the level of the financial sector. For genuine impact studies on low-carbon financial policies, see notably Mésonnier and B. Nguyen (2021).

through their portfolios. Hence, it is worth studying the evolution of exposures from these two angles.

2.2 Significance in market capitalisation

On the one hand, this paper will look at the significance of given financial agents within the market capitalisation of the GHG-intensity quantile under study. Like Benz et al. (2021), let us define two indicators:

$$\theta_{i,q,t}^S = \frac{S_{i,q,t}}{S_{q,t}},$$

where i is a given investor indexed q is the quantile under study, and t is the period. $S_{i,q,t}$ is the (real) number of shares of a given quantile held by a given investor i at time t , and $S_{q,t}$ is the total amount of shares outstanding. $\theta_{i,q,t}^S$ is, therefore, the weight of a given investor in the total amount of shares outstanding for a given quantile. Now suppose that this investor is endowed with a certain number of characteristics, such that $i \in J$, with J the set of investors sharing the same vector of characteristics \mathbb{J} (*e.g.* type, regional origin, size). Note that in this example, J includes investors with an arbitrary set of characteristics, either a single one (*e.g.* same nationality) or several (*e.g.* same nationality and size). We can define:

$$\Theta_{J,q,t}^{Shares} = \sum_{i \in J} \theta_{i,q,t}^{Shares}$$

as the representativeness of a given investor characterisation in total shares outstanding.

Similarly, we can write:

$$\theta_{i,q,t}^V = \frac{V_{i,q,t}}{V_{q,t}},$$

where $V_{i,q,t}$ the value of holdings of investor i in company quantile q at time t . $V_{q,t}$ is the total market capitalisation of quantile q at time t . Both are the equivalents of

the $S_{i,q,t}$ and $S_{q,t}$ variables above, but weighted by adequated asset prices.

We can eventually define $\Theta_{I,q,t}^{Values}$ as:

$$\Theta_{J,q,t}^{Values} = \sum_{i \in J} \theta_{i,q,t}^V$$

the equivalent of $\Theta_{I,q,t}^{Shares}$ but considering the actual financial value of investments of investors with characteristics \mathbb{J} .

The paper will expand this approach by considering this picture from the non-financial companies' standpoint. More precisely, I can pinpoint those companies that have remained, left or entered the capital of each of the companies in the relevant quantiles. I can also track companies that have remained at the capital of these firms. This feature allows me to characterise the stability of the ownership structure of the most GHG-intensive companies worldwide. The paper will study the evolution of these indicators between 2015 and 2020 at a quarterly frequency.

2.3 Individual portfolio weights

In a second step, the paper will tackle the issue of exposure from the standpoint of investors, *i.e.*, by looking at the weight of equity ownership in financial agents' balance sheets. To do so, I build a dataset of portfolio weights $\omega_{i,q,t}$, defined as:

$$\omega_{i,q,t} = \frac{V_{i,q,t}}{A_{i,t}},$$

with $V_{i,q,t}$ the value of holdings as defined above, and $A_{i,t}$ the portfolio's total value. Note that unlike Benz et al. (2021), the entirety of the portfolio is considered, not only the equity portfolio's value. It provides a more relevant picture of the equity exposures of financial agents, which other assets can mitigate. These portfolio weights built, I consider a binary variable defined as follows:

$$l_{i,t_0,t_1} = \begin{cases} 0 & \text{if } \omega_{i,q,t_1} - \omega_{i,q,t_0} \leq 0 \\ 1 & \text{otherwise} \end{cases} .$$

This dummy variable gives whether a given investor has increased its exposure to the quantile of GHG-intensive companies q between time t_0 and time t_1 . Then, the paper will develop a logit binary choice model of the form:

$$P(l_{i,t_0,t_1} > 0|X) = \exp(\alpha + \beta X_i + \varepsilon_i), \quad (1)$$

which will link the propensity to increase exposure to GHG-intensive companies to a vector of investor characteristics X_i .

Using a binary variable over a continuous variable like $\omega_{i,q,t_1} - \omega_{i,q,t_0}$ is motivated by several elements. First, such a variable allows us to consider a wide array of financial agents with very diverse portfolio compositions and avoid that, for instance, agents with significant ownership stakes occult the behaviour of others by driving the variance of the sample. Second, it reduces the investment in GHG-intensive companies to a pure choice variable, which retains a clear interpretation. Finally, using a binary variable within a logit model allows us to systematically compare the behaviour of investor categories and test their significance.

With this specification, this study also departs from similar endeavours in the literature linking changes in exposures and portfolio choices to risk factors (Kacperczyk and Peydro 2021) or firms' characteristics (Benz et al. 2021). These papers measure the average responsiveness of financial agents to crucial financial factors and environmental indicators displayed by firms and determine whether investors or sub-categories of investors respond to the environmental performances of companies. The present study is instead interested in characterising what kind of investors fail to consider environmental performance and does increase exposure. Therefore, our approach departs from the goal of determining an average reactivity to indicators to dig into some determinants of reactions on the side of the financial investors.

2.4 Characterising investors

The final stone of this analysis is the choice of characteristics for investors. Due to data limitations, but also to limit the dimensionality of this descriptive analysis, I will focus on three categorical variables: regional origin, investor type and size of the portfolio.

As sketched above, the literature has already emphasised that investors from distinct world regions have either exhibited or may show different behaviours with regard to financial transition risks (IMF 2021). These variations may be attributable to differences in regulation (Mésonnier and B. Nguyen 2021) or in investor culture and sensitivity to climate-related issues (Bos and Gupta 2019). From this, highlighting changes in the distribution of exposures to climate-related risk is important in several respects. From a distributional standpoint, it can characterise the geography of future losses and, therefore, highlight possible obstacles to decarbonisation in some countries (Semieniuk, Holden, et al. 2022; Colgan, Green, and Hale 2021). Second, what regions of the world are most exposed to transition risks pose different challenges, either in terms of overall vulnerability of the financial system, or in tracking corresponding causality channels and regulation, and even including coordination across national regulatory bodies. Losses in emerging countries, for instance, may have deeper impacts due to lesser policy space due to external constraints and less powerful regulatory bodies than in Northern financial systems.

Furthermore, differentiating across investor types is essential because various agents have distinct investment motivations and bear different types of financial risks. For instance, financial agents are not all equally regulated and limited in their risky behaviours. Hedge funds, for instance, are much less regulated than other kinds of funds, which are themselves under less oversight than banks (M. Lambert 2012). Furthermore, some agent types are intrinsically more connected to others and are, therefore, more relevant regarding financial risks. Finally, different financial agents carry different types of risk. Banks, for instance, are much more prone to liquidity risk than investment funds, which are by design more exposed to equity and fixed-income

risks (European Central Bank 2018).

Last, the size of financial agents matters. Larger institutions may be more able to stomach some shocks and likely benefit from more cautious oversight on the part of regulatory bodies (Araujo, Coffinet, and El Fathi 2023). However, due to their position at the centre of financial networks, a large shock on these companies may flow to the entire system. Smaller institutions, on the other hand, carry less systemic risk individually, although, like any institution, they could embark on herd behaviours leading to adverse aggregate outcomes (Hirshleifer and Hong Teoh 2003). They may also be less tractable and less easy to regulate than larger institutions.

This triple characterisation will be used to offer a glimpse of how the equity transition risk profile of financial markets and the attitude of investors towards these risks have evolved between the Paris Agreement and the beginning of the Covid crisis. More precisely, I will use it to answer three questions:

This empirical analysis will be performed through the use of a rich dataset of emission and ownership data described in the next section.

3 Data

Data is driven from the Refinitiv Eikon database. Refinitiv provides comprehensive indicators on firm ownership and emissions, which allows to match portfolio weights with relevant GHG-intensity quantiles.

3.1 Emission data and sample selection

Refinitiv references Scope 1 and Scope 2 emissions at the firm level for 3,189 listed companies worldwide at a yearly frequency. Unfortunately, Scope 3 emissions are scarcely available among listed firms. This work thus focuses on Scope 1 and Scope 2 emissions, expressed as CO_2 equivalents (CO_2e) for all greenhouse gases (GHG).

Emission data are referenced based on declared emissions drawn from shareholder reports. Companies abiding by some ESG standards (TCFD 2017) provide their

estimates of their carbon emissions. However, working with declared emissions has several inconveniences. First, mismeasurement or misreporting by Refinitiv is possible and challenging to check *per se*. Second, reported emissions are subjected to information asymmetries issues. Firms using internal carbon accounting methods may be incentivised to reduce declared emissions as much as possible to display better ESG performances (Fan, Tang, and L. Pan 2021). As a result, many studies rely on third-party estimates, like Trucost, Urgentem or 421. However, while third-party estimates bypass some defects of declared emissions, they have deficiencies. Notably, Bingler, Colesanti Senni, and Monnin (2020) show that third-party estimates may also be unreliable, given their lack of consistency across providers' methods. Second, Aswani, Raghunandan, and Rajgopal (2023) show a strong correlation between third-party estimates and company fundamentals, like turnout. They conclude that the models used to generate these estimates are overly sensitive to cyclical variables rather than medium-to-long-run technological features of companies' production processes. Finally, I am not interested in a precise estimate of emissions. Rather, I base this study on a ranking of emitters, which only requires a sufficiently precise ordinal emission measurement. In this respect, Kalesnik, Wilkens, and Zink (2020) show that reported emissions are more appropriate than estimated emissions, especially in identifying tail emitters. As a result, reported emissions seem suited for this paper, although results should be interpreted with some caveats, especially the importance of possible information asymmetries.

A second difficulty arises from many firms declaring their carbon emissions later than the start of our period or declaring emissions at a less-than-yearly frequency. Refinitiv provides some estimates based on its own models to bridge this gap, but they can sometimes significantly drift from declared emissions when available. Furthermore, for some companies, estimates are only available for some years. Hence, I only have complete declared emission series for the entire sample for 2018-2020. Therefore, I refrain from building on emission series. I consider only emissions for 2020 and assume that high-carbon companies in 2020 were as carbon-intensive in 2015. This

choice also maximises the number of companies in the sample, given that some firms, especially in developing countries, only started to report their emissions after the Paris Agreement. It thus allows overlooking some high-carbon companies that may not appear in the database at the sample's start. Finally, to mitigate size effects, whereby large companies structurally emit more than smaller ones, I normalise emissions by sales, drawn from income statements provided by Refinitiv, to obtain GHG intensity measures. I then rank firms according to their emission intensity in 2020.

A first concern may arise regarding the Covid crisis, to the extent that many companies saw their emissions decrease significantly, with some sectors remaining afloat. Considering the ranking for the year 2019, it is only marginally different from that of 2020. I thus stick to the 2020 ranking to remain consistent with the period under study. A second related issue pertains to the start of our period in that the 2020 ranking may differ from investment decisions taken before this date. Since many companies did not declare emissions before 2017-2018, investors may not have had the firm-specific emission information necessary to orient their investments. Keeping this caveat in mind, one could also argue that estimated emission series have existed for a long, meaning that investors could already rely on some emission metrics to orient their investments. Second, considering the 2020 ranking as a good proxy for the 2015 ranking would require that this ranking had stayed the same over time, which roughly verifies over the periods when data is available. Thus, the 2020 ranking is a good proxy for the whole period. Furthermore, this practice is consistent with part of the empirical literature considering portfolio ranking, which typically considers a ranking of emissions at a specific date in the building of their representative portfolios (Daumas (2023), Chapter 1).

Since this paper is interested in the change in exposure to the most carbon-intensive companies, it will focus on the Top 100 GHG-intensive companies as of 2020 and provide some elements of comparison with less carbon-intensive companies in the 101-500 ranking positions. This choice is justified by the distribution of GHG intensities across companies. Figure 1 shows the log distribution (Panel a) and cumulative

distribution (Panel b) of emission intensities for the companies we use in the sample. As can be seen, the distribution is heavily skewed, with a handful of companies characterised by a very high GHG intensity, then a log-linear part, until a tail of companies emitting very little per sale. In cumulative terms, Panel (b) shows that the 500 most GHG-intensive terms represent more than 90% of the cumulative distribution, while the Top 100 represents around 70%.

Therefore, focusing on the Top 100 companies, with some extensions to the Top 500, is justified, given their representativeness in the distribution of GHG intensities. Further, this restriction allows to leave aside possibly tiny quoted companies, whose ownership structure reduces to a handful of investors and with little significance at the scale of the financial system.

Figure 2 provides information on companies' geographical and sectoral distribution in the Top 100. They are mostly electricity production firms located all around the world, followed by cement producers and metal ore miners located all around the world. This is hardly surprising, given the many direct and energy-related emissions involved in these activities. Some residual sectors are included, like some banks, which may also serve as holdings for carbon-intensive activities, one software developer and some agricultural branches. Note, finally, the absence of oil extractors, whose emissions are mostly Scope 3 and are therefore not included in the analysis.

3.2 Ownership data

Refinitiv Eikon is one of the most exhaustive databases on ownership structures available. For most listed companies, it tracks how their equity holdings are dispatched across investors yearly, quarterly or monthly for most periods since the early 2000s. It also gathers information on investors, like their category, business model, investment strategy and country of residence. Using ownership data has several advantages, such as identifying investors in specific companies, for instance, high emitters, gauging when and how equity investments in these companies have evolved for each particular investor and relating these evolutions to investor characteristics. Therefore, I

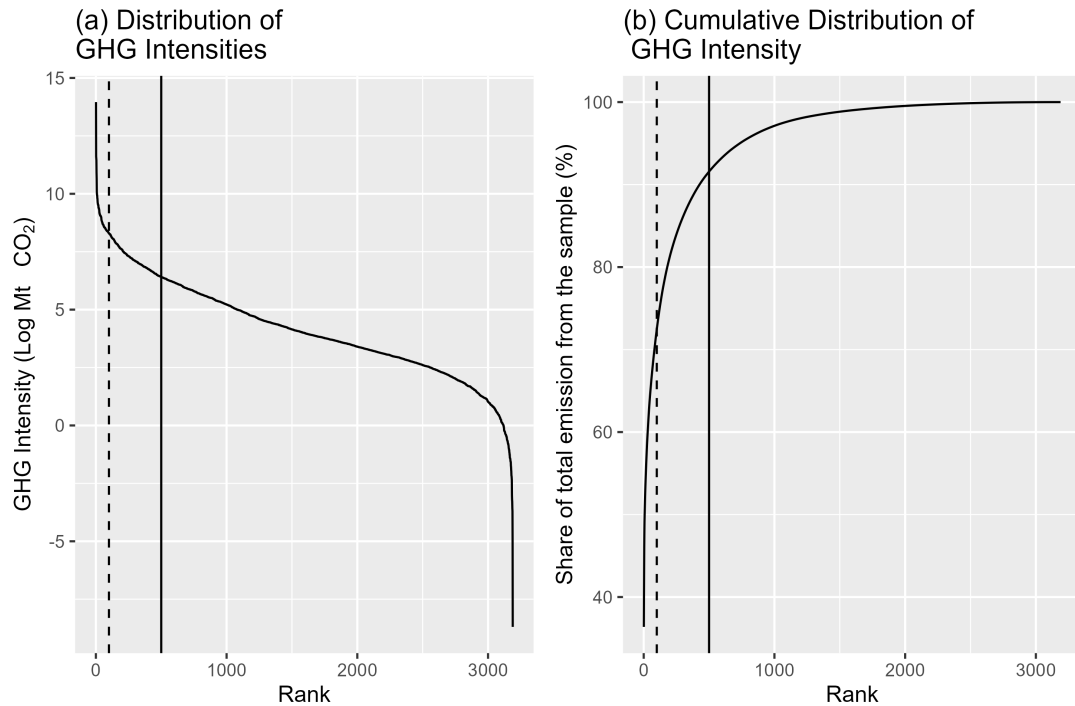


Figure 1: Distribution and Cumulative Distribution of greenhouse gas intensities across our sample.

consider each company’s ownership structure in the ranking described above in each quarter between the first quarter of 2015 and the last quarter of 2020. The quarterly frequency is chosen because ownership is usually updated at this periodicity through “quarterly reports”.

However, despite its extensive coverage, the Refinitiv database is not 100% exhaustive. Hence, the market capitalisation of some companies may not to be fully mapped. It is due to reporting obligation discrepancies across jurisdictions and difficulties in tracking very small stockholders and inside investors. For the Top 100, the dataset reports 80%-90% (Figure 3) of the market capitalisation of most companies, with an increasing trend. To allow for better readability, I neglect this non-mapped market capitalisation, the sample being sufficiently representative.

Refinitiv also differentiates between “Shareholders” and “Fund Shareholders”. However, for the problem at hand, they can be considered on an equal footing. Plus, their

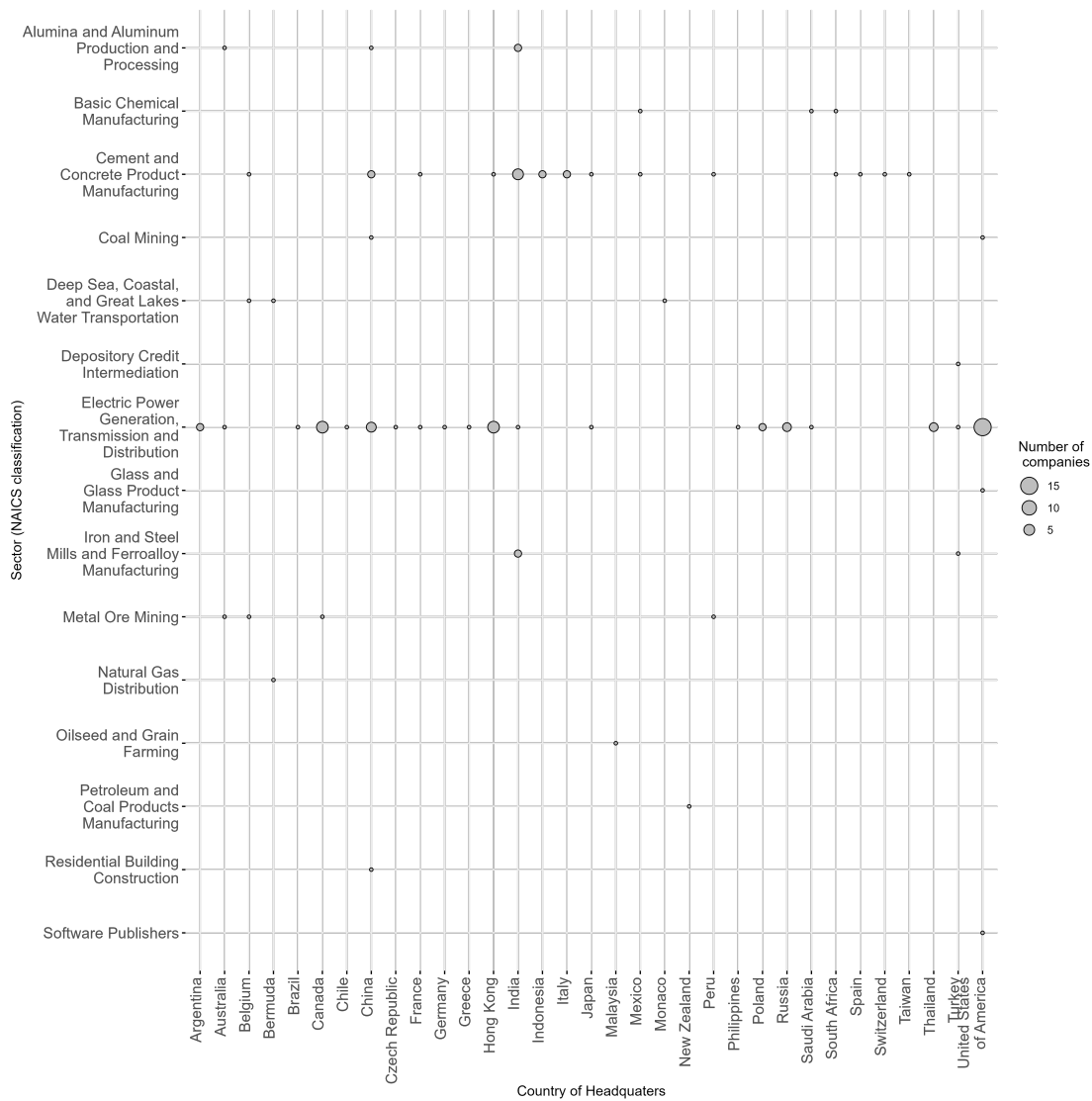


Figure 2: Sectoral and geographical distribution of Top-100 companies. Bubble size corresponds to the number of companies.

characteristics are referenced under similar items and holdings can be interpreted similarly. As a result, for each company in the database, Fund and Shareholder Investors are merged. Furthermore, as ownership structure changes, some investors may enter the company's capital, while others may leave. Refinitiv's ownership reports for a given date display non-available values in this case. However, such entries may also correspond to genuine missing values. For simplicity, all non-available data points are

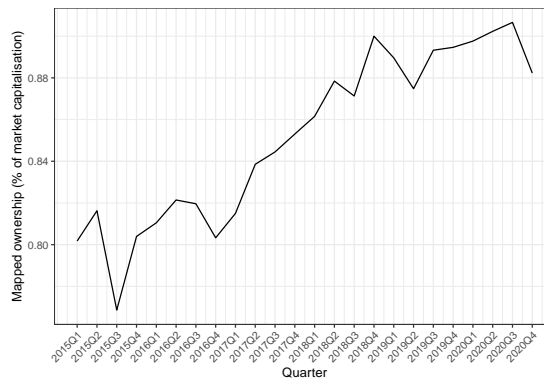


Figure 3: Mapping of Top 100 market capitalisation, as a percentage of total market capitalisation.

taken as zeros, the implicit assumption being genuine missing values that correspond to negligible holdings.

Finally, the dataset only allowed us to track immediate investors consistently. Due to cross-ownerships, many financial agents are ultimately owned by others. For instance, many of the funds considered in this study can be owned by other funds or larger asset managers, like Blackrock. As a result, the exposures measured in this paper may ultimately concern agents beyond those immediately mapped, calling for caution in interpreting results. On the other hand, even though they belong to larger entities, these agents are independent from their ultimate owners and make their own investment decisions. Since this paper is interested in portfolio reallocation, considering immediate owners seems more suited from a conceptual perspective.

3.3 Building the portfolio weight dataset

Building on the ownership structure data, I build a dataset of portfolio shares invested in the 100 highest polluters worldwide for individual portfolios.

For this purpose, the Refinitiv database reports, for equity holding above a certain threshold, how much of the investors' portfolio the holding represents. This feature allow to compute portfolio shares corresponding to emitter categories for a large number of investors. However, Refinitiv only displays these investment shares with a

precision of two digits, which, for large amounts of money, may result in non-trivial discrepancies with regard to true values. If fractions are very small, the reported number may even be zero with a non-zero holding. Furthermore, portfolio fractions for the same investor may be reported for one company and not for another while the value of the holding is reported. Summing reported portfolio shares would also mistakenly overlook non-zero holdings.

These issues forbid strictly sum portfolio fractions across companies. To bypass this, I take advantage of all the companies over the whole emission ranking for which I have ownership data. I first consider all unique investors having non-zero equity holdings in the top 100 emitters for at least one quarter over the 2015-2020 period. A company name and a unique identifier² typically identify investors. I then track these unique investors within the ownership structure of all companies in the ranking and collect corresponding holdings and portfolio fractions. I compute portfolio size approximations by dividing the value of the holding by the reported fraction across the whole ranking of emitting companies. I then build an estimator of the actual portfolio size for each investor each year by taking the average across portfolio size approximations by correcting for outliers among approximations. In the end, around 350 portfolio sizes could not be computed due to missing values on portfolio sizes across the whole sample, representing around 10% of the mapped market capitalisation. I finally compute the portfolio share corresponding to the Top 100 emitters for a given investor by dividing the sum of holdings across companies in the group by the estimated portfolio size. Divisions above one by a 5% margin are given the value 1, while all others are given a missing value.

From this, I obtain a raw dataset of around 32,000 investors, with some series incomplete. I fill data gaps through linear interpolation when the holding value is non-zero and when the value is at the beginning or the end of the sample.³ After this, only a residual amount of investors (between 100 and 200) exhibit missing values for our

²Some investors, however, only display a company name. For these, unique identifiers were provided. Furthermore, some investors exhibited the same identifiers but different names, due to changes ultimate owners. Investors with the same identifiers were consolidated and the most recent characteristics applied.

³These interpolation never concerned more than four quarters over the whole period and rarely more than two consecutive quarters.

periods of interest, which adds up to around 500 investors.

Finally, I check through Refinitiv whether investors are still in activity. Unfortunately, no historical data is available on this, meaning it is impossible to pinpoint which companies were still on the market at a given date. Therefore, I take out all investors declared inactive as of today. Albeit conservative, this approach allows me to avoid mixing companies that decreased their exposure willfully and those that went off-market efficiently. In the end, the sample is composed of around 27,000 investors.

3.4 Investor characteristics

The final stone of the sample includes variables used to characterise investors. The paper will first use two categorical variables: regional origin and investor type.⁴

The dataset features close to 80 countries. For readability and to avoid countries with very few individuals, I aggregate countries into ten world regions as described in Appendix, Figure A.3.1. Noteworthy, I distinguish the UK and affiliated countries (mostly overseas British territories with autonomous governments, like Guernsey, British Virgin Islands and others) to make for the particular position of London and its affiliates within the worldwide financial system, in particular in channelling funds for high emitters such as fossil majors (Manych, Steckel, and Jakob 2021). Unfortunately, the country of origin is unknown for a residual number of investors (around 0.2% of the sample), which are dropped from the sample.

Luckily, the Investor Type variable spans the entirety of the sample from Refinitiv across around twenty categories, including a minority of non-financial agents holding stocks for reasons other than financial returns. They are summarised and explained in Table A.2.1 in Appendix A.

In the course of the analysis, focused on financial instability potentials, particular attention will be given to a subset of agents which have been pinpointed by regulatory institutions for their higher financial instability potentials:

⁴Unfortunately, useful information on financial variables, prudential ratios or investment strategies are either not publicly available, or only usable for a very reduced share of the sample. On top of their heuristic value, regional origin and investor type span almost the entirety of sample, allowing for greater statistical power.

Table 1: Values of Categorical Variables

Region	Investor Type	Portfolio Quartile
China, Hong Kong and Macau	Bank and Trust	1
Central and Eastern Europe	Corporation	2
East Asia and the Pacific	Exchange-Traded Fund	3
Europe	Hedge Fund	4
Latin America and Caribbe	Mutual Fund	
Middle East and North Africa	Individual Investor	
North America	Insurance Company	
South Asia	Investment Advisor	
Sub-Saharan Africa	Other Institutional	
UK and affiliated	Pension Fund	

- Banks (and Trusts), due to their pivotal role in credit provision and their high degree of connectedness with other financial agents, are usually intensely supervised and regulated, given their relevance in fueling financial instability (Schularick and A. M. Taylor 2012).
- Because of their light regulation, Hedge Funds typically take on more significant risks and are more prone to a variety of risks, notably liquidity issues (M. Lambert 2012). They have also been pinpointed as key vehicles of systemic risk, as they benefit from prime brokerage relationships with banks that allow them to take on high leverage levels (Kambhu, Schuermann, and Stiroh 2007).
- Exchange-Traded Funds (ETFs) are, in principle, a safe investment. These agents usually track an underlying index, trying to reproduce its performance as best as possible. Most of them are passive investors. However, because their units are traded as any other security, they have been seen as potential amplifiers of financial disturbances in other markets, mostly in case of liquidity shortage and counterpart default in case the ETF engages in security lending for liquidity purposes. Finally, since ETFs are both tradeable securities and investment funds, current regulatory frameworks may not be sufficient to cover the risks linked to this specific situation (European Central Bank 2018).

To reduce the number of agent types and to avoid populations with very few observations, I merged some categories as follows, reducing them to thirteen:

- Refinitiv's "Investment Advisor/Hedge Fund" category is somewhat blurred and difficult to

interpret. I assume it gathers hedge funds compelled by regulation to register as investment advisors in some jurisdictions and merge it with the “Hedge Fund” category.

- Given their proximity in business model and functioning and their small share in the sample, I merge Closed-End Funds, Venture Capital, Investment Trust and Private Equity into an “Other Institutionals” category – partly following Benz et al. (2021).
- Because they relate more directly to company management than asset returns or control, I merge Corporations, Holding Companies and Research Firms under the “Corporation” label.
- Individual investors and Foundations are merged under the “Individual Investor” label. Because of their philanthropic goals, Endowment funds are added alongside foundations.
- Finally, Sovereign Wealth Funds and Government Agencies are grouped as Public Entities.

Finally, building on my portfolio size estimates, I characterise investors by their sizes. Taking the mean value of their portfolio between 2015 and 2020, I divide them into four quartiles. This division allows me to temper the possible inaccuracies in estimating portfolio sizes, while, at the same time, being more readable than a continuous variable. Table 1 reports my three categorical variables and their values. I provide some descriptive statistics for each in the following.

3.5 Descriptive statistics

Figure 4 describes the data structure along the Region and Type variables by showing all possible combinations. Panel a reports the number of observations by sub-category relative to the total. Panel b shows the weight of each combination in the sample in terms of value held.

Panel (a) shows that the overwhelming majority of stockholders are mutual funds, which account for more than 50% of all investors. It is not surprising given the rapid development of asset managers over the 2010s (Bouveret 2017). Note, however, that these funds typically do not have essential holdings individually, the Top 100 polluters representing, on average, rarely more than 5-10% of these agents’ portfolios, as per

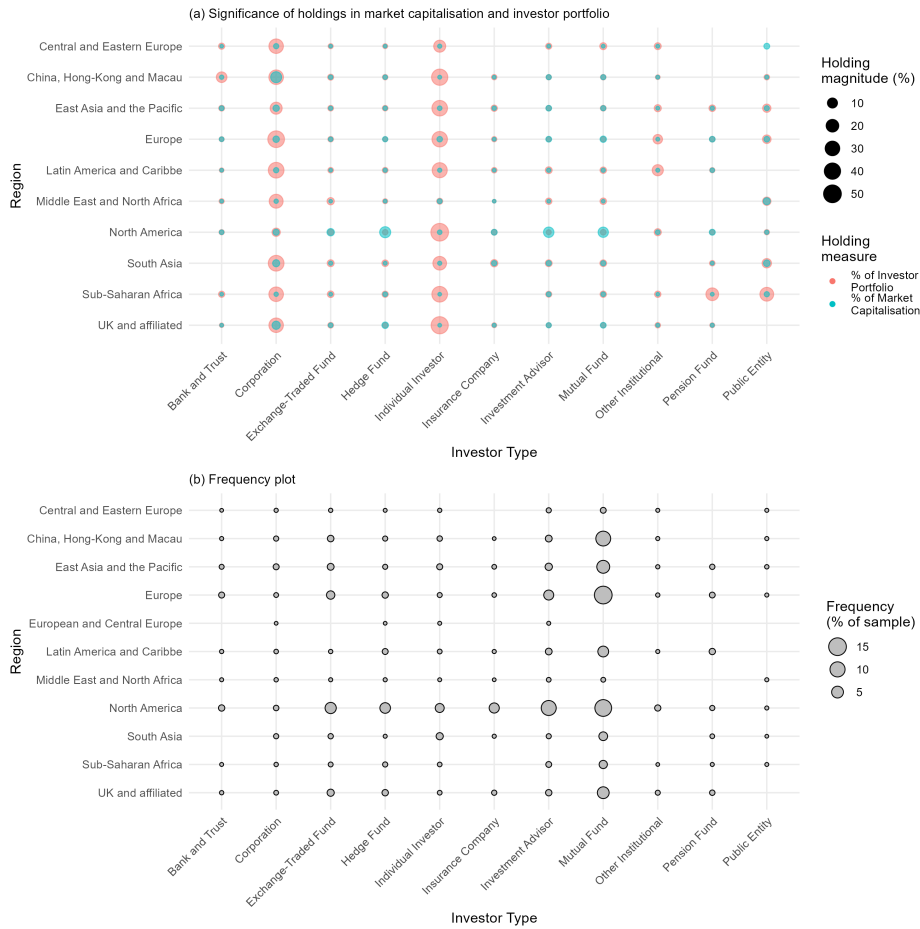


Figure 4: Structure of the sample along Regions and Investor Types. Panel (a) offers a view of the significance of holdings in agents’ portfolio (red bubbles) and in the Top 100 market capitalisation on average over 2015-2020 (blue bubbles). Size indicates magnitude. Panel (b) shows the frequency of agents in each category in percentage of total, signalled by the size of the bubbles.

Panel (b). Mutual Funds are followed by Investor Advisors and Exchange-Traded Funds. Other agent types represent less than 10% of the sample, with some residual categories. Panel (a) also shows an unsurprising dominance of core financial systems: North America, Europe and UK-cum-affiliated. China and South-East Asia come second through the presence of key financial centres (Hong Kong, Macao, Singapore). Other regions exhibit more residual shares due to relatively less important financial sectors and sizable State ownership in energy utilities.

Panel (b) offers further insights on how holdings in the Top 100 are distributed within this population. The market capitalisation of the Top 100 emitters is dominated by Mutual funds, Investment Advisors, Hedge Funds and Corporations, with a clear lead in core financial sectors. On the other hand, these agents hold more balanced portfolios than less dominant categories within the market capitalisation. For most leading categories in the market capitalisation, the Top 100 always represents less than 5-10% of their portfolio on average over the period. On the other hand, Corporations and Public Entities have much more skin in the Top 100 emitters as measured by their portfolio weights. It is hardly surprising, given that these agents hold naturally less diversified portfolios (Benz et al. 2021). Public Entities tend to control utilities, usually polluting, while corporations usually have stakes in their subsidiaries. Sovereign wealth funds and Banks and Trust also hold Top 100 equities in more significant proportion than their representativeness in market capitalisation. Finally, the Top 100 emitters represent a higher share of portfolios on average for most agents outside of core financial sectors, notably due to a more significant population of Individual Investors and insiders. This is notably the case for South Asian and Central European agents, whose economic structures are likely more biased towards polluting industries. The Middle East also stands out due to the opening of the capital of former publicly held extractors.

Figure 5 follows by showing the distribution of our individuals across portfolio quartiles by showing the proportion of each category in the total. Again, we see the clear dominance of the core-country fund industry.

Funds generally exhibit a relatively homogeneous portfolio distribution, with a slightly higher weight of small portfolios. Individual investors, unsurprisingly, show smaller portfolios. Finally, all other categories show a skewed distribution of portfolio sizes, with a more considerable prevalence of large portfolios.

This skewness of categorical variables calls for caution in interpreting results since some populations include a meagre number of agents or do not exist in the data. If, in principle, this does not invalidate the use of the econometric model developed in

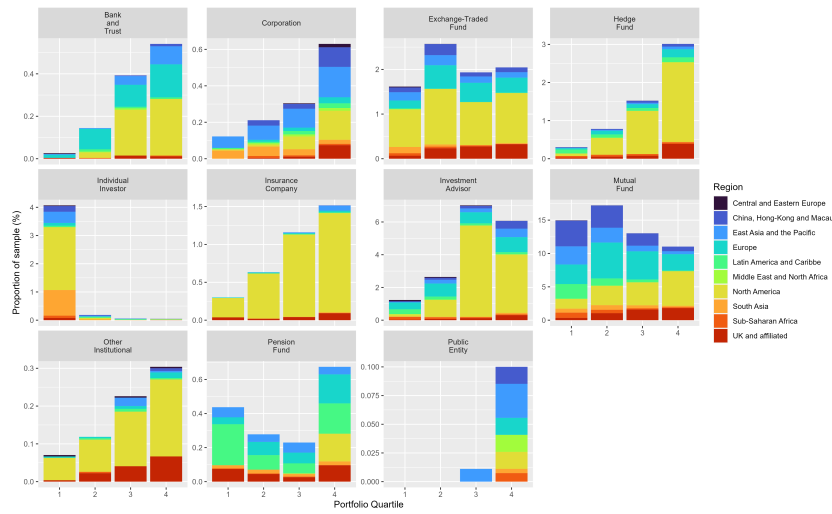


Figure 5: Distribution of portfolio sizes across Regions and Subtypes. Each panel isolate an investor type, colours designate regions. Note the different scales across graphs.

Section 2, the low number of observations may limit the statistical power of estimates.

A solution could be to drop relevant categories. However, this would prevent detecting meaningful effects for some populations. Therefore, I stick to the entire dataset and postpone dropping small populations to robustness checks.

Finally, Table 2 displays some dispersion indicators for $\Delta_{i,Top100,t_1,t_0} = \omega_{i,Top100,t_1} - \omega_{i,Top100,t_0}$, the change in equity exposure and $\iota_{i,Top100,t_0,t_1}$ the indicator variable showing whether investor i increased its exposures in the Top 100 between t_0 and t_1 . The chosen period is between $t_0 = 2015Q4$, the quarter of the Paris Agreement, and $t_1 = 2019Q4$. The choice of this end date is motivated by the will to avoid the year 2020, characterised by the Covid shock. Although the outbreak had already started in China in 2019Q4, the economic shock only hit from late 2020Q1 onwards.

As can be seen, it appears that, on average, investors have reduced or maintained their exposures constant, with only 43% of investors increasing their exposures during 2015Q4 and 2019Q4. Furthermore, the average change in exposures is 0.01%, highlighting that most agents kept their exposures constant through time. However, restricting to investors that increased their exposures, the average reaches around 5% and is close to 3% when investors putting their whole wealth in the Top 100 are

Table 2: Descriptive statistics

Statistic	N	Mean	St. Dev.	Min	Max
$\omega_{i,Top100,2015Q4}$	27,412	0.023	0.127	0.000	1.000
$\omega_{i,Top100,2019Q4}$	27,446	0.036	0.148	0.000	1.000
$\iota_{i,Top100,2015Q4,2019Q4}$	27,331	0.454	0.498	0	1
$\Delta_{i,Top100,2015Q4,2019Q4}$	27,331	0.013	0.139	-1.000	1.000
$\Delta_{i,Top100,2015Q4,2019Q4}$ (Net increases)	12,419	0.049	0.162	0.00000	1.000
$\Delta_{i,Top100,2015Q4,2019Q4}$ (Net increases without 100% increases)	12,150	0.028	0.079	0.00000	1.000

removed. Considering that portfolio weights are normalised by whole portfolio sizes, such changes are significant and justify this paper’s endeavour. Finally, note that the average exposure has increased between 2015Q4 and 2019Q4, suggesting that financial agents that have increased their exposures over that period did it by taking higher positions than those who diminished their ownership.

I close by complementing Table 2 by showing the density of changes in portfolio weights in Figure 6.

As can be seen, a very high mass of investors only marginally changed exposures. However, because I normalise by total portfolio size – and not only equity portfolios – small changes can represent sizeable absolute increases in exposures. Furthermore, the distribution is skewed in favour of increasing exposures. This feature confirms that investors who increased their exposures did so more relative to the size of their portfolio than those who diminished their exposures. This asymmetry further motivates my endeavor in two ways. First, it implies that agents increase their exposures more easily than they diminish them, suggesting a downward stickiness in portfolio weights. Second, it suggests that investors who increased their exposures did it with the will to put more skin in the game than previous investors.

The consequences of these patterns will be explored and detailed in the next sections.

4 Macroscopic trends in exposures

This section studies changes in exposure from the standpoint of market capitalisation.

It first depicts how the representativeness of given agent types in the Top 100 market

capitalisation has changed between 2015 and 2020. Then, it examines the stability of the Top 100 ownership. Whenever possible, a comparison with less GHG-intensive firms from the Top 500 will be provided to assess the significance of evolutions.

4.1 Trends in equity exposures top 100 emitters (2015-2020)

Trends in weights in total market capitalisation are displayed in Figure 7. It displays the evolution of the shares of investor types and regional origins.⁵ Figures showing the evolution of weights in total shares outstanding are postponed to Appendix B. They show patterns consistent with those for value in market cap.

Starting with agent types, the first striking feature is the progressive withdrawal of non-financial agents. The shares of corporations and public entities diminish significantly over the period, except in the very late quarters. This pattern is attributable to the Covid crisis, which has prompted public authorities to step in many companies. A general progress of financial institutions compensated for this withdrawal of non-financial agents, a pattern consistent with an increasing financialisation of economic systems. Most interestingly, this progress of the financial system operated for the benefit of Hedge Funds, Mutual Funds and Exchange-Traded Funds. Again, this pattern is consistent with the rise of asset managers in the past years. Banks and Trusts have kept relatively constant, if not decreasing, ownership of the Top 100 companies. Also, their equity exposure is shallow, with loans representing the most significant share of their assets.

Regarding regional origins, results highlight the reinforcement of the domination of core countries, notably North American investors, with a net acceleration in early 2015, despite the Paris Agreement, which may reflect the uncertainties related to the US Presidential election 2016. These dynamics correspond to a withdrawal of China, South Asia and Sub-Saharan Africa. The UK and its affiliates maintained an essential role in funding high-carbon activities. On the other hand, Europe witnessed a slight withdrawal from 2017 onward. Amongst Global South countries, Latin

⁵The evolution of portfolio quartiles is not displayed given the incommensurable weight of large portfolios and the stability of portfolio quartile shares through time.

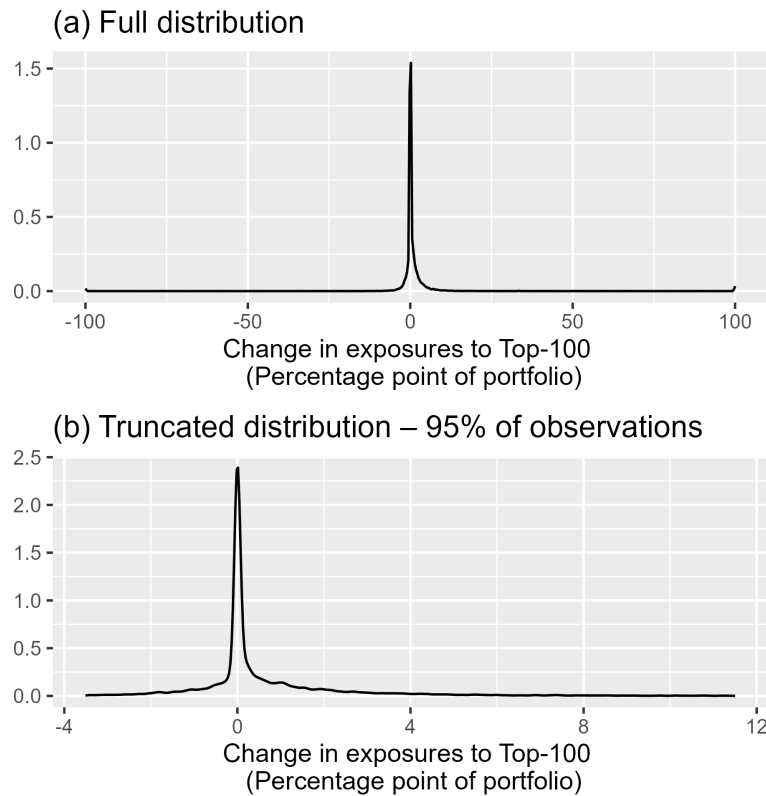


Figure 6: Density distribution of changes in exposures, as percentage point changes. Panel (a) provides the full distribution, while Panel (b) zooms in to only show the part gathering 95% of observations.

American countries are the only ones with a net progression, although their weight in market capitalisation remains pretty low. As a result, although the intuition of Bos and Gupta (2019) seems partly verified for Latin America, there is considerable heterogeneity amongst Global South countries. Further, most exposures remain concentrated in the hands of Western agents. These patterns and trends contrast much with those found for lower quantiles of the GHG intensity distribution. As shown in Figure C.2.1, the distribution of the market capitalisation of lower parts of the distribution (101-500th most GHG-intensive companies) is characterised by a much greater stability of regional and investor-type share, except for the progression of ETFs, which is also fond for this end of the distribution. Notably, hedge funds are much less critical for this part of distribution. Hence, the dynamics of market

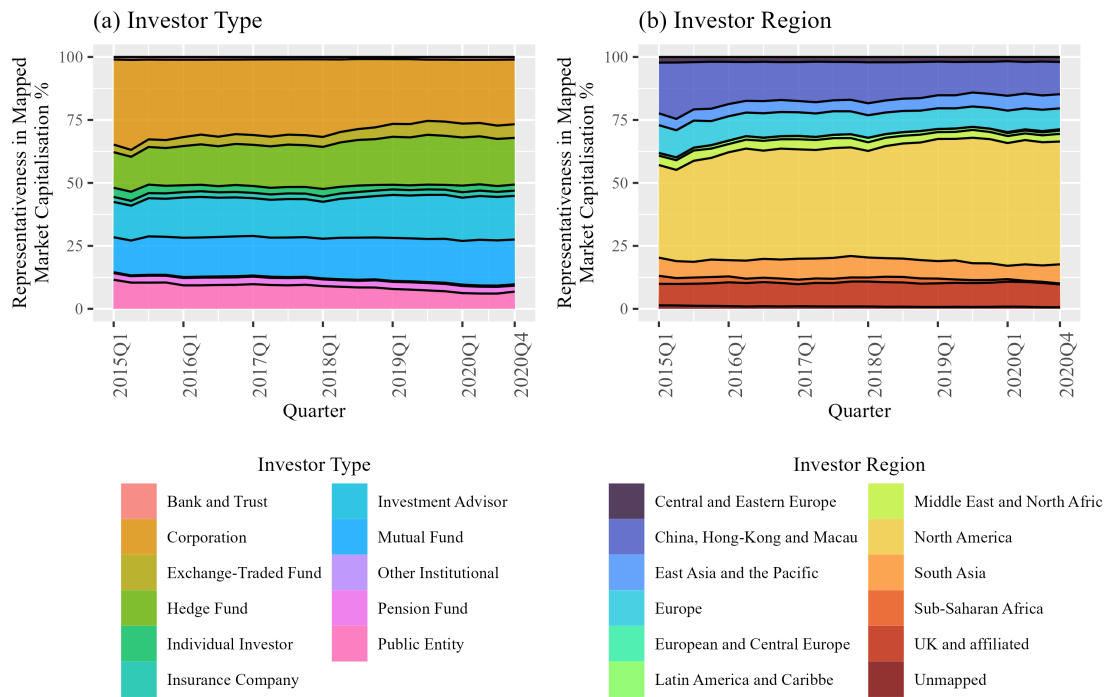


Figure 7: Evolution of representativeness of Regions and Investor Types in Top 100 emitters (2015-2020)

capitalisations of the Top 100 are significantly different from those of the 101-500 part of the distribution.

These trends show that the structure of the top 100 investors has evolved significantly and that the profile of financial risks that a transition shock could bring about has evolved accordingly. Overall, the Top 100 investor base is increasingly composed of members of the so-called shadow-banking sector (IMF 2014), whose role in fuelling financial crises has been repeatedly pointed out (Guttman 2016). Notably, the increased prevalence of ETFs, for instance, may increase the potential for amplification effects in case of large transition shocks (see Section 3). Furthermore, hedge funds' relatively high – and growing – prevalence further suggests that the Top 100 carries greater systemic risk through the equity channel than the 101-500 rankings (see Section 3). These dynamics correspond to a withdrawal of Public Entities and non-financial companies, highlighting an increasing financialisation of the Top 100 equity

investor base, shifting its risk structure away from firm and sovereign risks.

Regarding regional origins, the dominance of Western investors has ambiguous implications. On the one hand, these countries have solid regulatory capabilities, with monetary-financial authorities able to react quickly to avoid the propagation of financial shocks – as witnessed, for instance, with the recent crash of Silicon Valley Bank in the United States. On the other hand, a mishandled shock in core financial systems, notably the US, could bear significantly adverse consequences. Noteworthy here is that the bulk of the rise in asset managers in the market capitalisation of the Top 100 was largely fueled by the North American industry (Figure 4). As noted by the IMF (2014), investment funds in the US have been greater catalysts of financial disturbances than in other regions. This feature strengthens the concerns linked to these developments.

4.2 Ownership stability

Figure 8 shows the other side of the coin by offering a view of the stability of the ownership structure of the Top 100 companies.

These results show a remarkable stability of ownership structures, with very few agents exiting and entering the market capitalisation through time. It is relatively unsurprising given the relatively long-term nature of equity investments. However, a remarkable pattern is the increasing stability of ownership, with more and more companies sticking period to period and a relatively constant share of investors present since 2015Q1 from 2018Q2. In parallel, entries and exits exhibit relatively constant patterns.

In short, this section has shown that, between 2015 and 2020, the ownership of the most GHG-intensive companies entailed a distribution of exposures centred around Western financial systems – with the slight exception of Europe – and with an increasing dominance of Fund investors. Furthermore, these investors seem to adopt a stickier and more durable investment strategy in the Top 100 companies. Although equity investment does not cover the whole of portfolios and has not been at the

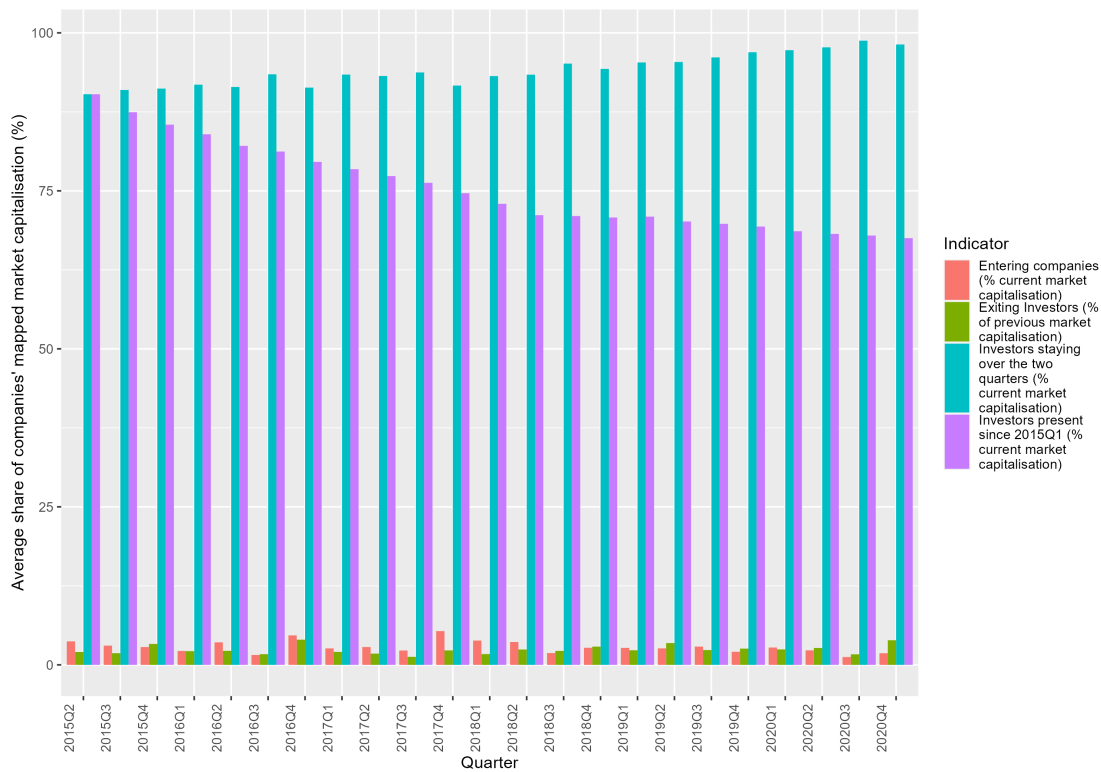


Figure 8: Stability of the Top 100 GHG-intensive firms ownership structure (2015Q2-2020Q4). Bars are average shares of the market capitalisation held by investors exiting, entering or staying at the capital of the companies across the Top 100. Reading: between 2016Q1 and 2016Q2, on average, around 90% of the market capitalisation of the companies in the Top 100 stayed in the same hands. The chart starts in 2015Q2 because we consider market capitalisation one quarter before in some computations.

centre stage of recent financial crises, these patterns nonetheless provide some insights into the long-run behaviour of financial agents. Notably, it invites caution in highlighting net preferences away from carbon-intensive assets or “green sentiments” from some financial agents, like Mutual Funds and ETFs, which have hardly reoriented their equity portfolios meaningfully despite a tightening of climate ambitions and policies.

However, these trends are aggregated and occult potential differences in strategies that various agents could adopt. Furthermore, this discussion only gives a partial vision of exposures. There is a need to look at portfolio weights and the behaviour of individual portfolios. This task is carried out in the next section.

5 Investor behaviour regarding the Top 100 GHG-intensive firms

As sketched in Section 2, this section goes beyond macroeconomic trends to tackle the behaviour of individual portfolios. It develops a logit model studying the choice to increase or decrease (or leave constant) equity exposures to the Top 100. This section will examine the results from a series of logit regressions and run a *post hoc* analysis on the most comprehensive models to disentangle meaningful differences across investor types.

5.1 Baseline model

The baseline model is the one shown in Section 2, Equation (1):

$$P(l_{i,t_0,t_1} > 0|X) = \exp(\alpha + \beta X_i + \varepsilon_i). \quad (2)$$

I start by running four models that differ by the regressors in X_i . The first, second and third models include region, investor type and portfolio quartile factors only. The fourth model puts all of them together.

Furthermore, a categorical model requires choosing a benchmark value. Given the predominance of Northern American investors in the sample, this zone was chosen as a geographical benchmark. Then, Mutual Funds, given their weight in the distribution of investors, are the type of benchmark. Finally, the largest institutions are benchmarked for the portfolio quartile. Hence, the results below should always be interpreted as *deviations* from the benchmark, the intersection of all categorical references in the specification. It follows that the results for the reference category should be read on the intercept of the logit regression.⁶ Results are shown in Table 3.

First, most regional zones (Model (1)) exhibit significant effects, which contrast with

⁶Note that this choice mechanically influence the shape of the results, as choosing another benchmark could result in other deviations. However, it has no influence on the estimated probabilities drawn from the model, which will be the object of focus of the next section.

Table 3: Determinants of Investors' Probability to increase exposures to the Top 100 GHG-intensive firms (2015Q4-2019Q1)

	<i>Dependent variable:</i>			
	Inc.Exp. Top 100 (2015Q4-2019Q4)			
	(1)	(2)	(3)	(4)
Central and Eastern Europe	0.088 (0.211)			0.187 (0.215)
China, Hong Kong and Macau	-0.036 (0.041)			0.079* (0.044)
East Asia and the Pacific	-0.087** (0.044)			-0.005 (0.047)
Europe	-0.463*** (0.034)			-0.405*** (0.036)
Latin America and Caribbe	-0.183*** (0.055)			-0.124** (0.059)
Middle-East and North Africa	-0.316 (0.246)			-0.151 (0.253)
South Asia	0.152** (0.067)			0.364*** (0.071)
Sub-Saharan Africa	0.406*** (0.082)			0.510*** (0.084)
UK and Affiliated	-0.182*** (0.048)			-0.173*** (0.050)
Investment advisor		0.242*** (0.034)		0.165*** (0.036)
Insurance Company		0.347*** (0.066)		0.205*** (0.069)
Hedge Fund		-0.010 (0.054)		-0.134** (0.057)
Corporation		-0.311*** (0.114)		-0.472*** (0.117)
Exchange-Traded Fund		0.403*** (0.046)		0.366*** (0.047)
Individual Investor		-0.189*** (0.062)		-0.327*** (0.069)
Pension Fund		0.567*** (0.099)		0.555*** (0.102)
Other Institutional		-0.039 (0.152)		-0.109 (0.155)
Bank and Trust		0.048 (0.118)		0.027 (0.120)
Public Entity		0.265 (0.427)		0.026 (0.430)
Portfolio Quartile 1			-0.206*** (0.035)	-0.187*** (0.041)
Portfolio Quartile 2			-0.242*** (0.034)	-0.220*** (0.037)
Portfolio Quartile 3			-0.202*** (0.034)	-0.203*** (0.034)
Intercept	-0.066*** (0.020)	-0.265*** (0.016)	-0.002 (0.024)	0.010 (0.034)
Observations	27,228	27,228	26,926	26,926
Log Likelihood	-18,625.090	-18,665.300	-18,545.170	-18,326.870
Akaike Inf. Crit.	37,270.180	37,352.600	37,098.330	36,699.740

Note: *p<0.1; **p<0.05; ***p<0.01
In each model, the reference category is the intersection of all reference categories.

the results of the previous section. Notably, North American investors (Intercept) slightly reduce exposure to the Top 100. Most other regional zones also exhibit a reduction in exposure compared to the reference category, most of all Europe. The only exceptions are Sub-Saharan Africa and South Asia, which display a relative

increase in exposure compared to the benchmark. Furthermore, the log odds of these categories (sum of their coefficient and the intercept) go beyond zero, suggesting that these agents have, on average, a more than 50% chance to increase their exposures. Regarding investor types (Model (2)), almost all categories show significant deviations from the reference, here Mutual Funds. All of these agents but two types (Corporations and Individual Investors) show a higher propensity to increase exposures than the reference. Pension Funds, Insurance Companies and Exchange Traded Funds exhibit sufficiently high deviations for their log odds to cross the zero threshold, suggesting a systematic bias in favour of increasing exposures from their agents. Finally, there is an apparent decreasing size effect (Model (3)). Large portfolios do not exhibit a significant bias, while inferior quartiles exhibit a downward slant. This finding illustrates a higher stickiness of large portfolios concerning smaller investors, which may be due to longer-term investment strategies or a more control-oriented approach to stockholding.

Merging all the effects in Model (4) shows a rough stability of the regional categories, highlighting the relative lack of correlation between regions and portfolio sizes, except for China, whose coefficient becomes significantly positive. The same goes for types. Portfolio quartiles retain sign significance, with moderate changes in magnitude.

However, these models do not consider possible interactions across or factor variables, which could be meaningful if specific types of agents exhibit particular behaviours.⁷ Furthermore, the interpretability of the results above is difficult because some Type-Region portfolio triplets may not exist. Hence, the following subsections will explore interactions between types and regions and then between portfolio sizes and the two other categorical variables.

5.2 Region-Type interactions

In the following, models (1) and (2) in Table 3 are merged as follows:

⁷Chi-square tests comparing models with and without interactions clearly suggested that interaction models were more informative.

$$P(l_{i,Top100,t_0,t_1} > 0|X) = \exp(\alpha + \beta_1 Region + \beta_2 Type + \beta_3 Region \times Type + \varepsilon_i).$$

The portfolio quartile variable is purposefully left aside in the first instance to focus on the effects of interactions alone and to avoid disturbing the following *post hoc* analysis. Results are displayed in Table 4.

They suggest that some interactions have meaningful effects, for instance, European Pension Funds, which have exhibited a more important disengagement than other Pension funds and other European investors compared to North American Mutual Funds. By contrast, European Individual Investors have invested way more than other categories, similar to European Corporations. These results thus allow for a more precise picture than the basic specifications by picking up some particular profiles whose behaviour may drift from those exhibited by more significant categories they could belong to. In particular, European ETFs stand out as particularly prone to invest in GHG-intensive companies despite the generally “virtuous” behaviour of European investors.

However, these results must be taken with caution. Indeed, computing odds with such a model requires adding the coefficients of Table 4. However, although each one of these coefficients may be significant alone, there is no guarantee that the sum of the coefficients is still significantly different from the benchmark. Furthermore, results from the regression only consider the reference categories as comparand, while differences – or lacks of difference – may exist across categories. Hence, accurately pinpointing these differences is crucial in highlighting what kind of investor stands out from other categories.

For this purpose, the analysis will proceed with a *post hoc* analysis of this model, which will work in two steps. First, estimated probabilities for each existing category will be displayed, with corresponding confidence intervals, allowing to disentangle which investor categories have significantly meaningful effects. Second, with these

Table 4: Determinants of Investors' Probability to increase exposures to the Top 100 GHG-intensive firms (2015Q4-2019Q1)

	<i>Dependent variable:</i>	
	Inc.Exp. Top 100	
Europe	-0.450***	(0.047)
Latin America and Caribbe	-0.306***	(0.072)
South Asia	0.424***	(0.093)
Sub-Saharan Africa	0.528***	(0.103)
UK and affiliated	-0.258***	(0.065)
Investment Advisor	0.110**	(0.051)
Insurance Company	0.248***	(0.075)
Hedge Fund	-0.181**	(0.072)
Exchange-Traded Fund	0.406***	(0.069)
Individual Investor	-0.253***	(0.088)
Pension Fund	0.825***	(0.318)
Latin America and Caribbe Investment Advisor	0.793***	(0.167)
UK and affiliated Investment Advisor	0.349*	(0.183)
Europe Hedge Fund	0.711***	(0.200)
Latin America and Caribbe Hedge Fund	0.370*	(0.219)
Europe Exchange-Traded Fund	-0.256**	(0.128)
Sub-Saharan Africa Exchange-Traded Fund	-0.802**	(0.373)
Europe Individual Investor	1.070***	(0.358)
Latin America and Caribbe Individual Investor	0.690*	(0.393)
South Asia Individual Investor	-0.704***	(0.179)
Europe Pension Fund	-1.029***	(0.398)
Constant	-0.132***	(0.033)
Observations	27,228	
Log Likelihood	-18,420.490	
Akaike Inf. Crit.	37,012.980	

Note: *p<0.1; **p<0.05; ***p<0.01
Only statistically significant coefficients are displayed.
The reference category is the intersection of all reference categories.

estimated probabilities, I can contrast investor categories to assess which investor categories stand out compared to the others.

Results are reported in Figure 9, starting with estimated probabilities. Overall, results show that most Type-Region pairs exhibit a positive deviation from 50% within the population of non-transient investors, *i.e.*, their investment behaviour

concerning the Top 100 is biased in favour of increasing exposures. However, results exhibit large variability.

Many Type-Region pairs show large confidence intervals crossing the 50% line. In other words, their choice to increase or maintain/decrease their exposures is, in the aggregate, not statistically different from the toss of a coin. In many cases, large confidence intervals are due to the small number of observations for some agent category pairs, like corporations and public entities. In other cases, where there is a relatively large number of observations, like for Banks and Trusts or Individual Investors, it can denote a certain heterogeneity in investment choices and strategies concerning the Top 100.

Other type-region pairs exhibit statistically significant deviations from a 50% probability, mostly among Mutual Funds, Investment Advisors, ETFs, Pension Funds and Individual Investors. Biases, however, do not play out in the same directions, which highly depend on the regional origin. Hedge Funds and Mutual Funds exhibit more systematic downward biases. For Mutual Funds, the most pronounced effects are for Europe, Latin America and the UK, with others remaining close to a 50-50 probability. Sub-Saharan Africa and South Asia stand out as the only regions with Mutual Funds with an upward bias. Investment Advisors, on the other hand, show positive biases for China, Latin America and South Asia, with, again, a strong negative bias for Europe. ETFs show numerous positive biases, especially for Northern America, China, East Asia and the Pacific. Finally, Pension funds, except in Europe and Sub-Saharan Africa, exhibit a bias in favour of increasing exposure.

In short, peripheral financial systems show more positive deviations from a 50-50 dispatch than core ones, although it depends on the investor type. Deviations remain relatively small, except for Investment Advisors and Mutual Funds. Core financial systems, however, do exhibit positive biases for Exchange-traded Funds (North America) and Pension Funds (North America and the UK).

These comparisons across type-region pairs suffer from overlapping confidence intervals, which may render comparisons statistically insignificant. To control for this

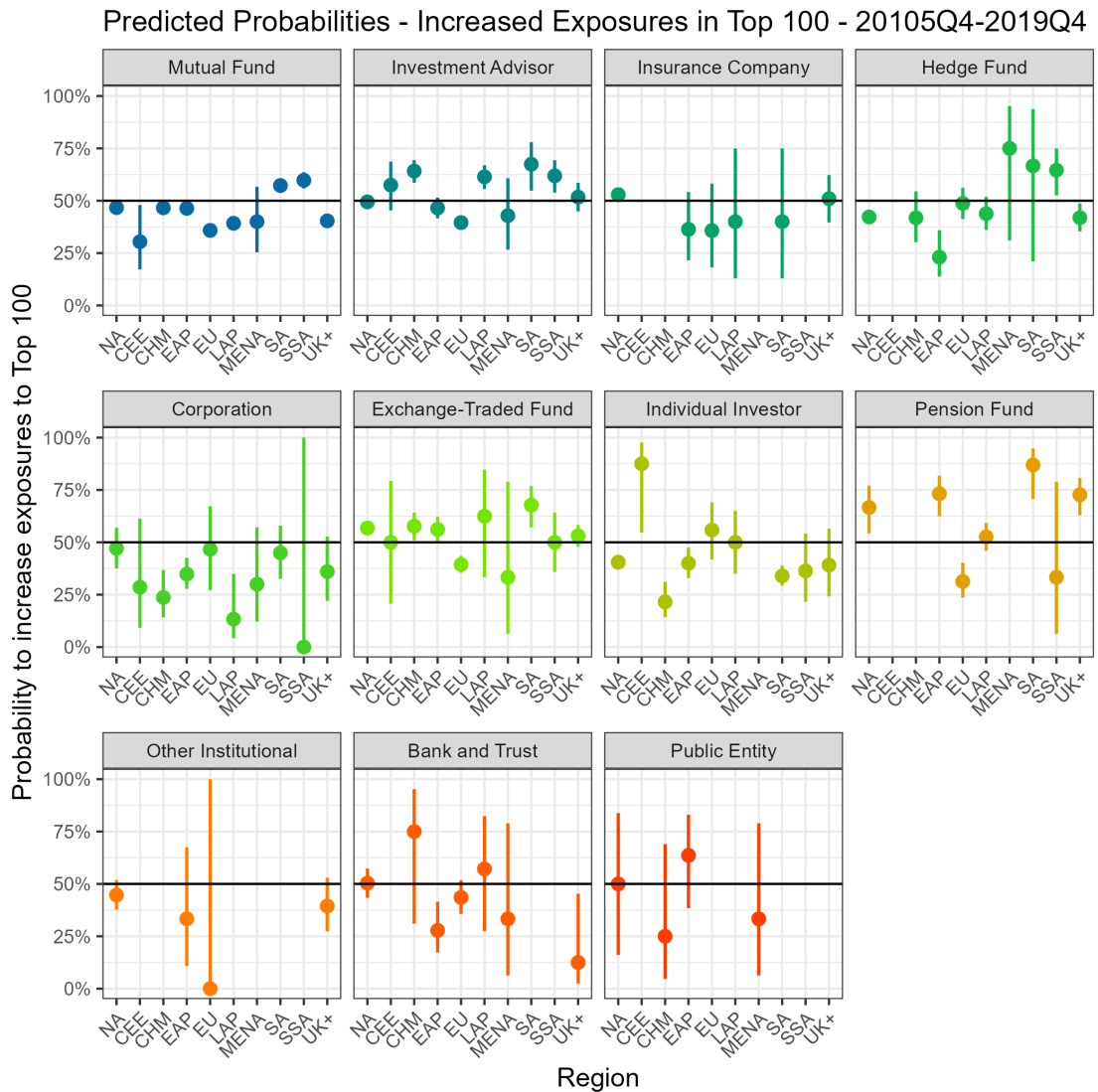


Figure 9: Predicted probabilities – Interaction model. Reported confidence intervals are at 90%. The horizontal black line shows the 50% probability. Non-appearing points are interactions not appearing in the data.

and highlight significant contrasts, I complement the study of estimated probabilities with a *post hoc* analysis, developed in Appendix B. Overall, the *post hoc* analysis confirms the insights drawn from the study of estimated probabilities while confirming the adverse behaviour of developing countries notably South Asia and Sub-Saharan Africa and Pension Funds as regards investment types. It also showed substantial

deviations on the part of some ETFs and Insurance companies.

These results thus highlight a combination of two dynamics that could only be partly seen at the macroscopic scale of Section 4. First and foremost, the picture is one of split financial markets. Many agents do not exhibit behaviours significantly different from the toss of a coin. When they do, most deviations are relatively small in either direction. However, this divide is only partially homogeneous across investor types and regions. Emerging economies are more prone to exhibit positive biases among most investor advisors. Global North countries have relatively heterogeneous behaviours, with Anglo-Saxon countries mainly being split, while Europe exhibits a quasi-systematic withdrawal, except for Individual Investors. These results confirm the findings of Bos and Gupta (2019), *i.e.*, that peripheral financial systems will likely increase their exposure to asset stranding and transition risks, while this hardly showed at the macro scale. However, the results only illustrate this pattern in relative terms since core financial systems, except for Europe, do not exhibit an apparent withdrawal from the most GHG-intensive companies.

5.3 Portfolio size interactions

This picture must nonetheless be complemented by studying the importance of the size of institutions in determining changes in exposures. As sketched above, there seems to be a negative correlation between size and propensity to increase exposures. Further, some categories exhibit a significant skewness towards extensive portfolios. Hence, digging more into the size of institutions could help draw a more precise picture of the behaviour of some agent categories. In what comes next, I interact portfolio quartiles with Region and Investor Types separately through the two following models, starting with the Region interaction:

$$P(\iota_{i,t_0,t_1} > 0|X) = \exp(\alpha + \beta_1 Region + \beta_2 PortfolioQuartile + \beta_3 Region \times PortfolioQuartile + \varepsilon_i), \quad (3)$$

$$P(\iota_{i,t_0,t_1} > 0|X) = \exp(\alpha + \beta_1 Type + \beta_2 PortfolioQuartile + \beta_3 Type \times PortfolioQuartile + \varepsilon_i). \quad (4)$$

For the sake of brevity, I only discuss estimated probabilities, to retain a visual approach to the results.⁸

Results for the Region-Size interaction are displayed in Figure 10. They clearly show the positive relationship between portfolio size and the probability of increasing exposure, except for China and the UK, which exhibit non-linear relationships. The pattern is particularly pronounced in South Asia and Latin America, where the difference between Q1 and Q4 can be as high as 25% and spread across the 50-50 limit. As developed in Appendix B.2, the *post hoc* analysis shows that differences across quartiles are most of the time significant. It also illustrates that positive differences across regions are primarily found in Latin America and South Asia for large portfolios and China and Sub-Saharan Africa for small portfolios. This differential importance of size may be due to different financial market infrastructures and strategies regarding the transition between small and large investors across regions. In particular, while Northern financial systems are roughly aligned in structure, there is significant heterogeneity across emerging countries, which may imply different exposures to transition risks in the long run.

Moving on to type-quartile interactions, patterns confirm the negative correlation for Investment Advisor, Insurance Companies and Banks and Trusts to a lesser extent. Other agent types exhibit more non-linear relationships. For instance, Mutual Funds, Hedge Funds and ETFs exhibit an inverted-bell behaviour, with non-substantial differences between small and large portfolios and lower probabilities to increase exposures for portfolio sizes closer to the median. The *post hoc* analysis in Appendix B.2.

⁸The *post hoc* analysis is developed in Appendix B.

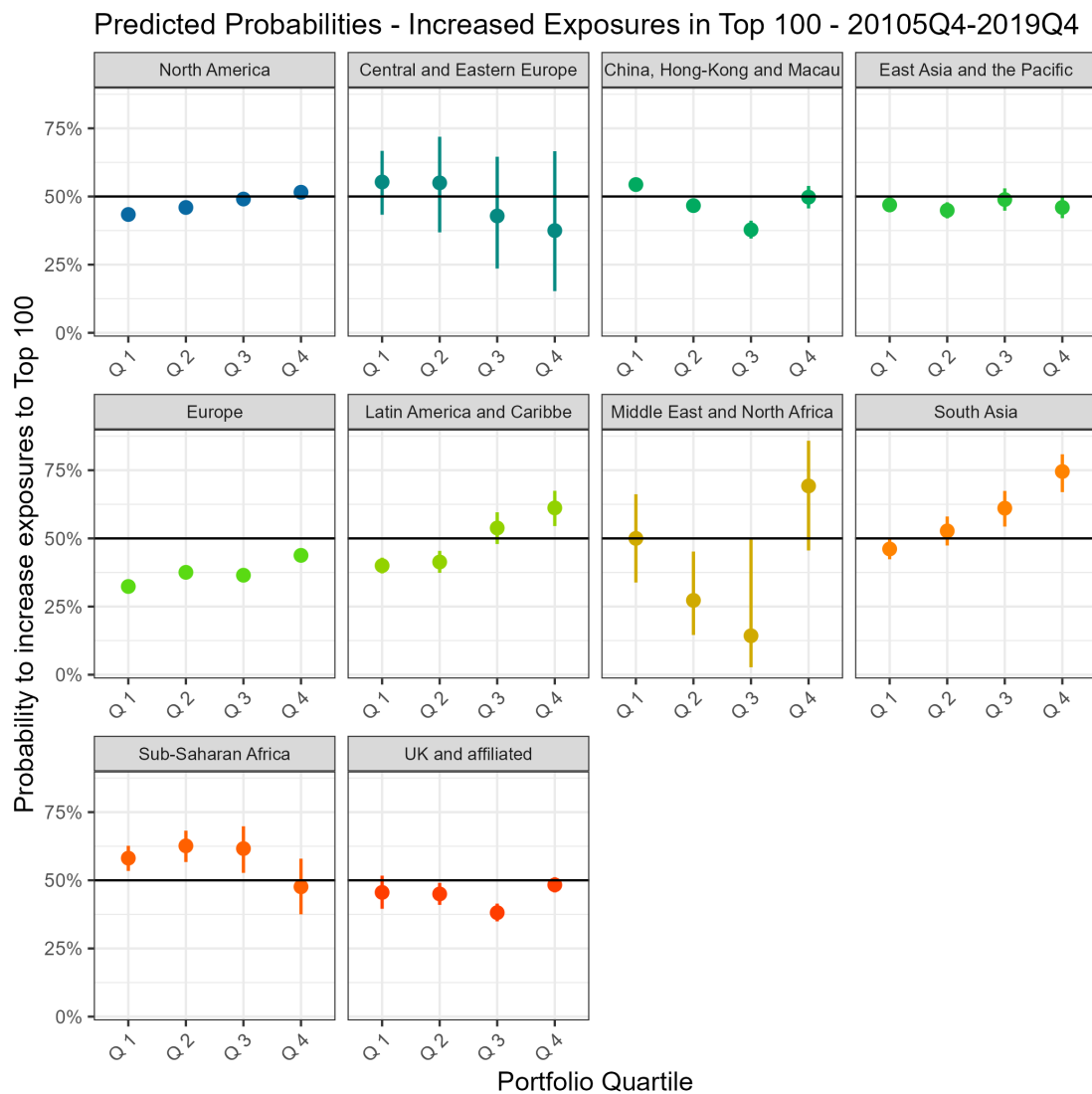


Figure 10: Predicted probabilities – Interaction model – Portfolio and Regions. Reported confidence intervals are at 90%. The horizontal black line shows the 50% probability. Non-appearing points are interactions not appearing in the data.

showed further that ETFs and Pension Funds exhibit the most substantial positive biases compared to other categories.

These results show the importance of the size effect, notably for developing countries and financial agents who are not financial managers. Indeed, the latter’s behaviours are broadly aligned across quartiles, with only minor differences, while

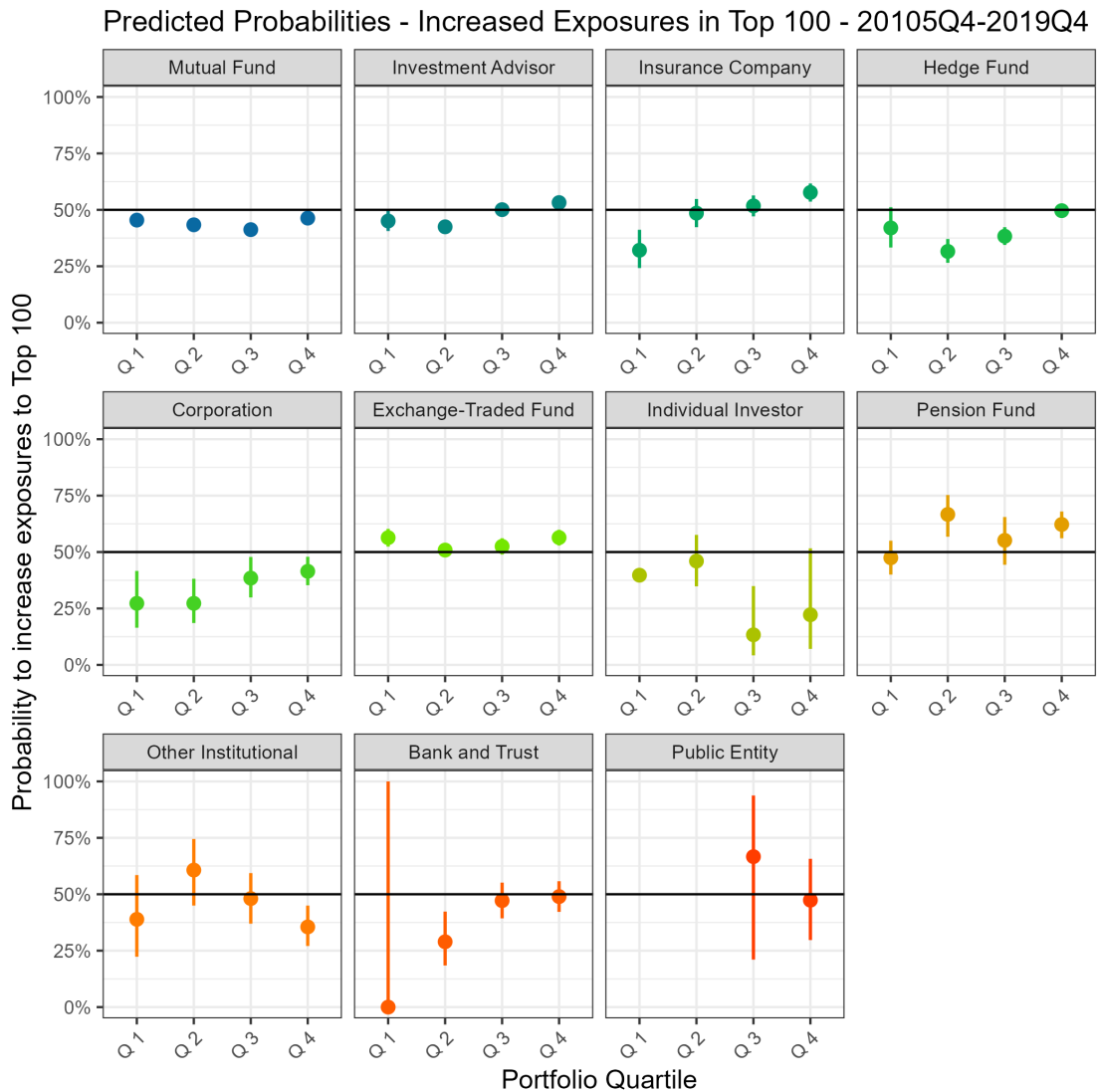


Figure 11: Predicted probabilities – Interaction model – Portfolio and Types. Reported confidence intervals are at 90%. The horizontal black line shows the 50% probability. Non-appearing points are interactions not appearing in the data.

other categories exhibit much more significant heterogeneity in terms of investment choices. This pattern may be due to the relative homogeneity of investment strategies amongst funds, which are increasingly characterised by adopting passive investment approaches based on indices. Results also highlight the greater stickiness of equity investments on the part of larger institutions, which may reshuffle their portfolios at

a lower frequency than smaller agents. On the other hand, given that most small investors exhibit increased probabilities close to 50%, other small investors may have replaced withdrawing ones in the course during the period of interest. If true, this crisscrossing of equity investments would suggest that, at the scale of financial systems, exposures were merely redistributed across small institutions.

5.4 Robustness checks

This section closes with a series of robustness checks. Only the main results are discussed for brevity. Other elements are postponed to Appendices. With the same motivation, emphasis was put on the full specifications with and without interactions when relevant.

Three robustness checks were implemented: (i) removal of small populations from the sample by considering only populations above 25; (ii) alternative start and end dates, respectively 2016Q1 and 2020Q4, to include the Covid year and check the robustness of the results to this shock. The regression results for the full models without interactions are shown in Table 5, with Model (1) corresponding to full specification reported in Table 3.

Overall, removing small populations or changing the boundaries of our study changes results only a little. Removing small populations has only a marginal effect on signs, significance and magnitude due to the underlying assumption of the independence of irrelevant alternatives embedded in logit models. On the other hand, changing the boundaries introduces some changes – although many coefficients retain signs and significance, with marginal changes in magnitude, except for portfolio size quartiles and China. Central and Eastern European countries and Investment Advisors exhibit a more significant and positive deviation from Northern American Funds; while China exhibits a clear withdrawal. Except for these, deviations from the benchmark remain the same. More importantly, the intercept becomes negative, suggesting Northern American Mutual Funds reverted their high-carbon investments during the COVID-19 shock. The negativity of the intercept implies a downward shift of log odds,

Table 5: Robustness Checks

	<i>Dependent variable:</i>			
	Inc.Exp. Top 100 (2015Q4-2019Q4)		Inc.Exp. Top 100 (2016Q1-2020Q4)	
	(1)	(i)	(ii)	(iii)
Central and Eastern Europe	0.187 (0.215)	0.324 (0.297)	0.792*** (0.228)	0.120 (0.277)
China, Hong Kong and Macau	0.079* (0.044)	0.080* (0.045)	-0.339*** (0.046)	0.577*** (0.066)
East Asia and the Pacific	-0.005 (0.047)	0.004 (0.048)	-0.070 (0.048)	-0.191*** (0.058)
Europe	-0.405*** (0.036)	-0.404*** (0.037)	-0.300*** (0.036)	-0.395*** (0.045)
Latin America and Caribbe	-0.124** (0.059)	-0.108* (0.060)	0.291*** (0.059)	0.797*** (0.104)
Middle-East and North Africa	-0.151 (0.253)		-0.417 (0.261)	-0.321 (0.310)
South Asia	0.364*** (0.071)	0.339*** (0.072)	0.437*** (0.071)	0.339*** (0.093)
Sub-Saharan Africa	0.510*** (0.084)	0.542*** (0.087)	0.214** (0.083)	0.445*** (0.116)
UK and Affiliated	-0.173*** (0.050)	-0.175*** (0.051)	-0.075 (0.050)	-0.041 (0.063)
Investment advisor	0.165*** (0.036)	0.161*** (0.037)	0.227*** (0.037)	0.041 (0.045)
Insurance Company	0.205*** (0.069)	0.233*** (0.071)	0.002 (0.077)	-0.037 (0.081)
Hedge Fund	-0.134** (0.057)	-0.142** (0.058)	-0.191*** (0.058)	-0.028 (0.071)
Corporation	-0.472*** (0.117)	-0.370*** (0.136)	-0.471*** (0.121)	-0.777*** (0.130)
Exchange-Traded Fund	0.366*** (0.047)	0.366*** (0.047)	0.361*** (0.047)	0.209*** (0.060)
Individual Investor	-0.327*** (0.069)	-0.319*** (0.071)	-0.469*** (0.070)	-1.050*** (0.084)
Pension Fund	0.555*** (0.102)	0.503*** (0.104)	0.448*** (0.125)	0.621*** (0.146)
Other Institutional	-0.109 (0.155)	-0.019 (0.166)	0.612*** (0.101)	0.354 (0.221)
Bank and Trust	0.027 (0.120)	0.037 (0.125)	-0.010 (0.121)	-0.308** (0.131)
Public Entity	0.026 (0.430)		0.833* (0.438)	0.601 (0.589)
Portfolio Quartile 1	-0.187*** (0.041)	-0.196*** (0.041)	0.206*** (0.041)	0.705*** (0.057)
Portfolio Quartile 2	-0.220*** (0.037)	-0.223*** (0.037)	0.108*** (0.037)	0.348*** (0.046)
Portfolio Quartile 3	-0.203*** (0.034)	-0.203*** (0.035)	0.036 (0.035)	0.177*** (0.041)
Intercept	0.010 (0.034)	0.012 (0.034)	-0.314*** (0.034)	0.462*** (0.040)
Observations	26,926	26,507	26,818	18,639
Log Likelihood	-18,326.870	-18,050.780	-18,114.070	-11,486.890
Akaike Inf. Crit.	36,699.740	36,143.560	36,274.140	23,019.770

Note:

In each model, the reference category is the intersection of all reference categories.

*p<0.1; **p<0.05; ***p<0.01

implying that more agents decreased their exposures in the wake of the pandemic.

This pattern can be explained by the significant downturn the outbreak represented for many high-carbon companies, notably oil extractors, which triggered withdrawals on the part of economic agents. This pattern justifies not going beyond 2019Q4 in

the main results. However, the stability of deviations from the intercept for regions and types is remarkable. It clearly shows that the structure of relative stances *vis-à-vis* the Top 100 was left unchanged by the outbreak, suggesting that the main results depict a resilient long-run trend.⁹

A further issue encountered in running this model is that some investors in the dataset display a zero portfolio weight in 2015Q4 and 2019Q4. In contrast, they exhibit non-zero holdings in between. These “transient” investors thus create a mass of zeros for the ι_{i,t_0,t_1} that may artificially inflate the number of zeros in the distribution of the outcome variable, and therefore drag the estimated probability of our logit model downwards. In a third model (iii), I thus leave aside these investors from the sample, representing a rough 30%. Because they entered and exited the capital of the Top 100 over the period, they represent short-term changes in the ownership structure. Removing them gives a sense of longer-run trends in portfolio choices. This specification thus focuses on net entering and net exiting institutions, as well as on those keeping ownership stake through the period of interest. Finally, not accounting for transient investors controls for “late conversions” to withdrawal from the Top 100, *i.e.*, for investors that definitively reduced their exposures with a lag with respect to the starting date of the analysis. As a result, it can help determine whether the results above are more recent than the start of the analysis.

Removing transient investors has sizeable implications since it mechanically shifts up the share of investors increasing their exposures.¹⁰ With this specification, the intercept becomes significant and positive, suggesting that non-transient American investors did increase their exposures during the period of interest. Other coefficients exhibit large changes in magnitude – although significance levels are broadly left unchanged. The effect of being a Latin-American investor becomes strongly positive, suggesting that most downward biases found before were due to transient investors. Hedge Funds become insignificant. More importantly, the relationship between increased exposure and portfolio size becomes positive. Finally, the magnitude of the

⁹Results with interactions are displayed in Appendix C.3, and also show a stability of the results.

¹⁰A discussion of estimated probabilities and corresponding *post hoc* analysis is postponed to Appendix C.4.

effect of China sizeably increases. These patterns suggest that the Latin America, Hedge Fund and Mutual Fund categories, and to a lesser extent China, host a large share of transient investors that have increased then decreased their exposures during the late 2010s.¹¹ Furthermore, these results demonstrate that transient investors are primarily concentrated in the lower ends of the portfolio size distribution, given the now positive relationship between size and probability of investing in the Top 100. Note, however, the resilience of the Pension Fund coefficient in this specification. Due to their long-term commitments, Pension Funds only naturally host a few short-term investors. Hence, they still exhibit more positive biases favouring investing in the Top 100. The *post hoc* analysis developed in Appendix C.4 demonstrates that Global South countries exhibit much higher upward biases than Global North countries in the specification, while cross-type comparisons are left unchanged. More precisely, except for some changes, like the more upward-biased behaviour of Latin America and a general increase in contrast magnitude, the structure of relative investment behaviours is left intact.

This specification brings up several conclusions. First, it confirms a crisscrossing of equity exposures among small investors, with small non-transient investors increasing their exposures significantly compared to other quartiles. Furthermore, it suggests that the relative polarisation of the market found above is a relatively recent phenomenon, with a turning point between the bounds of the period of interest. Together with Model (ii), this trend seemingly continued during 2020. However, the longer trend since the Paris Agreement is relatively bleak, in the sense that investors that increased their exposure to the top 100 seem to exhibit a greater stickiness in behaviour, consistent with the funding about ownership inertia in Section 4. Finally, the *post hoc* analysis suggests that the above conclusions about the relative behaviour of Region-Type combinations are robust but exacerbated by the removal of transient investors, which calls for caution regarding further developments in the exposure of developing countries.

¹¹This result is consistent with the findings of the IMF (2021) who showed that funds in emerging economies increased the carbon intensity of their portfolios until around 2018 before receding.

6 Conclusion and ways forward

6.1 Summary of the results

At the macroeconomic scale, trends showed an increasing supremacy of Northern American investors and asset managers. A comparison with lower quantiles in the distribution (see Appendix C.2) shows that this pattern is specific to the Top 100, the 101-500 investor base, which showed greater stability of shares in market capitalisation and a much lesser role of hedge funds than in the Top-100. Furthermore, the ownership of the Top 100 has become increasingly sticky.

These macroeconomic trends may hide significant heterogeneity at the agent's scale. Considering all investors together at the microeconomic scale, around 45% of investors net-increasing their exposures, suggesting that a (small) majority of investors reduced their exposures. The study of disaggregated categories somewhat confirmed this finding by showing that financial markets are split on their exposures to the Top 100, with relatively small deviations from a 50-50 overall.

However, this general picture hides a non-negligible degree of heterogeneity across regions, investor types and portfolio sizes. Emerging markets are more likely to exhibit positive biases in favour of increasing exposures, notably Sub-Saharan Africa and South Asia. It confirms the insights of Bos and Gupta (2019). Furthermore, some investor categories exhibit positive biases, mostly Pension Funds¹² (in Anglo-Saxon countries) and Exchange-Traded Funds. Results also document a higher propensity to reduce exposures on the part of European investors. Furthermore, these patterns are not homogeneously distributed across investor characterisations. While ETFs show a general bias in emerging countries, Mutual Funds and Hedge Funds are only slanted upwards in Sub-Saharan Africa and South Asia. Conversely, Pension Funds have increased their exposure mainly in the Global North and emerging countries.

I finally document a sizeable heterogeneity in attitudes towards the Top 100 alongside size, both when crossed with regional origin and investor types. Notably, I show that

¹²See EIOPA (2022) for a climate stress test of the European pension fund sector.

large institutions are the investors most prone to increase their exposures, while smaller agents have been more inclined to decrease their exposures. This is the case in most regions, except in China. It is also the case across agent types, with the exception for ETFs, Hedge Funds and Mutual Funds. They exhibit a U-shaped relationship between size and probability of increasing exposures, highlighting that exposure reductions came mostly from middle-sized agents.

Finally, an important finding is that these developments were mainly driven by a population of “transient” investors that first entered and then exited the Top 100’s capital during the period of interest. Removing this population of existing agents gave rise to quite different patterns. Notably, most non-transient investors increased their exposures significantly, contrasting with the overall optimistic picture offered by the whole sample. Furthermore, developing countries, including some that showed a propensity to reduce exposure in the entire sample, exhibited much higher biases in favour of the Top 100 once transient investors were removed.

This pattern hints at two things. First, it shows that many investors divested from the Top 100, although they did it with a lag compared to the Paris Agreement. This trend is, therefore, relatively recent and seems to have been robust to the year 2020. Second, removing transient investors suggested that a significant population stepped in and replaced those who exited. This study thus documents a crisscrossing of exposures between a population of investors that withdrew from the Top 100 and another that exhibits a longer-run commitment to the Top 100. This crisscrossing, however, was not symmetrical. I indeed document that the investors that increased their exposures did so more than proportionately to the decrease in exposures of other investors. This pattern seems particularly true for Hedge Funds: while exhibiting a dispatch close to 50-50 in the base regressions, the increase of their significance in the Top-100’s market capitalisation can only be reconciled by a stepping-in of investors with higher exposures than those they replaced.

These broad findings have implications for transition risks.

6.2 Implications for transition risks

Patterns at the macroeconomic level highlight a quite specific and evolving financial risk profile of the Top 100 investor structure. Away from firm and sovereign risk, due to large public and NFC ownership at the start of the sample, the risk profile increasingly concerns the financial sector in itself through a rampant financialisation of the Top 100. Due to the increasing presence of hedge funds and exchange-traded funds, a large shock to transition-exposed companies may have higher chances of triggering amplification effects.

At the microeconomic level, results have mainly two implications for financial transition risks.

First, the upward bias of many emerging economies, especially when transient investors are removed, calls for considering the specifics of these world regions in terms of vulnerability to financial disturbances and handling of financial risks. Being often dependent on financial inflows and on exchange-rate stability (Magacho et al. 2021; Valdecantos 2021), financial disturbances in these countries may have important macroeconomic outreaches if large losses for their investors translate into financial outflows. Relatedly, as sketched above, monetary and financial policy interventions may be limited in these countries, in part by the external constraint. Transition risks could thus become transboundary, flowing from emerging economies to developed ones (Volz et al. 2021).

Second, the upward biases of ETFs and Pension Funds create some specific issues. ETFs being usually passive investors, it suggests that the indices they follow hardly account for environmental dimensions. Furthermore, the lack of clear regulation of these agents and their potential for amplification could pose a high risk in case of large transition shocks. Pension Funds' behaviour is problematic especially in Anglo-Saxon Countries. The procyclicality of their behaviour in times of financial turmoil (Bank of England 2014) could create problems similar to that of ETFs. Furthermore, they could transfer financial shocks to the macroeconomy through the diminution of pension entitlements and pension wealth.

Third, the asymmetric crisscrossing of exposures hints at the creation of a non-trivial pocket of higher exposures, most likely to be found amongst small institutions, emerging economies, and Hedge Funds. This finding is consistent with an increase in the concentration of exposures. Although this paper cannot quantify how these exposures may translate into vulnerabilities (see below), a growing body of literature suggests that agents taking on high-carbon investments usually perform worse than greener counterparts, and may therefore be more sensitive to shocks (Reboredo and Otero González 2021b; Vioto, Curcio, and Gianfrancesco 2022).

All in all, these results suggest that, in prudential terms, the evolution of exposures between 2015 and 2020 was mostly characterized by a shift towards more fragile institutions overall, whose exposures to the Top 100 are higher than in the past. From a microprudential perspective, it hints at greater exposures, and possibly vulnerability, to transition-related shocks. It also casts some doubt on the possibility for investors to autonomously stave off high-carbon companies without policies or broader incentives.

6.3 Limits of the study

However, this study is nonetheless not without limits. Hence, the above conclusions should be taken with some caution.

First and foremost, I cannot observe portfolio rebalancing towards significantly greener alternatives. As a result, I cannot quantify investors' vulnerability to transition risks. Appendix C.5. provides a tentative assessment in that direction by showing that portfolio rebalancing did not occur within the 101-500 most GHG-intensive companies, highlighting that investors in the Top 100 did not look for close substitutes along the GHG intensity curve. However, the increases in exposures I document may be compensated for by higher exposures to companies much more down the distribution, like the bottom-100 GHG-intensive companies. This endeavour will be carried out in further works.

Second, because I could only characterise investors broadly, I cannot disentangle their

motives for increasing their exposure. In particular, I cannot decide whether investors simply do not take transition risks into account, are characterised by transition-contrarian expectations, or hope to control companies into decarbonising. Furthermore, many agents following a passive investment strategies. These results may suggest more that the following indices are deficient regarding transition risks. Results on ownership stability, however, provide some insights in this direction. They suggest that new entrants to the capital of the Top 100 firms adopted a longer-term approach to their equity exposures. It can also hint at greater investment inertia, which the expansion of passive investment strategies may fuel. Results on ownership stability, however, provide some insights in this direction. They suggest that new entrants to the capital of the Top 100 firms adopted a longer-term approach to their equity exposures. It can also hint at greater investment inertia, which the expansion of passive investment strategies may fuel. On the other hand, investors may stick to high-carbon companies to exert a longer-run control over them, possibly to induce changes in favour of low-carbon modes of production. However, empirical evidence for this hypothesis is mixed (Baines and Hager 2022; Barko, Cremers, and Renneboog 2022; McDonnell, Rempel, and Gupta 2022). Hence, these results suggest that equity exposures to low-carbon transition risks become stickier and more durable. Some agents are embarking on long-run bets on either the absence of transition or their ability to trigger meaningful changes within these companies.

Another important caveat is that this study focuses on equity without information on other assets. The increased equity exposures documented in this study may be hedged by other asset types, like bonds or (securitised) loans. Furthermore, equity has hardly been at the root of major financial disturbances after the Dotcom bubble. All this invites caution in the interpretation of the results.

Then, I had to build on an estimator of portfolio sizes, which could introduce some biases – although using binary variables should temper them to some extent. Furthermore, the study had to focus on categorical variables and could not use continuous regressors, like debt or liquidity ratios or other interesting characteristics of investors.

Unfortunately, this data is not publicly available due to the limited reporting obligations of non-listed companies, which represent the overwhelming bulk of the sample. Finally, our inability to track ultimate investors consistently may bias our picture somehow.

Finally, due to computational constraints, we had to split portfolio interactions across our two other categorical variables, barring the possibility of exploring a three-way interaction in a meaningful way. Some patterns may have been neglected with this partial approach.

Tackling these issues would require, in priority, an extension of the datasets used in the study. Notably, crossing Refinitiv with Bureau van Dijk's Orbis, which has been used in other studies (Semieniuk, Holden, et al. 2022), could be very useful in making our mapping of ownership more robust and possibly more comprehensive while at the same time tracking ownership network more precisely, down to ultimate owners. Furthermore, Bureau van Dijk provides more comprehensive information on non-listed companies, including financial agents, which could allow for a better understanding of the determinants of the increase in exposure. Also, this methodology could be, in principle, ported to more comprehensive datasets, like those managed by financial regulators themselves. However, they would only be able to focus on a particular jurisdiction, reducing the scope of the study. Finally, exploring investment behaviours down the distribution of GHG intensity emissions, applying other rankings, for instance, based on absolute emissions, or using other data sources could represent valuable extensions.

6.4 Policy implications

However, despite these caveats, this work bears some policy teachings.

Indeed, the progressive shift of exposures towards emerging economies calls for the coordination of prudential policies across jurisdictions to avoid localised financial disturbances and possible ripple effects on other financial sectors. This could notably take the form of a harmonisation of transition risk regulation frameworks across ju-

risdictions (D’Orazio 2023). More radical proposals (Espagne 2020) have put forward the idea of a renewal of the international monetary system to ease wealth and liquidity transfers aimed to better balance financial disequilibria across world regions. At a domestic level, our results also suggest considering with caution the increasing exposure of funds to transition risks, notably ETFs and Hedge Funds, through the adoption of adequate policy steps, like stricter reporting obligations, tighter supervision of highly exposed funds, and some regulatory limits such as a brake on leverage for funds deeply involved in high-carbon activities.

Second, this work can serve as a basis for a better representation of the financial sector in modelling exercises aimed at measuring transition risks. The results have highlighted a large heterogeneity in investment strategies and stances with regard to the low-carbon transition. It clearly calls for embracing this heterogeneity as much as possible by representing populations of agents with different attitudes towards high-carbon investments. For instance, this study could be used to generate short- to medium-run portfolio scenarios, which, considering a population of balance sheets with well-defined characteristics, would reallocate exposures stochastically based on our estimated probabilities without relying on declared investment behaviours from financial institutions. Results from this paper could also inform the building of a fully-fledged a disaggregated agent-based model of the financial sector by providing some empirical groundings to the behaviour of modelled agents.

Furthermore, the chapter reports that financial policies and broader discussions on climate-related risks can have short to medium-run impacts on agents’ portfolio behaviours, although this effect is differentiated across agents. In our results, the relative virtuousness of European investors clearly points to a positive effect of the higher climate concerns of European investors (Hunt and O. Weber 2019) and of stronger financial and reporting policies (Mésonnier and B. Nguyen 2021). It tends to suggest that discussions on climate risks and corresponding policies can be effective in inducing portfolio reshuffling. Including such reactions and their extent in dynamic portfolio assumptions is therefore crucial and can be carried out safely.

Finally, as highlighted above, exposures were redistributed to potentially more fragile agents, who do not put the same weight on transition-related matters. Dynamic portfolio hypotheses should, therefore, take into account as much as possible the fact that, so far, exposures to transition risks have mostly been reshuffled across agents. Said otherwise, exercises should account for the fact that agents cannot diminish their exposures in isolation and that they could still be indirectly exposed to transition shocks if they are vulnerable to the new asset holders of high-carbon companies.

This chapter closes the second movement of this PhD, dedicated to extension proposals for the study of transition risks. Its results clearly calls for taking the heterogeneity of financial agents seriously in modelling the financial sector. They also cast some doubts on their ability to foresee future transition developments and develop “climate sentiments”. Existing policies, although they have led to a reduction in exposures for some agents, have not led to an outright disengagement of the financial sector. Hence the need for preventive policies, able to palliate the deficiencies of the financial sector in accounting for transition developments. Chapter 6 offers a tentative exploration of a radical policy with this precise aim.

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Appendices

A. Categorical Variables

A.1. Sector and Geographical Distribution of 101-500 companies

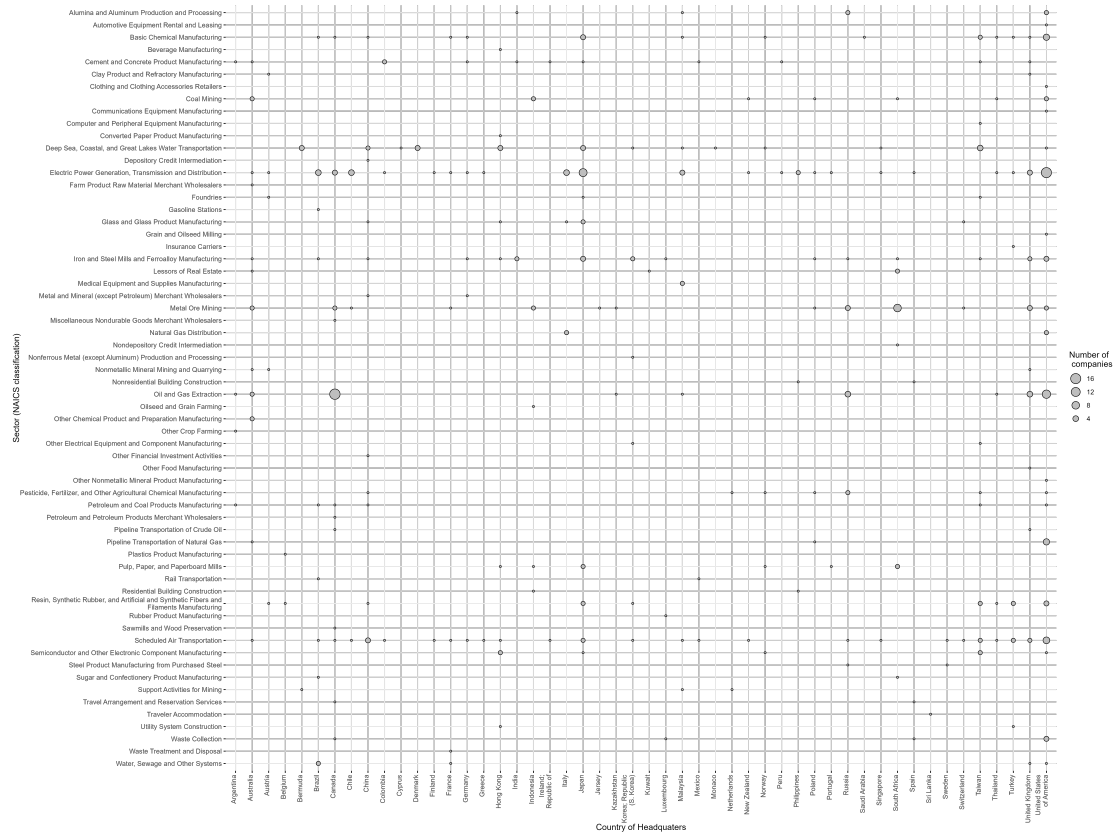


Figure A.1.1: Sectoral and geographical distribution of 101-500 companies. Bubble size corresponds to the number of companies.

A.2. Description of Investor Types

Table A.2.1: Description of Investor Types

Investor Type	Description	Regulatory oversight	Potential <i>vis-à-vis</i> Systemic Risk
Bank and Trust	Deposit-taking institutions providing credit and diversifying their portfolio into equity or other tradables	Very High (Capital ratios, reserve requirements, etc.)	Variable, depends on bank type and size and reactivity of monetary authorities
Closed-End Fund	Asset manager with fixed capital and unit number, with no redemption possibility, and whose shares are traded on financial markets. Active management strategies and low trading frequency	High (Leverage limitations, protection of subscribers)	Low
Corporations	Non-Financial agents with financial investments (cross-ownerships, subsidiary interests, etc.)	Irr.	Low
Endowment Fund	Non-profit organisations with financial interests used to fund charity missions	High	Low
Exchange-Traded Fund	Asset manager with variable capital and unit number, redemption possibility whose shares are traded on financial markets. Usually passive management strategies	High	Possibly high (But lack of historical evidence)
Foundation	Philanthropic bodies with financial interests	Irr.	Low
Government Agencies	Public bodies owning companies, notably utilities	Irr.	Low, but could translate into sovereign risks
Hedge Fund	Limited partnership between private investors with funds managed by professionals with a wide range of strategies. Seek above-average returns	Low	Very high
Holding Company	Non-financial company gathering ownership in several companies to actively manage them	Irr.	Low
Individual Investor	Direct equity owners	Irr.	Low
Insurance Company	Companies offering risk coverage in exchange for annuities. Allowed to invest collected money to generate profits. Look for safe investments ensuring regular flows	High	Low in principle, can become systemic due to increasing common exposures
Investment Advisor	Individual providing investment guidance and possibly directly managing investors' placements	High (from a certain portfolio size onwards)	Low
Investment Advisor/Hedge Fund	Hybrid category when, under some jurisdictions, hedge funds must register as investment advisors	Low	High
Investment Trust	Asset manager with a stated expiration date, and whose units are not traded on the market	High	Low
Mutual Funds	Open-ended asset manager with redeemable units, and with part of their units traded on financial markets, but with limits on when they can be traded	High	Medium
Pension Fund	Asset manager pooling money against payment when the customer retires. Typically invest in long-run, safe investments	High	Low (But high for retirees)
Private Equity	Company buying companies to actively manage other companies before selling them at a premium	High	Low
Research Firm	Companies offering analyses to their customers, with sometimes financial interests	Irr.	Low
Sovereign Wealth Fund	Public body pooling money from citizens to invest it on financial markets, usually to fund pensions	Irr.	Low, but can increase sovereign risk
Venture Capital	Company funding young and innovative companies with high-risk profiles	Irr.	Low

A.3. Definition of regional groupings

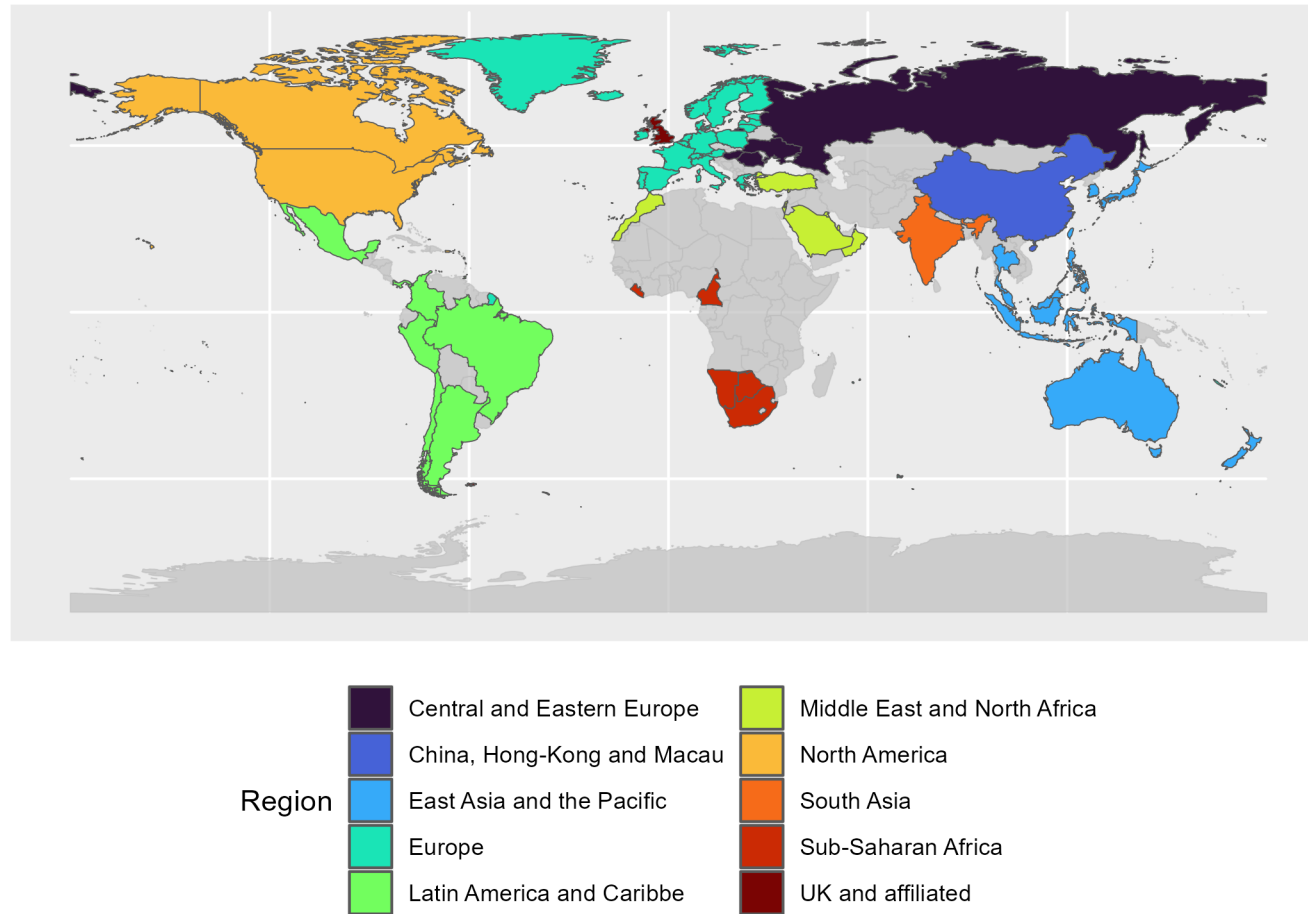


Figure A.3.1: Definition of regional groupings. Grey countries are absent from the sample.

B. Post-hoc analyses - Main Results

B.1. Region-Type interactions

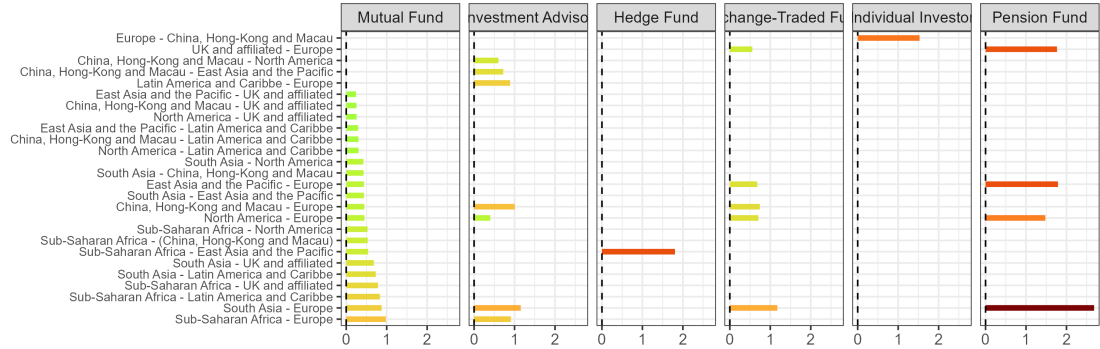
This Appendix develops the *post hoc* analysis. A first set of results is displayed in Figure B.1.1, which shows contrasts across agent categories while keeping the attribute constant. Note that contrasts are reported on the log-odd scale and that all contrasts were rendered positive for readability.

Panel (a) keeps Regions constant and compares agent types within a regional unit. It thus gives a picture of the heterogeneity of investment strategies for a given region. Overall, the largest deviations are Pension Funds, which exhibit the strongest relative biases when they are significant in the UK, Latin America and East-Asia and Pacific. In the latter, Mutual Funds also stand out as positively biased. In Europe, ETFs stand out as the agents with the greatest deviations from others, notably Mutual Funds and Investment Advisors. Finally, in North America, asset managers have increased their exposures relatively more than Individual Investors and Banks and Trusts.

Panel (b) keeps Types constant and thus highlights differences for the same agent type across regions. Here, the number of significant deviations is much higher, suggesting that contrasts are rather found across regions for the same category of agents. This Panel broadly confirms the result of Figure 9 by highlighting that significant differences are mostly found amongst financial agents, and notably investment funds. Most notably, Chinese, South Asia and North American mutual funds systematically exhibit positive deviations from other areas. Except for North America, this pattern reproduces for ETFs, while Latin America exhibits positive deviations for Investment Advisors. Finally, Pension Fund deviations are mostly due to Northern countries.

Remains to discuss comparisons across Region-Type pairs themselves, without fixing one of the two aspects. Given the high number of categories across the two variables, the around 110 significant contrasts cannot be displayed in full. To still offer insights on pairwise comparisons, I synthesise information as follows. Taking a given regions,

(a) Type Fixed



(b) Region Fixed

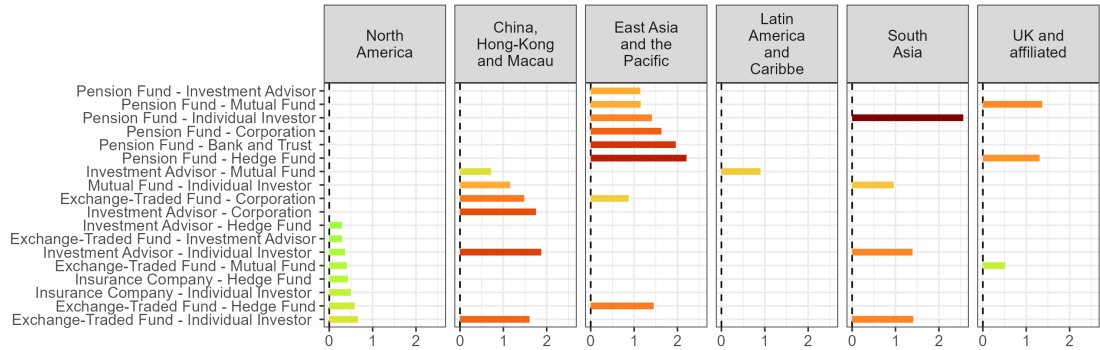


Figure B.1.1: Post-hoc analysis – Comparison of investor categories with one attribute fixed. In Panel (a), Region is fixed, and agent types are compared within a given Region. In Panel (b), Investment type is fixed, and the same Investment type is contrasted across regions. Only significant contrasts at 95% are reported. Deviations are reported on log scale, from the reference category, showing on the left-hand side.

I consider all contrasts it is involved in and transform them such that the financial agents of this region is on the left-hand side of the comparison. I then compute share proportion of positive estimates among those. I do the same exercise for each investor type. Results show in Figure B.1.2.

This approach clearly shows that Sub-Saharan Africa clearly stands apart, with 95% of its significant contrasts being positive. Other areas, on the other hands, show a relative homogeneity in their share of positive contrasts, which suggests a significant heterogeneity across Region-Type pairs in their behaviour towards the Top 100. Europe also stands aside with no positive contrast, further confirming its position as main withdrawing area. Regarding investor type, the behaviour of Pension Funds

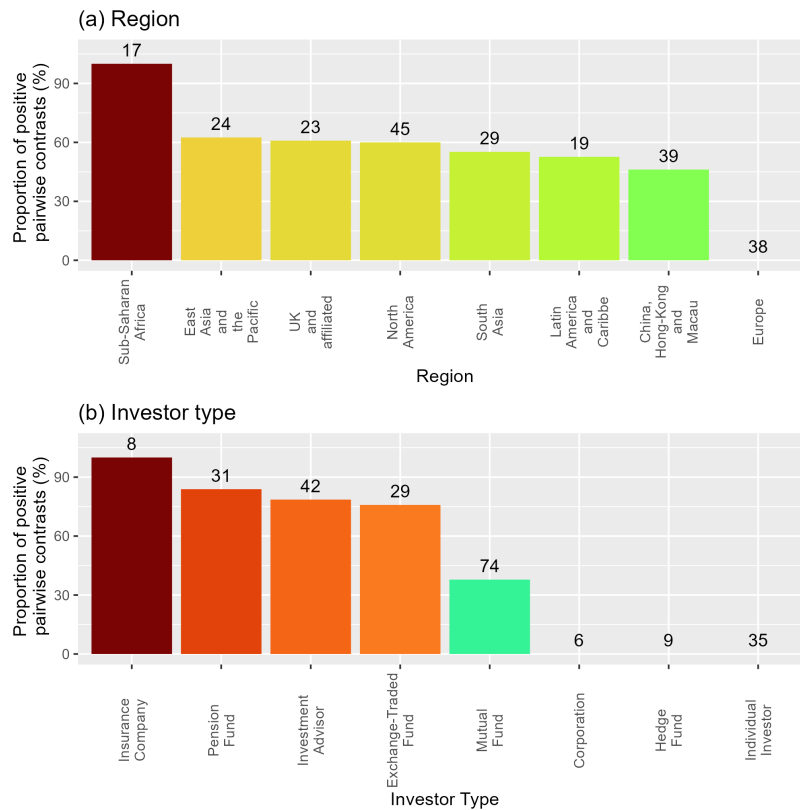


Figure B.1.2: Post-hoc analysis – Comparison of investor categories with both attributes free. The figure gives the proportion of positive contrast (relatively higher propensity to increase exposures) amongst all significant contrasts. Numbers indicate how many contrast involve the given category. Panel (a) compares contrasts across regions, while Panel (b) does so for investor types. *Reading: Within the 17 pairwise comparisons involving Sub-Saharan investors, around 95% are positive. Hence, amongst significant pairs, Sub-Saharan investors exhibit almost systematically a relative bias in favour of increasing exposure to the Top 100.*

and Investor Advisors is confirmed, while Insurance companies rank highest. To provide a sense of the magnitude of underlying deviations, Figure B.1.3 closes this discussion by showing the twenty highest absolute contrasts. South Asia, East Asia and the UK almost fill the ranking. Pension Funds, in general show the greatest positive deviations, especially compared to Hedge Funds, Corporations and Individual Investors. By contrast, Insurance companies do not show any deviation in the top-20, suggesting that although they stand higher than most of their comparands, spreads are relatively small.

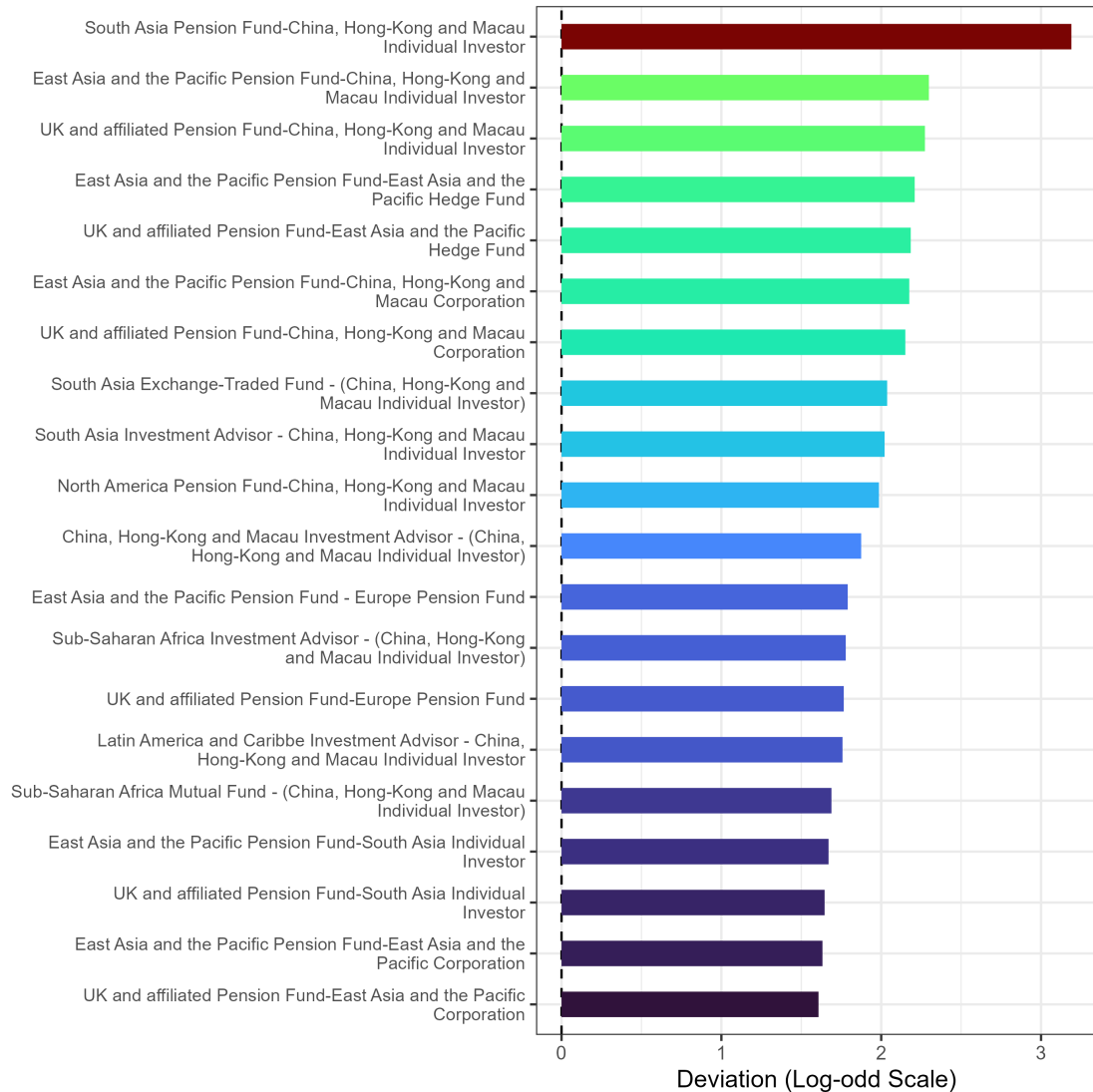


Figure B.1.3: 20 largest contrasts. Deviations are reported on a log scale. Contrasts were normalised to be positive by changing comparands when relevant. *Reading: The contrast between South Asian Pension Funds and Chinese Individual investors amounts to 3 log-odd units, which amounts to an around 60% greater probability.*

B.2. Portfolio size interactions

This Appendix shows the *post hoc* analysis for the interactions between Portfolio Quartiles and Regions, then between Portfolio Quartiles and Investor types. I first study results with one of the two categories fixed, then with both categories fixed.

Starting with the Region-Quartile interaction, Figure B.2.1 shows contrasts with one of the two categories fixed. Panel (a) clearly highlight important differences across regions, mostly driven by developing countries. While East-Asia and the Pacific, China and South Asia exhibit the highest relative biases for the first two quartiles, Latin America and South Asia drive the differences across investors with the largest portfolios. However, these differences emerge mostly in comparisons with other Global South Countries. It suggests that large investors from these two regions exhibit similar behaviours to large investors in the Global North – except for Europe, which always compares negatively.

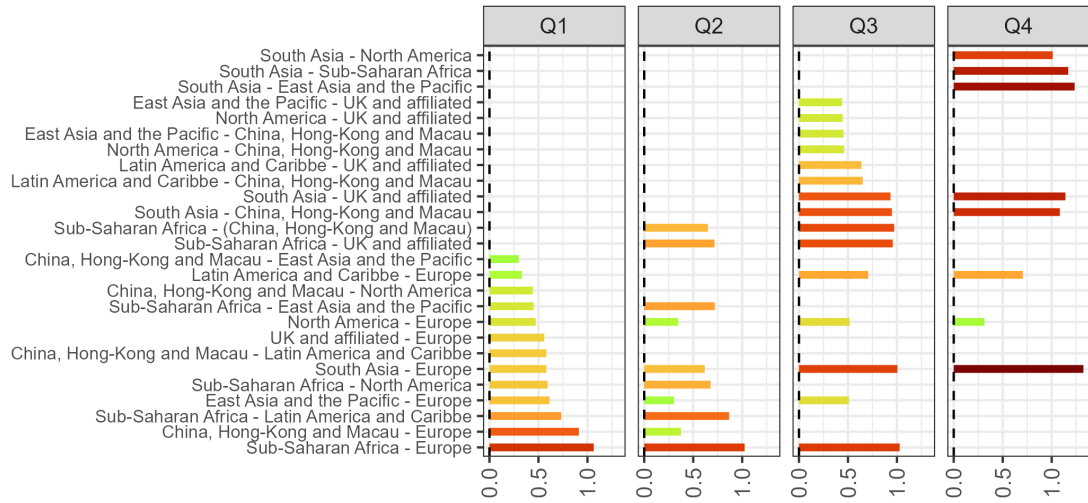
Conversely, with fixed Regions, results confirm the patterns shown in Figure 10, notably in showing the large differences existing between small and large investors in most regions of the world.

Finally, the study of contrasts with the two dimensions free show yields results consistent with those discussed in Section 5, Sub-Saharan Africa and the last quartile of the distribution ranking highest.

Type-Quartile contrasts with one of the two attributes fixed are displayed in Figure B.2.3. Across quartiles, biases are driven by Pension Funds, Exchange-Traded Funds and Mutual Funds, mostly compared to Individual Investors, Hedge funds and Insurance Companies. For Q4, only comparisons with Corporations are significant, highlighting the homogeneity of behaviours within the largest portfolios. Fixed-quarterly contrasts are consistent with estimated probabilities in showing either a positive correlation within investment types or a non-linear one, like for Mutual Funds.

Regarding pairwise comparisons, again, most of the positive biases are to be found amongst small investors. Furthermore, Pension Funds and ETFs show the greatest positive bias, consistently with results from the Region-Type interaction.

(a) Portfolio Fixed



(b) Region Fixed

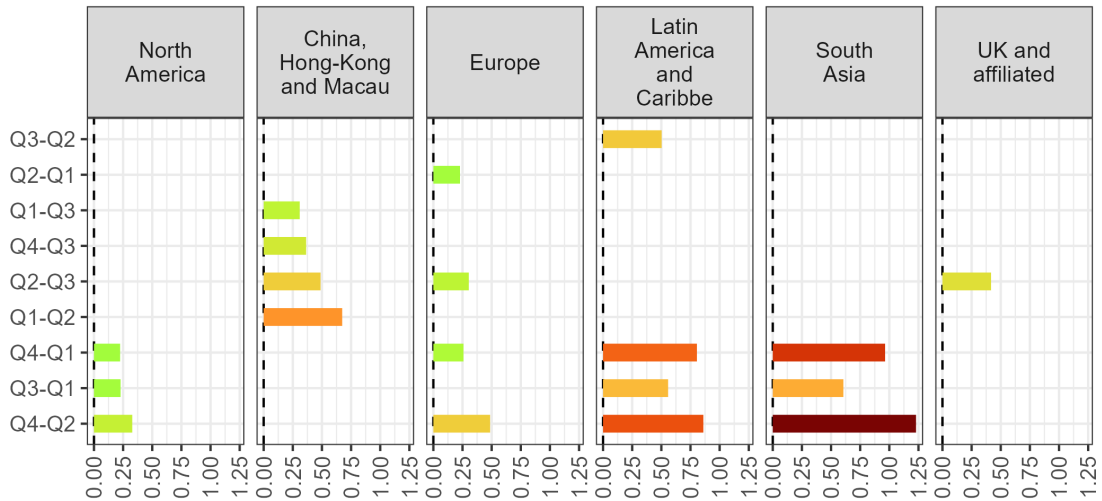


Figure B.2.1: Post-hoc analysis – Comparison of investor categories with one attribute fixed – Region-Size Model. In Panel (a), Portfolio Quartile is fixed and Regions are compared within a given Quartile. In Panel (b), Region is fixed and the same Portfolio Quartile is contrasted across Regions. Only contrasts significant at 95% are reported. Deviations are reported on log scale, from the reference category, showing on the left-hand side.

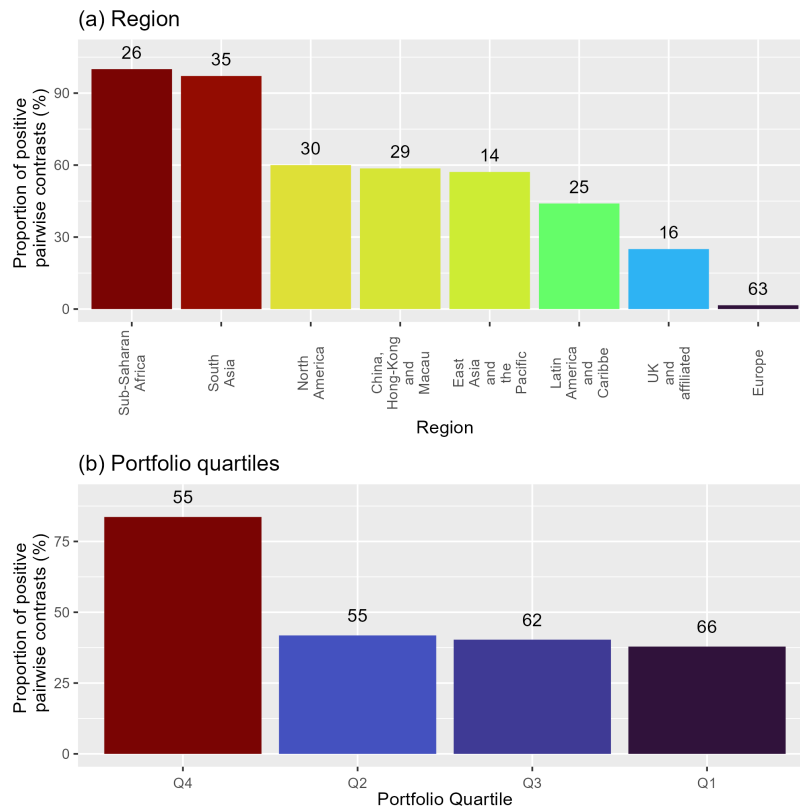
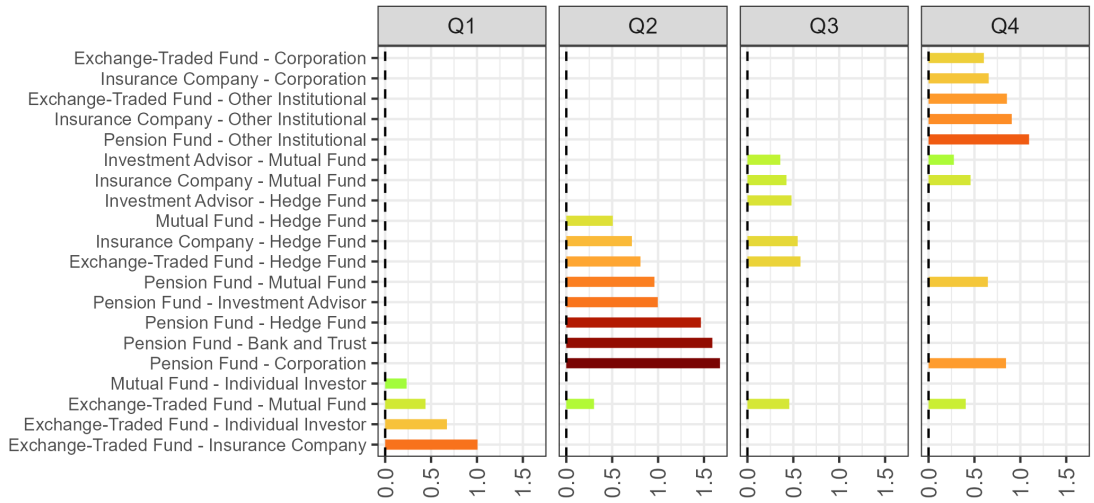


Figure B.2.2: Post-hoc analysis – Comparison of investor categories with both attributes free textendash Region-Size Model. The figure gives the proportion of positive contrast (relatively higher propensity to increase exposures) amongst all significant contrasts. Numbers indicate how many contrast involve the given category. Panel (a) compares contrasts across investor types, while Panel (b) does so for portfolio quartiles. *Reading: Within the 26 pairwise comparisons involving Sub-Saharan investors, around 95% are positive. Hence, amongst significant pairs, Sub-Saharan investors exhibit almost systematically a relative bias in favour of increasing exposure to the Top 100.*

(a) Portfolio Fixed



(b) Type Fixed

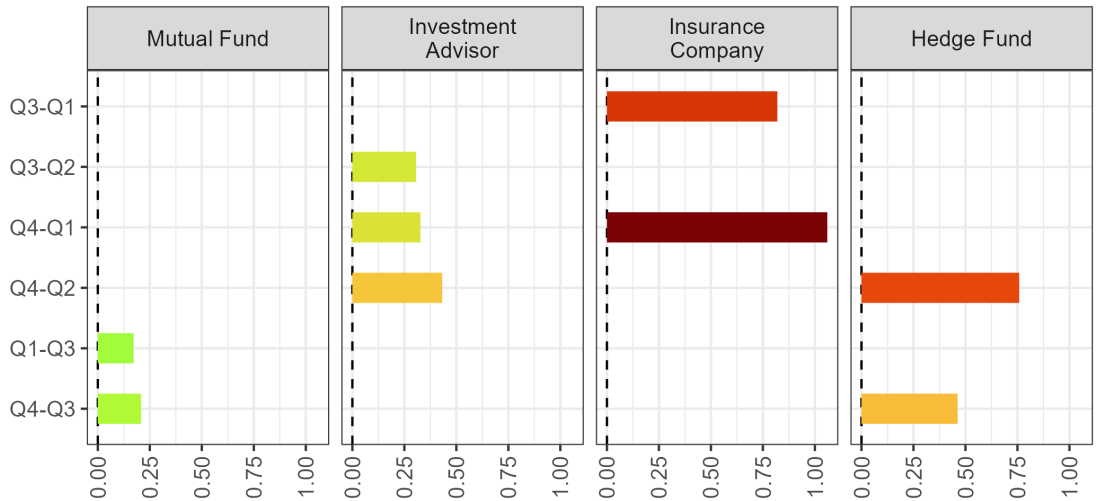


Figure B.2.3: Post-hoc analysis – Comparison of investor categories with one attribute fixed – Type-Size Model. In Panel (a), Portfolio Quartile is fixed and Types are compared within a given Quartile. In Panel (b), Type is fixed and the same Portfolio Quartiles is contrasted across Types. Only significant contrasts at 95% are reported. Deviations are reported on log scale, from the reference category, showing on the left-hand side.

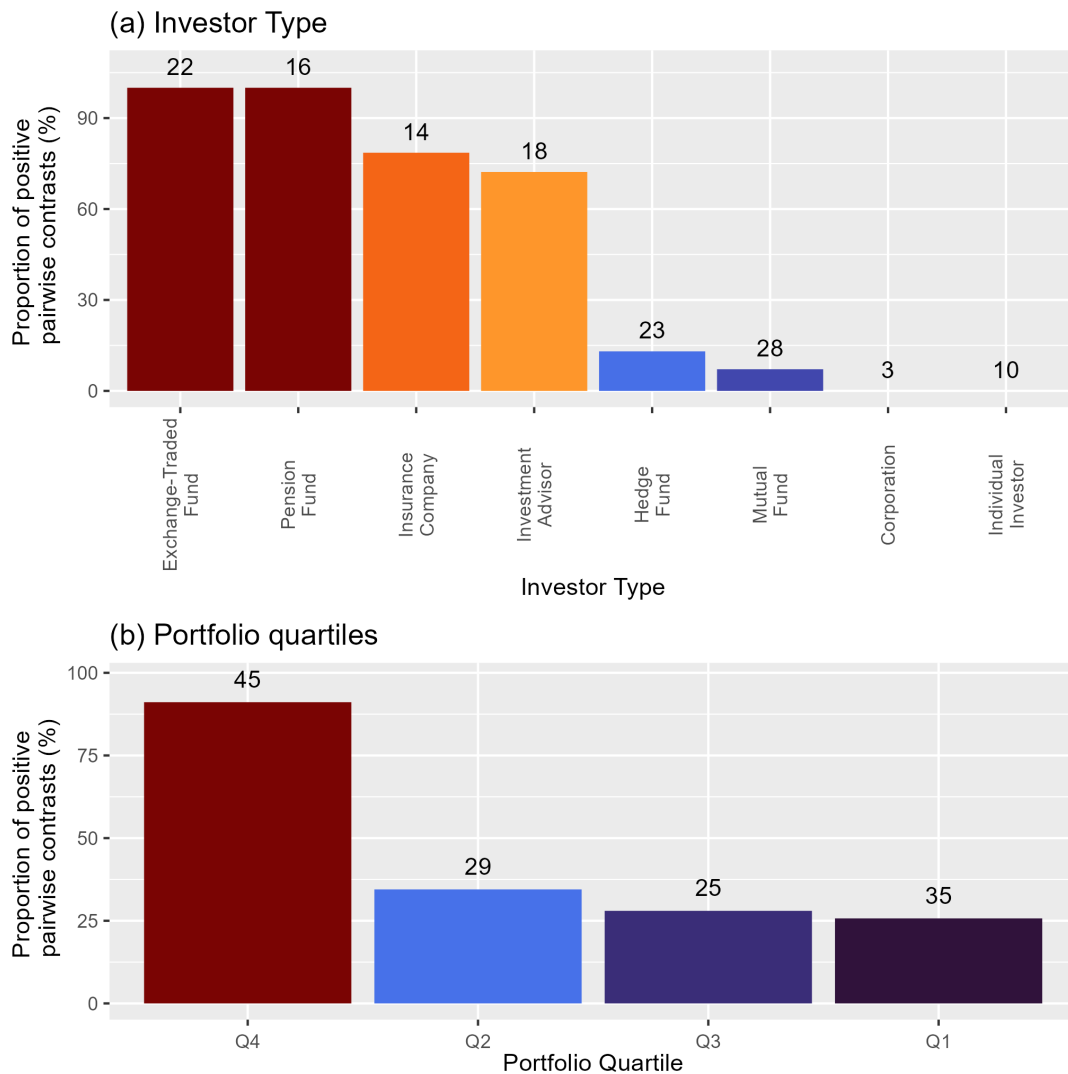


Figure B.2.4: Post-hoc analysis – Comparison of investor categories with both attributes free – Type-Size Model. The figure gives the proportion of positive contrast (relatively higher propensity to increase exposures) amongst all significant contrasts. Numbers indicate how many contrast involve the given category. *Reading: Within the 22 pairwise comparisons involving Exchange-Traded Funds, around 95% are positive. Hence, amongst significant pairs, ETFs exhibit almost systematically a relative bias in favour of increasing exposure to the Top 100.*

C. Supplemental results

C.1. Results - Evolution of weight in total shares outstanding

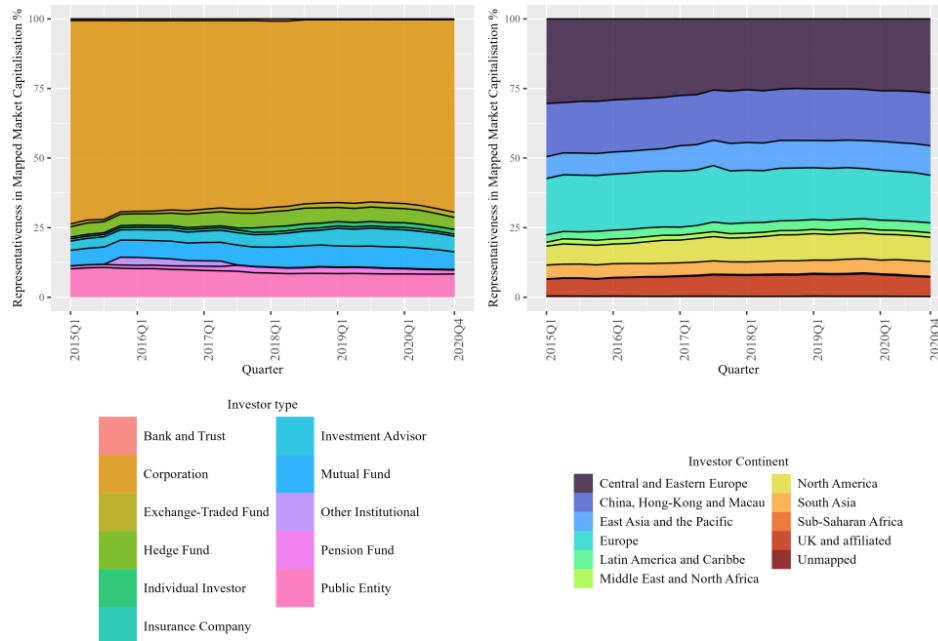


Figure C.1.1: Evolution of representativeness of regions and investor types in Top 100 emitters (2015-2020) – Shares Outstanding. The “Other Funds” category groups investors classified as funds but whose precise type is not mentioned (Investors in this category did not appear within the Top-100)

Figure C.1.1 reports the evolution of Types’ and Regions’ representativeness in total shares outstanding of the Top 100. As can be seen, there is an important heterogeneity in terms of number of shares across countries, which indicates that some regions hold shares with higher price son average. It is notably the case of core financial sectors. The same goes for investor types, with corporations holding many shares, but with likely a lower market value. The representativeness in total share outstanding provides a complementary picture of market capitalisation, since it gives how the actual positions of agents have evolved. It therefore controls for possible price effects, whereby an increase in company valuation would artificially inflate the

representativeness of some agents. Here, results are in line with with Figure 7, by showing the progresses of investment funds and of Anglo-Saxon financial systems. It also confirms the relative withdrawal of Europe and other world regions. Note, however, that the trend seems to reverse by the end of the sample. It is explainable by the Covid shock, which probably witnessed a greater involvement of public authorities or public firms in the ownership of highly polluting companies, for instance through bailouts or transitory steering.

C.2. Results – Evolution of weights in market capitalisation – Top101-500

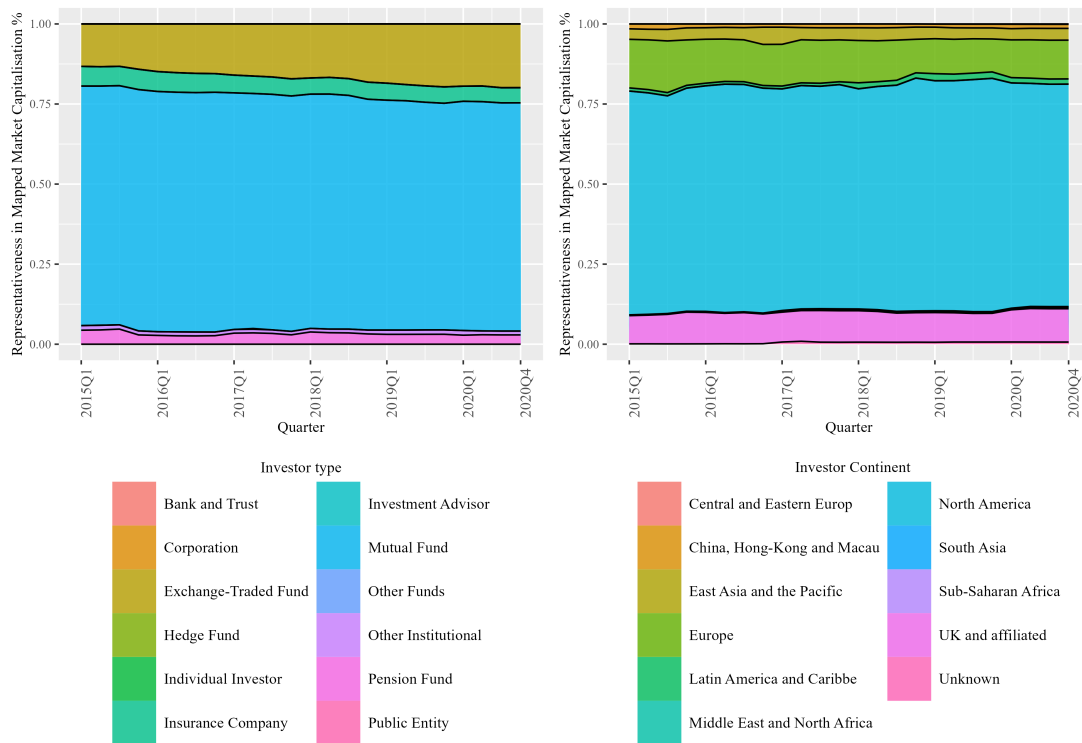


Figure C.2.1: Evolution of representativeness of regions and investor types in top-101-500 emitters (2015-2020) – Market Capitalisation

Figure C.2.1 displays the evolution the evolution of Types' and Regions' representativeness in the market capitalisation of the 101-500 GHG-intensive companies. As sketched in the body of the text, shares are strikingly much more stable. While ETFs unmistakably progress, it is only at the expense of mutual funds, which show a relative withdrawal. Regarding world regions, shares display a remarkable stability, with a slight increase of the importance of North American investors. These patterns contrast significantly with those found for the Top-100.

C.3. Results – Interactions – Alternative start and end date

In this Appendix, I display the results for the Region-Type interaction model with alternative starts and end dates. Regression results are shown in Table C.3.1. For brevity, I focus on logit estimates and predicted probabilities.

As can be seen, coefficients for non-interacted effects are stable *vis-à-vis* those shown with the non-interacted model in Table 5. However, significant interactions differ from those of Table 4. Only Sub-Saharan ETFs and East-Asian Investment Advisors remain, while other interactions become significant. This is hardly surprising given the shift in log odds documented in Table 5, which implies that some interactions will exhibit more significant deviations from the reference, which has moved. However, these changes hardly affect the picture of estimated probabilities. As shown in Figure C.3.1, only a few Region-Type couples exhibit large differences from the initial odds shown in Figure 9. This notably includes US and Latin American pension Funds and Chinese ETFs. Nevertheless, overall, the structure of relative odds remains stable across Region-Type couples.

Table C.3.1: Determinants of Investors' Probability to increase exposures to the Top 100 GHG-intensive firms (2016Q1-2020Q4) – Interaction Model

	<i>Dependent variable:</i>	
	Inc.Exp. Top 100	
China, Hong Kong and Macau	-0.364***	(0.053)
East Asia and Pacific	0.105*	(0.060)
Europe	-0.251***	(0.047)
Latin America and Caribbe	0.372***	(0.071)
South Asia	0.803***	(0.095)
Sub-Saharan Africa	0.379***	(0.102)
UK and affiliated	-0.129**	(0.065)
Investment Advisor	0.228***	(0.051)
Hedge Fund	-0.316***	(0.074)
Corporation	-0.494*	(0.260)
Exchange-Traded Fund	0.430***	(0.069)
China Hong and Macau Investment Advisor	0.498***	(0.152)
East Asia and Pacific Investment Advisor	-0.480***	(0.143)
South Asia Investment Advisor	-0.605*	(0.323)
Europe Hedge Fund	0.701***	(0.201)
Latin America and Caribbe Corporation	-1.384*	(0.809)
China, Hong Kong and Macau Exchange-Traded Fund	0.964***	(0.193)
Europe Exchange-Traded Fund	-0.317**	(0.128)
Sub-Saharan Africa Exchange-Traded Fund	-1.169***	(0.391)
UK and affiliated Exchange-Traded Fund	-0.266*	(0.157)
Constant	-0.286***	(0.034)
Observations	27,107	
Log Likelihood	-18,094.490	
Akaike Inf. Crit.	36,360.970	

Note: *p<0.1; **p<0.05; ***p<0.01

Only statistically significant coefficients are displayed.

The reference category is the intersection of all reference categories.

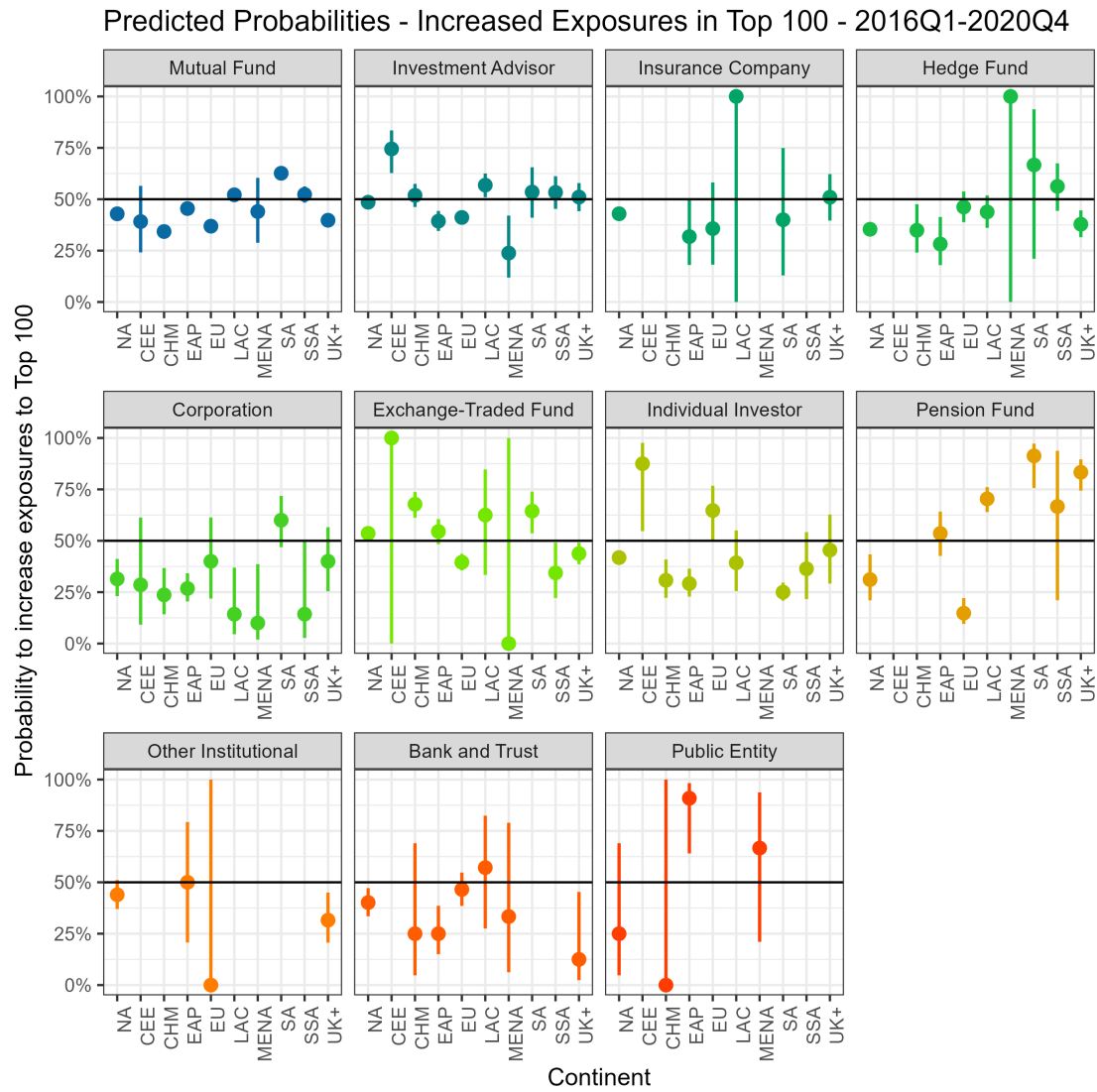


Figure C.3.1: Predicted probabilities – Interaction model – Alternative Start and end dates – Reported confidence intervals are at 90%. The horizontal black line shows the 50% probability. Non-appearing points are interactions not appearing in the data.

C.4. Results – Interactions Including transient investors

This Appendix is dedicated to discussing estimated probabilities and run the *post hoc* analysis for the robustness specification excluding transient investors from the base regression.

Figure C.4.1 reports estimated probabilities for this specification. Results contrast from those including transient investors, notably through a general upward shift of estimated probabilities. This is because, as mentioned in the main body of the text, adding transient investors adds a mass of zeros of the outcome variable. Confidence intervals are roughly the same and most probabilities are now above the 50% threshold, notably Mutual Funds and Exchange-Traded Funds. It suggests that these categories comprise many transient investors. In general, European investors show a clear disengagement from the Top 100 when transient investors are included. Furthermore, Compared to baseline results, Latin America exhibits a much more upward-biased behaviour, henceforth suggesting that this region is characterised by a large population of transient investors. Finally, European investors exhibit a positive bias most of the time, sometimes higher than other countries. It clearly suggests that the downward bias of European investors was due to transient investors and that most non-transient investors in Europe reacted negatively to policies and policy discussions during the late 2010. These non-transient investors are mostly found amongst ETFs and Hedge Funds.

Figure C.4.2 shows the contrast across one categorical variable while keeping the other fixed. While Panel (a) exhibits a similar pattern to those found with the baseline specification, cross-region comparisons are much more different and also higher in magnitude. It confirms that transient investors are not homogeneously distributed across world regions. However, except for the appearance of Latin America in the most positively biased, the results clearly show that Global South Countries concentrate significant positive contrasts, with only North America being significantly different from Europe for Mutual Funds and Investment Advisors. As a result, despite changes in results, the relative structure of behaviours remains broadly unchanged,

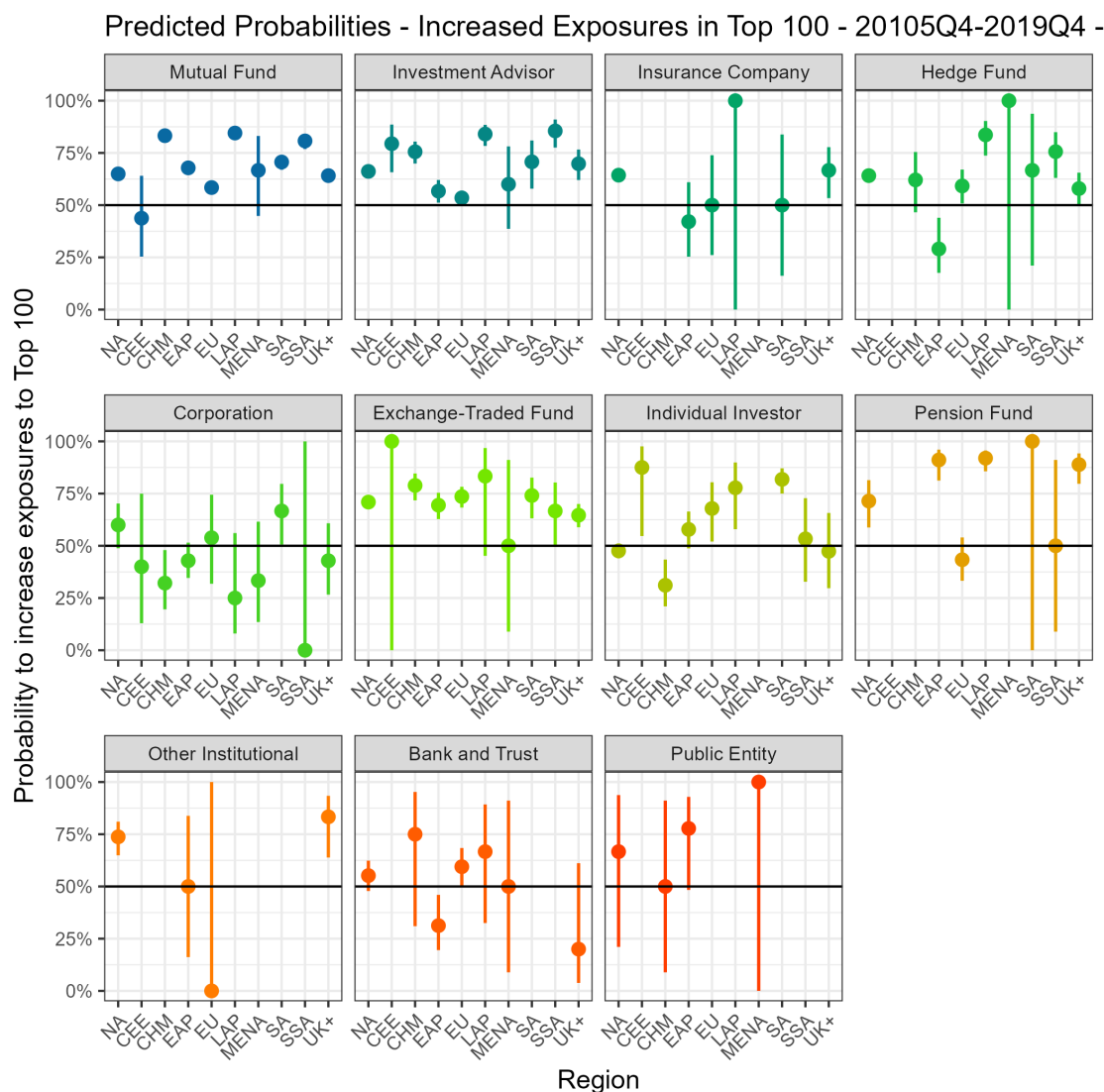


Figure C.4.1: Predicted probabilities – Interaction model – Transient investors excluded – Reported confidence intervals are at 90%. The horizontal black line shows the 50% probability. Non-appearing points are interactions not appearing in the data.

if not for the more upward bias of Latin America and a general increase in contrast magnitudes.

Figure C.4.3 displays estimated probabilities for the Region-Size Quartile interaction, while Figure C.4.3 displays those for Type-Size Quartile one. They both clearly show that the relationship between size and the probability of increasing exposures is

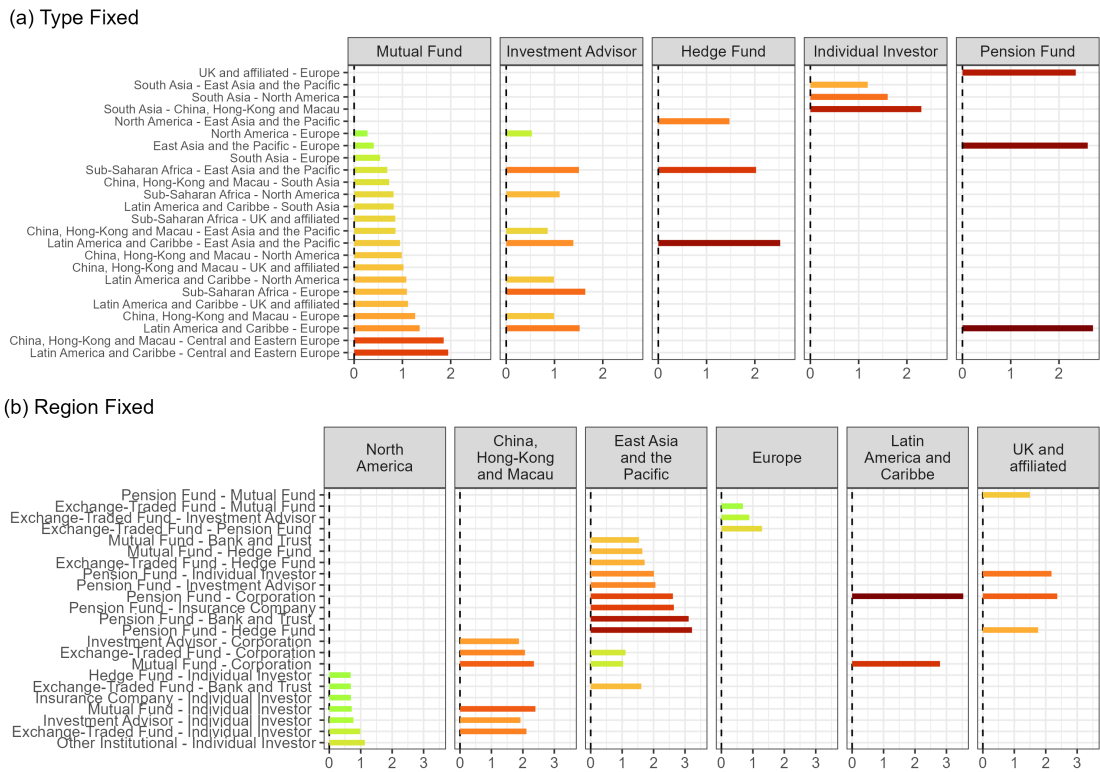


Figure C.4.2: Post-hoc analysis – Comparison of investor categories with one attribute fixed – Transient Investors Excluded. In Panel (a), Region is fixed and agent types are compared within a given Region. In Panel (b), Investment type is fixed and the same Investment type is contrasted across regions. Only significant contrasts at 95% are reported. Deviations are reported on log scale, from the reference category, showing on the left-hand side.

reversed for non-transient investors. It confirms that transient investors are concentrated amongst small portfolios, except in China and, to a lesser extent, Sub-Saharan Africa. This pattern is generalised across investor types. These results show the greater stickiness of exposure management on the part of larger institutions, which tend to exhibit longer-term commitments than institutions in the lower parts of the distribution. Conversely, smaller institutions exhibit short-term strategies, which may take the form of higher or lower exposures to the Top 100. Although this makes for a greater reactivity to changes in expectations or to a tightening of climate policies, it could also suggest more opportunistic behaviours from these investors, which may revert to their high-carbon investments if need be, although the post-Covid period

was not characterised by such patterns (Gourdel and Sydow 2022; IMF 2021).

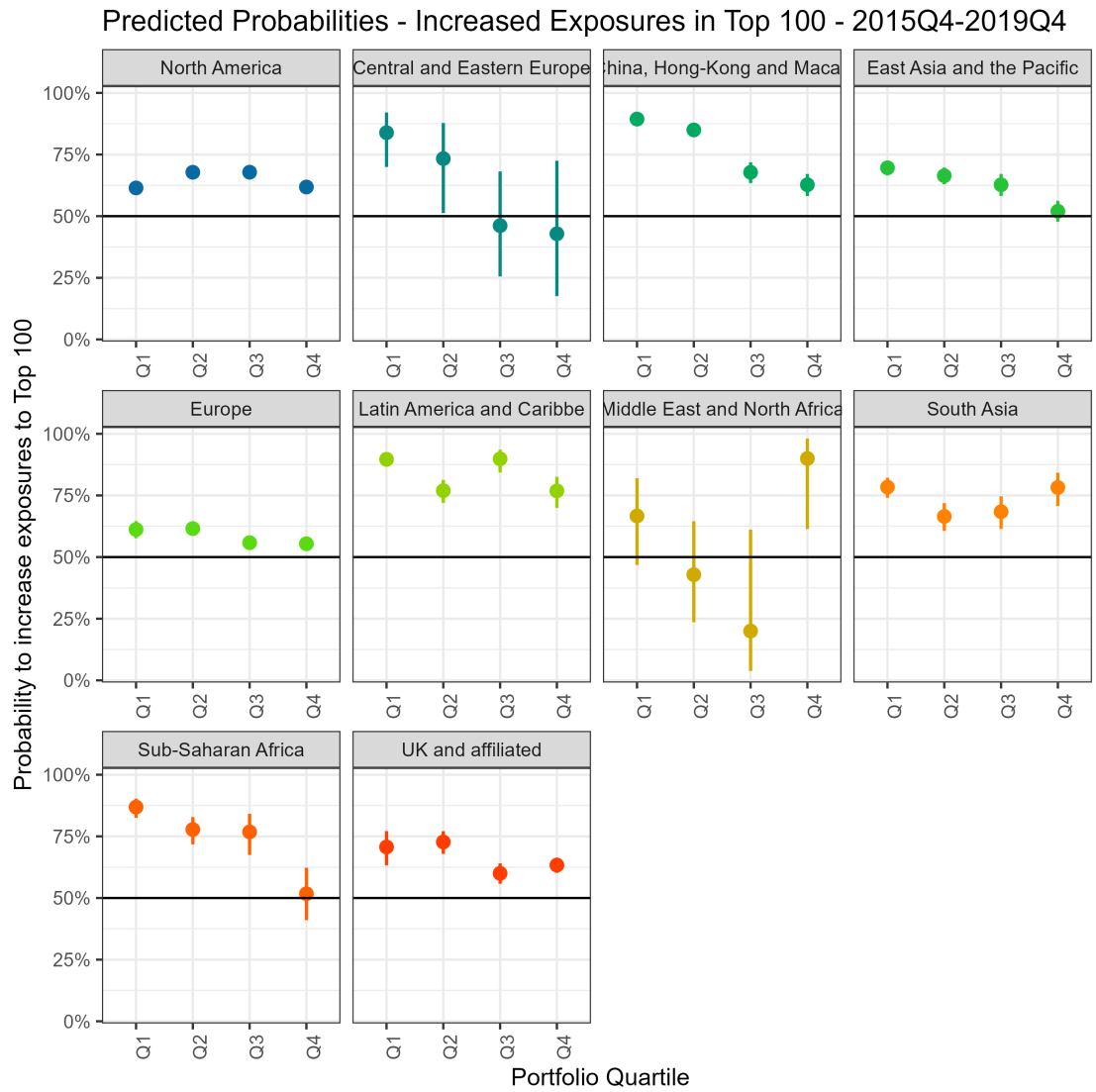


Figure C.4.3: Predicted probabilities – Interaction model – Transient investors excluded – Reported confidence intervals are at 90%. The horizontal black line shows the 50% probability. Non-appearing points are interactions not appearing in the data.

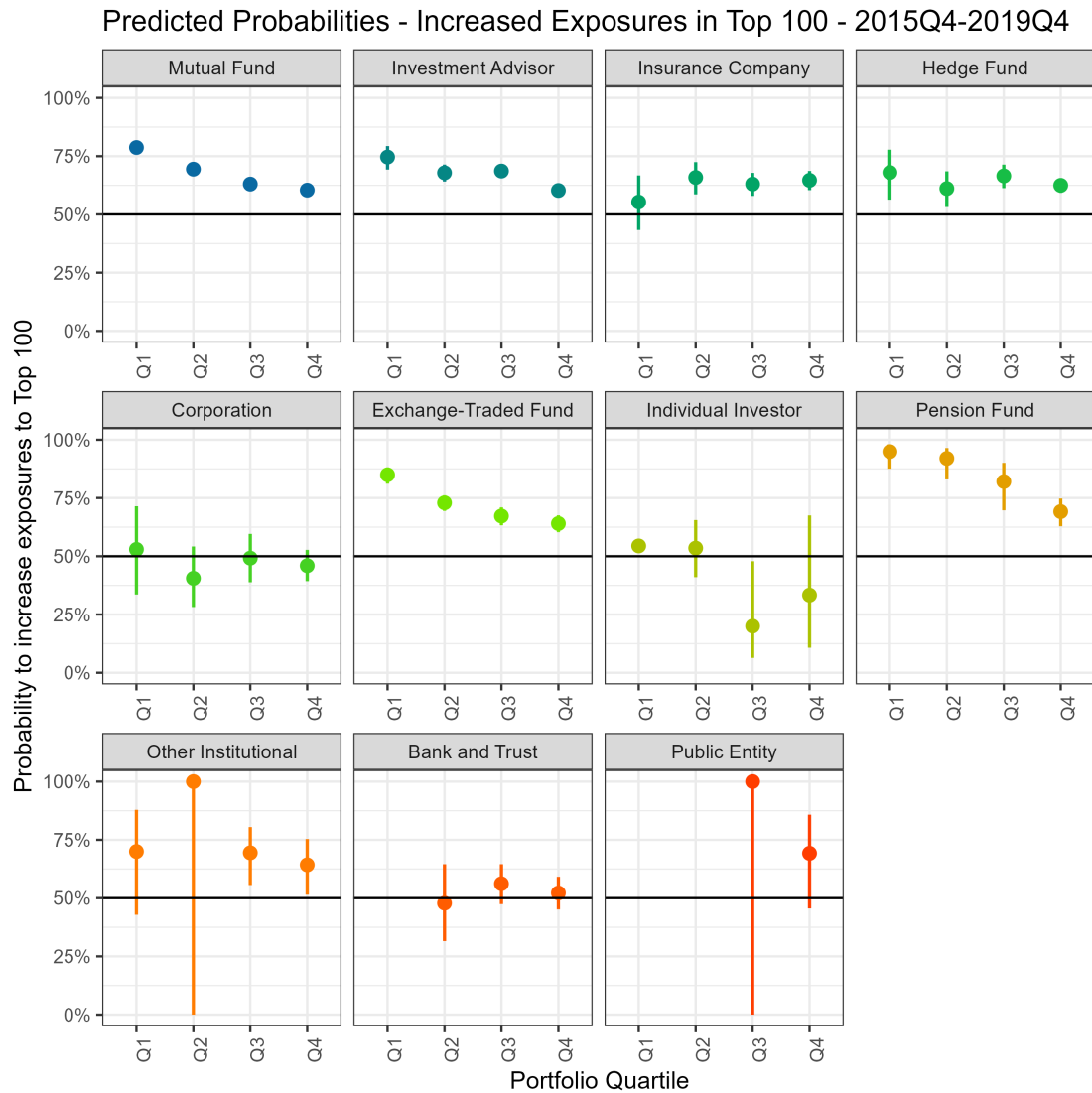


Figure C.4.4: Predicted probabilities – Interaction model – Transient investors excluded – Type-Size Model – Reported confidence intervals are at 90%. The horizontal black line shows the 50% probability. Non-appearing points are interactions not appearing in the data.

C.5. Results - Investment in 101-500

In this Appendix, I check whether exposures to the Top 100 were compensated by rebalancing portfolios favouring less GHG-intensive companies. I then build a similar indicator variable to $l_{i,Top100,2015Q4,2019Q4}$, $l_{i,101-500,2015Q4,2019Q4}$ that takes the value one if the investor increased its exposure to the 101th-500th most GHG-intensive companies. Note that I consider the same investors as in the base regression. As a result, investors that do not appear in the ownership structure of the 101-500 were attributed a value of zero since they did not rebalance their portfolios by entering the capital of these companies. I then run the model with Region-Types interactions with this variable and display estimated probabilities – for brevity, I waive the *post hoc* analysis. Results are displayed in Figure C.5.1.

As can be seen, we hardly see a portfolio rebalancing for most investors. Unlike Figure 9, Mutual Funds, Investment Advisors and Hedge Funds exhibit an even lesser propensity to invest in the 101-500 ranking. The only type exhibiting this behaviour are Pension Funds, which increased their exposures to the top 101-500 with roughly the exact probabilities as with the Top 100. More importantly, this need for rebalancing is mainly found in Global South countries, notably China, South Asia and Latin America. Only some European agents, notably ETFs and pension Funds, exhibit patterns consistent with a fully-fledged portfolio rebalancing. Hence, regarding equity exposures, agents have hardly rebalanced their portfolios, notably in China, highlighting heightened transition risk exposures for these agents.

Figures C.5.1 and C.5.2 show results for interactions with portfolio quartiles. As can be seen, the propensity to increase exposures to the 101-500 is primarily concentrated amongst large institutions, almost regardless of the interaction. It suggests that small institutions have mainly maintained or decreased their exposures to the Top 100 to temper possible transition risks without rebalancing their portfolios down the distribution of GHG intensity. Large institutions adopted a distinct strategy, more directed towards portfolio rebalancing.

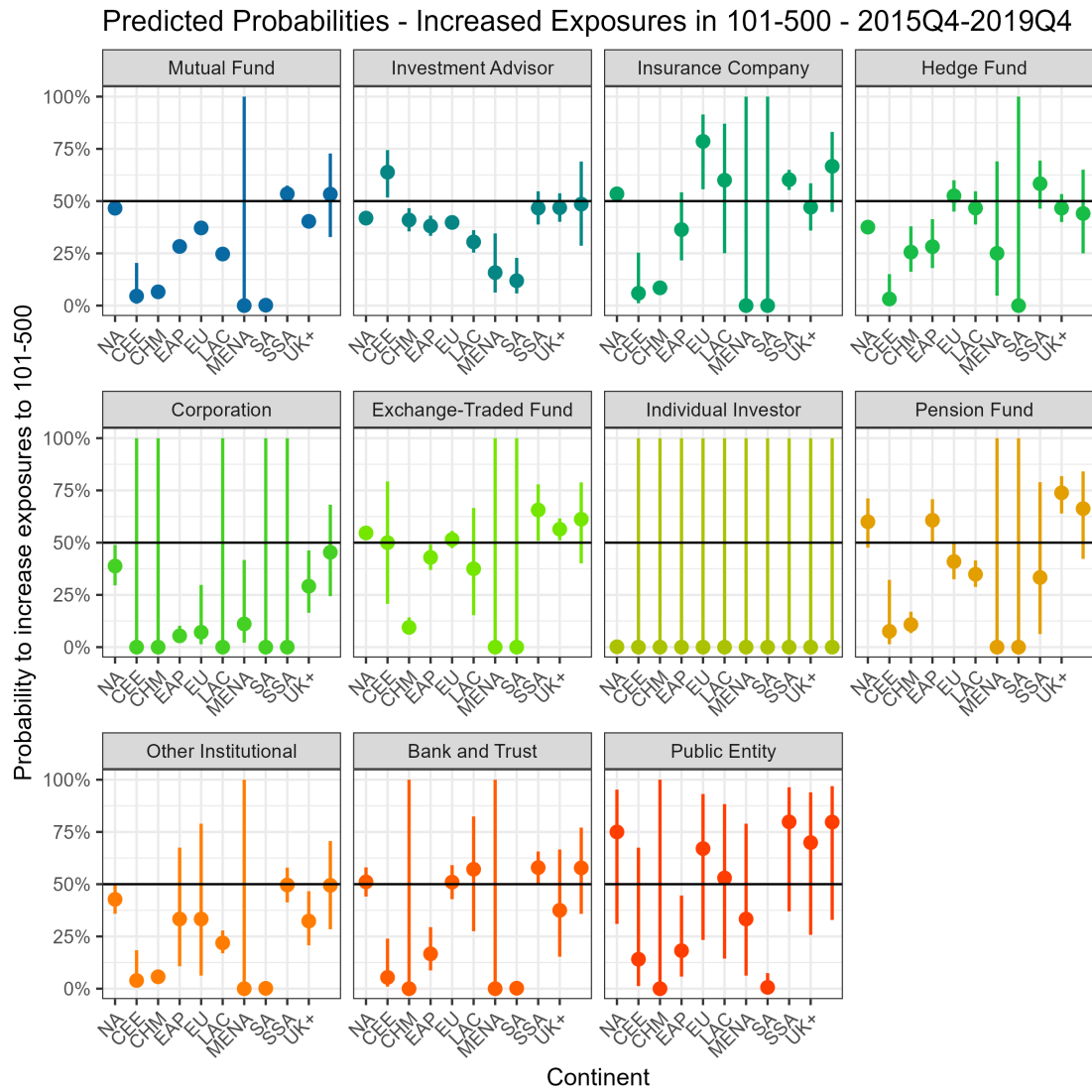


Figure C.5.1: Predicted probabilities – Region-Type Interaction model – 101-500. Reported confidence intervals are at 90%. The horizontal black line shows the 50% probability. Non-appearing points are Region-Type Combinations not appearing in the data.

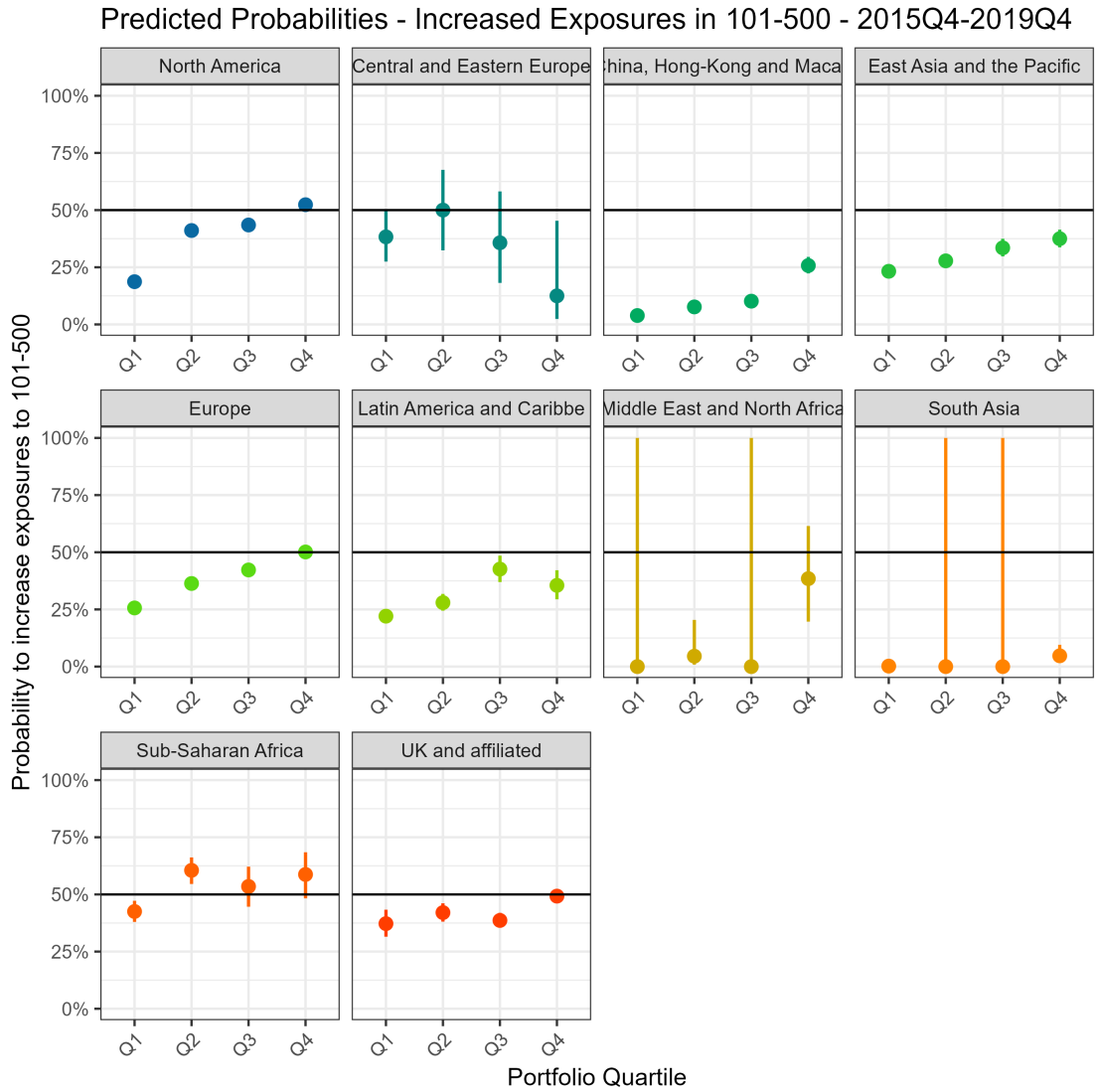


Figure C.5.1: Predicted probabilities – Region-Quartile Interaction model – 101-500. Reported confidence intervals are at 90%. The horizontal black line shows the 50% probability. Non-appearing points are Region-Type Combinations not appearing in the data.

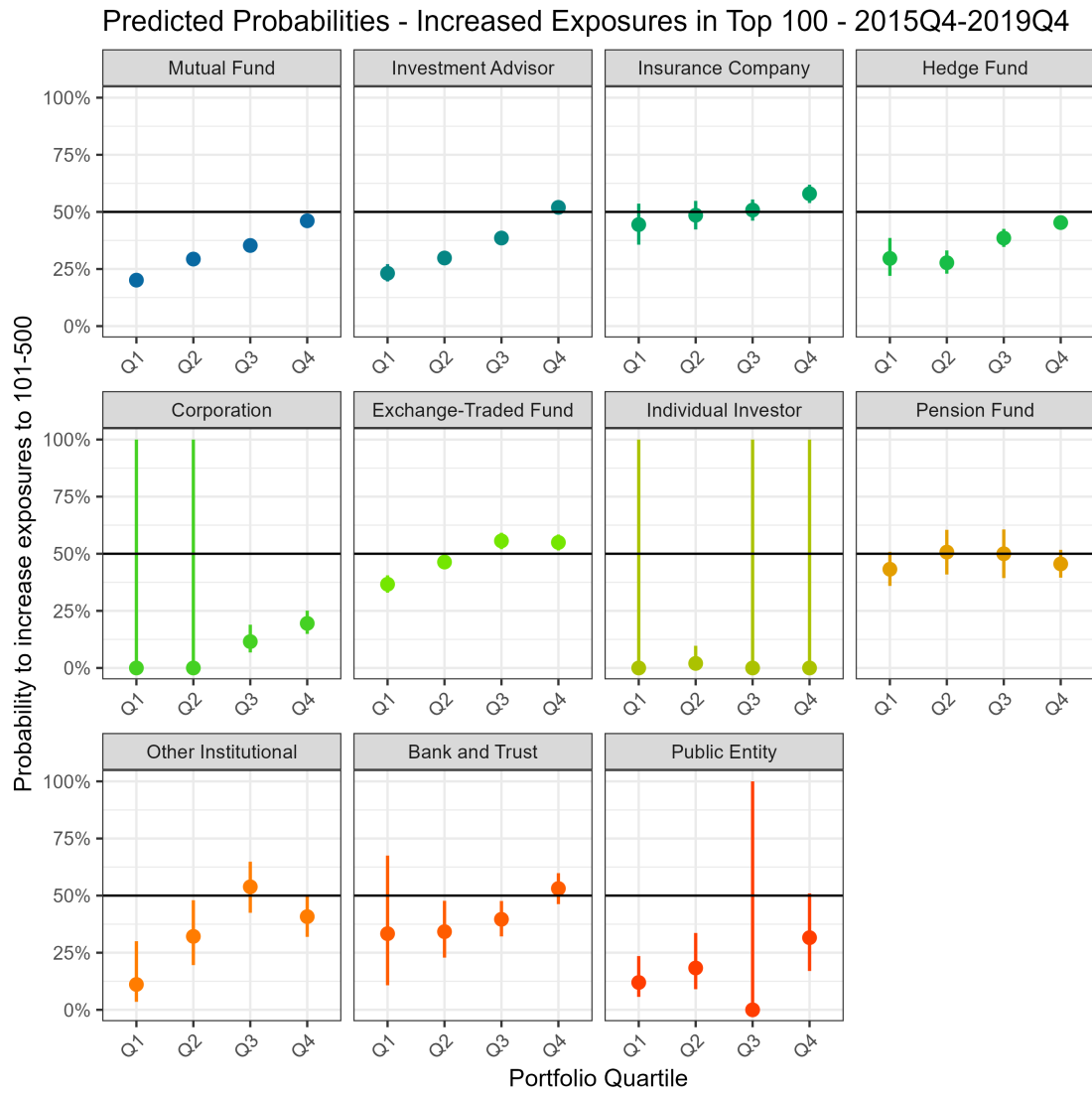


Figure C.5.2: Predicted probabilities - Region-Quartile Interaction model - 101-500. Reported confidence intervals are at 90%. The horizontal black line shows the 50% probability. Non-appearing points are Region-Type Combinations not appearing in the data.

Chapter 6

A Climate Bad Bank to alleviate transition risks?

Exploring an emerging policy proposal

WITH MATHILDE SALIN (CIRED-BANQUE DE FRANCE)

Abstract

Facing the threat of climate change will require a decisive commitment to climate action. However, a rapid shift to a low-carbon economy will bear macro-financial consequences. “Transition risks”, under the form of asset devaluations threatening financial stability, call for policies ensuring the good health of the financial system along transition paths. To this effect, some authors and practitioners have proposed the recourse to “climate bad banks” (CBBs). Similar to past “bad banks”, these institutions would house assets most exposed to transition risks and cleanse the balance sheet of economic agents. It could allow financial institutions to focus on funding low-carbon investments and avoid adverse disturbances in case of asset devaluation. It would also prevent the transfer of transition-exposed assets to less regulated and less solid financial agents. Nevertheless, however attractive, these policy proposals are barely emerging and are yet to be examined in detail. This article proposes a first exploration of this still prospective topic, absent real-world climate bad bank examples. We distinguish three main – intertwined – challenges for such an institution: economic efficiency, justice and governance. After taking stock of historical bad banks, we propose a way to classify their main features and build on this classification to identify the shape a climate bad bank could take.

Key Policy insights:

- A climate bad bank, housing high-carbon assets while the economy decarbonises, could reduce transition risks.
- A climate bad bank would have to face challenges similar to past bad banks’, and some particular to the context of the low-carbon transition.
- The shape of a climate bad bank could vary along six dimensions: its timing of action, whether it is centralised or decentralised, its refinancing mode, how it would manage high-carbon assets, its ownership structure and the incentives it would deploy to ensure efficiency.
- A desirable climate bad bank could be a public-private partnership acting preemptively by buying risky assets and applying an extinctive management approach. It could consist of a multiplicity of well-targeted institutions coordinated by an umbrella entity and buy assets at a time-increasing haircut with respect to book value.

Acknowledgements

The authors are grateful to Céline Guivarch, Etienne Espagne and most of all Christopher Schroeder for helpful feedback and comments. All remaining errors are ours.

Introduction

As made clear by Assessment Report 6 (IPCC 2022a), our window to transition to a low-carbon economy is shrinking by the clock. Immediate, strong and steady climate action is needed to avoid dramatic damage. This transition will bear macroeconomic and financial consequences. Carbon Tracker Initiative (Leaton 2011) emphasised that financial markets overvalue fossil reserves. A solid commitment to climate action may make these resources “stranded”, with possible systemic implications. Others (Caldecott 2018; van der Ploeg and Rezaei 2020a) have prolonged the “stranded asset” notion to physical capital, suggesting that energy and extraction infrastructures could suffer from brisk devaluations. Financial markets may not adequately price transition risks (Bolton and Kacperczyk 2021; Delis, S.-J. Kim, et al. 2021) and may sharply adjust to unexpected changes in low-carbon transition drivers (Thomä and Dupré 2014).

Malfunctioning or crashing financial markets may hamper the course of the low-carbon transition. Besides being burdened with high-risk assets, financiers may shun the funding of low-carbon investments to avoid precipitating losses on dirty investments (Geels 2013; Giraud 2020; Giraud et al. 2021). Finally, the threat of a financial crisis could provide a reason for delaying climate action. Hence, there is a need for a tool to favour financial stability along transition paths. This article explores the emerging policy proposal of a “climate bad bank” (Giraud et al. 2021; IEA 2021b; Tett 2021; Vaccaro and Barmes 2021).

Since the 1930s, “bad banks” have purchased assets with high loss risks from distressed financial institutions to cleanse the latter’s balance sheets and allow them to focus on their core activities. Similarly, a *climate* bad bank would buy assets at risk of depreciation during the low-carbon transition and ensure the soft-landing of underlying businesses. However, the literature has barely covered the topic of bad banks in the context of the transition, with only a few mentions in reports, blogs and interviews (Driouich 2020; D. Fischer and Baron 2015; Spencer, Berghmans, and Sartor 2017).

Traditional bad banks have been infamous for fostering reckless investment behaviours, subsidising bankruptcies (Schaefer and Zimmermann 2009) and socialising the losses entailed by financial crises. A climate bad bank would pose similar issues but differ in several aspects. Instead of short-run management of financial disturbances, a climate bad bank would likely act on a longer timescale. It would also have to organise the extinction of housed assets instead of trying to make them perform. Finally, it may dabble in industrial policy and go beyond mere stabilisation.

Thus, what can we learn from former bad bank schemes, and how far is the comparison relevant to designing a good climate bad bank? Our contribution lies in linking a prospective climate bad bank with past experiences and proposing an institutional blueprint.

Section 1 reviews past bad bank examples and draws broad lessons regarding challenges and conditions for success. Section 2 explores existing climate bad bank proposals, questions the degree of similarity between past bad banks and prospective bad banks and identifies challenges specific to climate bad banks. Section 3 builds on the two previous sections. Section 4 proposes a “climate bad bank” blueprint before we conclude in Section 5.

1 Bad banks as a tool to tackle financial instability

1.1 Goal and principles

A “bad bank” (BB) or “Asset Management Company” (AMC) is defined as an institution housing non-performing assets¹ held by a distressed company.² BBs can then seek to liquidate the assets as quickly as possible (Klingebiel 2002) while minimising

¹A non-performing asset is an asset whose financial payments are late or missing (ECB 2017).

²This definition is narrower than others. McKinsey & Company (2009) considers “bad bank schemes” as arrangements in which targeted assets remain on the balance sheet of the concerned institutions, which benefit from public support or set up an internal restructuring unit. However, we prefer to only consider “bad banks” clearly identified institutions with their own balance sheets (Caprio and Klingebiel 1999; Elliott 2009).

losses, or carry out asset management to make assets perform, or conduct “extinctive management” to allow for the soft-landing of dying businesses (L’AGEFI 2014).

Such schemes have been set up in crises to serve four non-mutually exclusive goals. The first two are “narrow” (or microeconomic) and consist of (i) restructuring or quickly liquidating assets at minimal costs and (ii) cleansing the distressed institutions’ balance sheet by taking on their toxic assets so that they can focus on their core activities (lending, etc.). BBs, if public, also have two “broad” (or macroeconomic) objectives. First, by buying distressed assets, they reinstate the price signal and substitute for the market. Second, they avert financial contagion by isolating toxic assets from the broader financial system. Some bad bank schemes have also had industrial development and restructuring functions (Weinland 2016).

1.2 A broad historical diversity

AMCs have been implemented in various ways. Building on the categorisations by Cas Medina and Peresa (2016) and Sajoy (2019) and on a literature review, we classify bad bank features (see Table A1 for a summary and Table A2 to A4 for a presentation of 50 BB cases through history).

BBs have first varied in their **timing of action**. Most schemes have acted *ex-post*, dealing with troubles once they erupt and are sufficiently severe. A minority of BBs, like China’s four AMCs (Rose 2005), have acted *ex-ante* as a prevention tool.

BBs have also varied in terms of **scope of action**. Some have been *centralised*, like NAMA (Ireland, 2009), and offered their services to most of the financial sector and took care of many kinds of assets. *Decentralised* institutions have been smaller entities dealing with the troubled assets of a single or a few institutions (like Securum and Retriva (Sweden, 1992)). Spin-offs from pre-existing entities were also created, with toxic assets on their books.

Historical BBs have further exhibited a large spectrum of **ownership structures**. Some have been fully *ad hoc* institutions (Danaharta, Cambodia, 1998), *i.e.*, set up

by the regulator to deal with financial troubles, which are ruled by public or private law. Others have been public-private partnerships (Sareb, Spain, 2010) with different degrees of participation.

Several kinds of **(re)financing modes** have been deployed. While initial equity injections have come from private and/or public funds, issuance of additional equity ensured refinancing (at the risk of changing control) or the emission of specific debt securities, like senior State-backed bonds (KAMCO, Korea, 1997) or even direct borrowing from the government (FOBAPROA, Mexico, 1998). Asset sales from liquidation also allowed banks to cover expenses. Some historical BBs have received a banking licence to ease access to private refinancing (K.A Finanz, Austria, 2013). Yet Fell et al. (2017) advised against it to ensure better control of the BB's operations. In some instances (StabFund, Switzerland, 2010), central banks provided support.

Regarding **management strategies**, BBs have mainly used two approaches: a "Warehouse" and a "Factory" strategies (Cas Medina and Peresa 2016). "Warehousing" is a passive rundown of assets. Keeping the assets on its books, the bank only acts if a loss threshold is crossed (McKinsey & Company 2009) and relies on time to recover asset value. A "Factory" strategy implies a more active approach (loan restructuring (NPART, Ghana, 1982) or quick liquidation (NAMA, Ireland, 2009). Finally, private BBs are growingly adopting an "extinctive management" approach (L'AGEFI 2014), drawing as much profit from housed assets as possible while monitoring the progressive obsolescence of underlying activities.

Finally, BBs have deployed various **incentive structures**. The main tool has been the valuation of purchased assets, a key variable to address moral hazard (Sajoy 2019). Cas Medina and Peresa (2016) recommend setting a purchase price between the asset's current market value and its book value estimated by the distressed institution.³ Buying above market price incentivises compliance while remaining below book value ensures that institutions are less than fully compensated. Bad banks also deployed other incentives like a total or partial takeover of stressed institutions

³Book value is typically higher than market value for distressed institutions, market players being unwilling to pay for a company in difficulty.

(Jonung 2009) or carrot-and-stick approaches to ensure compliance (Rose 2005).

Variations have depended on the AMC's goal, the economic situation's severity and political economy considerations (Klingebiel 2002). Decentralised, private institutions have handled contained financial risks. States have stepped in when private BBs failed (as France's Consortium de Réalisation, 1993) or when risk became too systemic.

2 Challenges to traditional bad banks: Moral Hazard, Ethics and Governance

Yet, public BBs have deficiencies that make their design difficult – and private schemes can face similar challenges if they benefit from public funding, albeit to a lesser extent due to their limited scope.

A public BB is a source of moral hazard. They act as implicit insurance for financial institutions, encouraging possibly reckless behaviour. They require an adequate incentive structure to limit harmful behaviours *ex-post*. However, ensuring compliance *ex-ante* is difficult. Too complex or too penalising schemes may deter subscription to the BB. Early German attempts at setting up an AMC at the beginning of the 2008-2010 financial crisis were quite ill-fated because of stringent conditions imposed on banks and the scheme's complexity (Ilgmann and van Suntum 2009).

Ethically, BBs also pose crucial justice issues. First, regarding *distributive* justice, *i.e.*, equity in allocating resources. BBs question how to share the burden of safeguarding financial stability. Besides, it raises issues of *retributive* justice, *i.e.* regarding how to punish wrongdoers. A BB can indeed be considered a subsidy to those who privately benefited from the situation before the crisis and fuelled the degradation of financial stability (Nicolaisen 2015; Shirakawa 2012). As a result, there is a tension between making reckless investors pay and reducing transition risks.

Finally, regarding governance, the bad bank's independence, transparency, and accountability are crucial (D. He, Ingves, and Seelig 2007). Some BBs have been con-

troversial for favouring some institutions or handing out unduly large compensations (Indonesia's IBRA (1997). Others, endowed with extended mandates or muddled in political quarries, have not delivered (Calomiris, Klingebiel, and Laeven 2012).

2.1 Conditions for a “good bad bank”

Given such challenges, the literature has examined the conditions for suitable BBs.

A “good” BB would limit the cost of asset management and allow for a prompt recovery of the financial system (*ex-post*) or a smooth functioning of financial markets at the lowest possible price (*ex-ante*) (Cas Medina and Peresa 2016; Klingebiel 2002).

External conditions are crucial to its success, including a healthy macroeconomic environment, easier asset recovery and higher returns, and a well-defined legal framework for managing impaired assets. AMCs have also been more efficient when handling homogenous assets, allowing for economies of scale (Cas Medina and Peresa 2016).

Regarding internal management, Klingebiel (2002) and Terada-Hagiwara and Pasadilla (2004) have underscored the need to focus on asset management only. BBs have also performed better if they stuck to a fixed asset management approach (Cas Medina and Peresa 2016), recruited asset disposal specialists with specific skills (Avgouleas and Goodhart 2017), aimed at rapid asset disposal (Baudino and Yun 2017) and remained politically independent but accountable based on firm evaluation criteria (D. He, Ingves, and Seelig 2007).

3 A Climate Bad Bank: Proposals, Perks, Challenges

Given the popularity of the BB principle, ideas for a “climate bad bank” (CBB) to handle transition risks have recently emerged. A CBB would allow agents to clean their balance sheet of assets stranded (*ex-post*) or at stranding risk (*ex-ante*).

3.1 Existing Climate Bad Bank Proposals and Justifications

We identified four proposals, most of them involving exclusive or near-exclusive public participation in the CBB and a centralised approach:

- Institut Rousseau’s European “fossil bank” (Giraud et al. 2021): an ECB-backed institution which would buy up to 70% of banks’ high-carbon assets with a 10% haircut in the case of several purchase rounds. The ECB would fund the scheme, which would house assets for extinctive management purposes.
- The United Nations Environment Programme Finance Initiative (Vaccaro and Barmes 2021) suggested the setting-up of national CBBs, which would buy assets *ex-ante* with a time-increasing haircut and a well-established schedule.
- The suggestion by BlackRock Chief Executive Officer Larry Fink (Tett 2021) that the finance industry creates bad banks to isolate carbon-intensive assets.
- The proposal from the IEA’s (2021b) Energy Transition Mechanisms (ETMs) is to dedicate a financial facility to organising the decommissioning of coal power plants in developing countries. The Asian Development Bank and private partners proposed a similar proposal (Al-Jazeera 2021; del Bello 2021).

The goal of CBBs would be to reduce the exposure of systemic agents to climate-related transition risks (Giraud et al. 2021). A CBB would isolate exposed assets from the financial system and prevent the emergence of disturbances due to asset stranding (Batten, Sowerbutts, and Tanaka 2016; Giese, Nagy, and L.-E. Lee 2021). It would also avoid perverse effects. During the transition, exposed institutions will hedge against transition risks and sell their assets, possibly to frail or less regulated agents, notably from peripheral financial systems (Bos and Gupta 2018). If those institutions fail, disturbances could ensue. Because such dynamics are hard to track, a preemptive bad bank like those above could thus be a way to solve the information asymmetries between regulators and the financial system and deal with the latter’s infamous complexity and intractability (Battiston and Martinez-Jaramillo 2018). The

CBB would limit the potential increases in financial fragility that may emerge from the reorganisation of the financial sector along a transition path.

Second, a CBB would allow for an orderly but firm eviction of high-carbon activities. It would increase the effectiveness of financial divestment from high-carbon industries, which have proven disappointing so far (T. A. Hansen and Pollin 2020). It would remove fossil assets from financial markets and not merely reshuffle them across agents.

Finally, many high-carbon assets on the balance sheets of key financial players (notably banks) may represent a brake to their commitment to a low-carbon world (Giraud 2020). Some argue that transition risks would more than offset the opportunities opened by the low-carbon transition, thus exposing financiers to important losses. Offering an explicit exit could induce the financial system to fund greener investments by lifting the fear of financial disturbances.

However, it is worth questioning whether the parallel between historical BBS and a CBB is legitimate. Notably, the CBB would deal with two externalities simultaneously: financially destabilising behaviours, like traditional BBs, and climate change. It would entail additional constraints and challenges.

3.2 Challenges

Hence, although much can be learnt from past bad banks, the particular implementation context and distinct goals of a climate bad bank pose additional challenges. Table 1 compares historical and climate BBs' goals, and we discuss precise challenges in the following.

3.2.1 Economic efficiency

The first challenge relates to costs. Although no definite estimate of “high-carbon” financial assets currently exists at the world level, several regional or national estimates do. Nieto (2019) reports that the EU, US, Chinese, Japan, and Swiss syn-

icated loan exposure amounts to US\$1.9 trillion. Baer (2021), considering bonds and equity, reports a US\$3 trillion exposure for the US. Orders of magnitude are high: for comparison, large BBs like Sareb (Spain) purchased up to \$350 billion of non-performing loans.

It relates to the “narrow” goal of the CBB, which should be to limit costs. As liquidation to third parties can hardly be envisaged,⁴ it includes managing the assets efficiently to ensure sufficient returns. However, because underlying firms would have to close, losses that will have to be incurred by the CBB will likely be higher than those of historical BBs, especially if the transition is costly in terms of growth.

A further difference between an *ex-ante* BB and an *ex-ante* CBB is that historical BBs have targeted non-performing assets that banks could not restructure. In the CBB case, most assets exposed to transition risks are still performing and profitable. The opportunity cost for relinquishing them may be high. Thus, agents would only participate in the scheme late once they have sufficiently benefited from their assets’ earnings, and making the CBB acceptable could entail buying above book value. *Ex-post* frameworks, by contrast, are somewhat shielded from such issues, though only under certain conditions (Ilgmann and van Suntum 2009).

CBBs may also deter voluntary decarbonisation through innovation or business evolutions or condone new high-carbon investments, creating additional moral hazard issues. Even if such investments were banned conditionally on CBB assistance, additional liquidity could go to risky or speculative assets. It may also fuel investments in unviable green assets or prompt “green bubbles” (Nauman 2021), representing a risk to financial stability.

Further, although most CBB proposals explicitly target financial institutions and banks, others are more blurred regarding the sectoral scope of the CBB’s operation. It is unclear whether the “coal bad bank” advocated by Spencer, Berghmans, and Sartor (2017) would remove financial liabilities emitted by coal producers and coal-plant operators on the balance sheet of financial institutions or whether it would

⁴Note that devalued assets in the case of an *ex-post* scheme would also be unattractive since underlying companies will have to exit the market unless they reconvert swiftly.

organise the extensive management of physical assets. Targeting physical assets would have several advantages, including the ability to limit the extent of stranded assets and their impact on non-financial companies. It would also allow for the decommission of capital incompatible with the transition and open investment space for new, less polluting production processes, which would be critical in the energy sector where one observes a “piling-up” of energy sources rather than an actual exit of high-carbon technologies (de Perthuis 2019).

Finally, defining future stranded assets for *ex-ante* CBBs is arduous. There are technical limits to designing readily usable metrics to determine the environmental friendliness of financial assets (Bingler, Colesanti Senni, and Monnin 2020; Bingler and Colesanti Senni 2022; Haslam et al. 2018; Monasterolo, Battiston, et al. 2017). Even if stranded assets were defined, determining which companies are most at risk of stranding may expose regulators to information asymmetries. Firms may inflate their amount of stranded assets to benefit more from the CBB or, on the contrary, underestimate it to keep running their activities as long as possible.

3.2.2 Ethics

Because it relates to the low-carbon transition, a CBB is doubly problematic regarding corrective and distributive justice.

For distributive justice, the question is who should (or in what proportion) pay for the CBB. The CBB’s funding structure can rely on three different sources:

1. Present resources from private entities or the public sector (taxpayer money).
2. Future resources in the form of debt.
3. Central bank backing through money creation.

Given possibly sizeable costs for the CBB, it seems unlikely that the bill will be footed exclusively with current resources, especially if the sacrifices linked to other climate policies, like carbon taxes, have encountered opposition. It would entail a recourse to public debt, which would put future generations at contributions, or even central

bank monetisation, which would seemingly not spoil anyone. These three possibilities (current resources, debt, monetisation) will ultimately determine how to share the burden.

Yet even a scheme acceptable from the standpoint of distributional justice would face ethical objections. Indeed, the CBB poses further retributive justice issues and breaches the principle of punishing wrongdoers. Daumas and Salin (2020) suggested a “stranded-compensated” policy principle, effectively buying some companies or investors out of business to accelerate decarbonisation and displace some technologies. The CBB would obey this principle, primarily if it targets non-financial entities. Broome and Foley (2016) and Guttman (2018) follow a similar line by advocating compensation for net transition losers or rewarding companies for their decarbonisation efforts in the form of liquidity.

This “stranded-compensated” principle opposes the “polluter pays” principle as it would entail paying polluters to cut their emissions. While it could seem fair to help businesses suffering from the transition due to a lack of knowledge or small margins of adaptation, financial institutions (Coste 2021; Ganswindt et al. 2021; Gilbert 2021) have been charged with either greenwashing or indifference concerning climate issues. Further, some fossil fuel companies have jammed scientific information on climate change to avoid regulation (Franta 2021; Oreskes and Conway 2010). Handing them out free cash and offering them an exit has something of paying off a ransom. However, not committing resources to avoid stranding could hamper the unravelling of the transition and equally decrease the well-being of future generations and current ones in the future.

3.2.3 Governance

Finally, on top of generic issues of accountability, transparency and independence faced by all BB schemes, a CBB would have to solve two additional problems.

First, whether the CBB targets financial or physical assets largely determines its goal regarding the low-carbon transition. In the first case, the CBB would primar-

ily tackle financial stability and the cleansing of balance sheets. In the second one, it would be principally an industrial policy tool, offering liquidity to facilitate the conversion of highly exposed companies. However, if the CBB offers the two services simultaneously, its precise purpose would be blurred, possibly weighing on its efficiency. BBs with mandates beyond strict financial stability purposes (corporate support, etc.) have had to be more efficient (Klingebiel 2002). However, because transition risks depend on the smoothness of the low-carbon transition (Monasterolo 2020a), disentangling both goals takes time and effort.

Then, the jury is still out on whether the (network of) CBB(s) should operate at a national, regional, or international level. All historical BBs have been implemented at a national or subnational level – with possible foreign participation in some developing countries (Terada-Hagiwara and Pasadilla 2004), suggesting that the costs of international cooperation are too high in times of financial turmoil. Meanwhile, some perennial BB proposals at the European Union level have been put forward to tackle the legacy of bad loans left by the 2008 crisis (Avgouleas and Goodhart 2017). Several CBB proposals would be at the supranational (Giraud et al. 2021) or even world level (Broome and Foley 2016). Given the interconnectedness of the world’s financial system (Guttman 2016) and the global nature of climate change (IPCC 2021), some international coordination seems necessary.

4 Taking up challenges: What would a good climate bad bank look like?

Considering the multiple designs of historical BBs, we sketch a CBB blueprint to tackle the challenges highlighted above.

Table 1: Missions and goals of various bad bank types

Mandate	Goal	Policy		
		Historical bad bank	Ex-post Climate bad bank	Ex-ante climate bad bank
Narrow mandate	Free balance sheets	Restore credit-making Restructure assets		Reorient credit towards low-carbon activities Conduct an Extinctive management of assets
	Asset management	Conduct a Factory – including Extinctive management of assets		
Broad mandate	Pricing	Give price to illiquid assets		Force climate externality into asset prices
	Financial stability	Avoid financial instability through:		
		An isolation of: - Still performing but very risky loans (ex-ante bad bank) - Non-performing assets (ex-post bad bank)	An isolation of non-performing assets	An isolation of still performing carbon-intensive assets

4.1 Basic features

Regarding the timing of action, an *ex-ante* (or pre-emptive) institution could be more suited. Given the significant uncertainties surrounding transition risks (Monasterolo 2020a) and the need for decisive action (IPCC 2021), an *ex-ante* CBB could represent a precautionary approach to transition risks (Chenet, Ryan-Collins, and van Lerven 2021).

Further, given the broad scope of transition-risk exposed assets, a purely decentralised solution seems unsuited. The choice lies between a network of decentralised institutions with an umbrella coordinator and a centralised unit, depending on how transition-exposed assets are concentrated. The literature suggests systemic financial institutions crystallise transition risk exposures (Cleveland, Schuwerk, and C. Weber 2015; ESRB 2020). Thus, a network approach seems more adapted.

Regarding ownership structure, a fully public framework would reduce transaction costs and give complete discretion to the public regarding the handling of stranded assets. However, private participation could reduce the cost to public finances and induce greater compliance by organising explicit profit sharing that may render the abandonment of assets easier. BBs involving private stakeholders have performed better (Rose 2005). Some private participation could, therefore, be justified, with sufficient public funding, to strike a balance between control, costs, and efficiency.

As for funding, we suggest an imbricated system. Private funding, under the emission of debt securities, possibly guaranteed by States, should be sought first. Public government debt could be used as a second option when all affordable private funding opportunities are exhausted.⁵ Finally, central bank monetisation could be used as a last resort when States are constrained (Giraud et al. 2021).

As for management strategy, an *ex-ante* CBB would have to adopt an extinctive management approach. It could entail renegotiating debt terms with debtors, like reducing interest rates while, in the meantime, extending maturities. Respecting a degree of distributional justice in a bailout scheme is tightly linked to the scheme's efficiency in dealing with non-performing assets. Sound practices following the strategy will limit the final losses born by the State.

We finally suggest that assets be bought at a discount to tackle moral hazard. A time-increasing haircut based on an established schedule (Vaccaro and Barmes 2021) would allow banks to determine their optimal sale time and foster a smooth alignment of expectations. Haircut schedules should be accompanied by a credible commitment to climate policy, with a carbon price path or a well-defined asset stranding schedule (Scott Cato and Fletcher 2020).

4.2 Remaining challenges

Several particular questions still need to be answered: whether the CBB should target physical assets, how to choose investments, and the CBB's geographical scale

⁵See Broome and Foley (2016) and S. M. Gardiner (2017) on the distributional stakes of this solution.

and governance.

Regarding physical assets, setting up an institution targeting both financial institutions and non-financial companies seems unfeasible, given the already sizable costs of finance-oriented CBBs. Further, if the primary objective of the CBB is to ensure financial stability along transition paths, dealing only with financial assets would be preferable. Given the current separation between financial-monetary regulation and democratic representation, it seems more cautious to endow a non-elected institution with prudential rather than an industrial policy mandate (Baer 2021).

Regarding choice criteria, a taxonomy of “green” and “dirty” activities should be established based on top-notch scientific evidence. It should be a public, single-window initiative, made stricter along the transition path. It should adapt to policy changes and technology opportunities, preferably according to a well-established schedule. Finally, the choice of assets should be made based on the financial soundness of the concerned institutions. Asset purchases should target primarily those firms most financially vulnerable.

Finally, the coordination costs of a worldwide agency would be high. Supranational levels could be targeted where high degrees of cooperation have already been achieved, like in the EU. National institutions could be prioritised elsewhere, with international coordination coming next. Table 2 summarises our proposal.

5 Conclusion

Because of its qualitative approach, this study did not venture far into the details and technicalities of a potential climate bad bank. A real-world study on a particular geographical zone, such as prolonging Institut Rousseau’s proposal for Europe (Giraud et al. 2021), could be performed by considering how our broad blueprint would apply. It could take the form of a more in-depth study of the institutional possibilities (political economy, mandates) for a CBB within the EU and its asset purchases and management costs. Another path would be to compare this climate

Table 2: Summary of climate bad bank blueprint

Type	Modalities	Precision
Timing of action	<i>Ex-ante</i>	Well-defined schedule for asset purchases/Pricing
Ownership Structure	Public-Private	Mainly private, sufficient public participation to ensure reasonable control
Scope of action	Decentralised with umbrella coordinator	Network of small entities aimed in priority at the most exposed agents, coordinated with an umbrella organisation
Management strategy	Factory	Extinctive management
Incentive structures	Pricing below book value Clear taxonomy Compliance incentive	Tame moral hazard, force externality into balance sheets Avoid information asymmetries Mandatory scheme for systemic actors (1st best) Subsidies (2nd best)
Other	Degree of international cooperation Sectoral target	Desirable but not a priority In priority financial assets

bad bank proposal to other radical suggestions, such as green nationalisations and vast public spending plans. Examining how the CBB would interact and complement other, more usual, climate policies is worthwhile. These endeavours allow for a better assessment of such schemes' strengths and weaknesses than the one-sided exercises we have performed in this article.

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Appendices

Table A1: Institutional Dimensions

Type	Modalities	Explanation	Examples	
Timing of action	<i>Ex-post</i>	Dealing with financial disturbances after they hit	Most schemes	46 out of 50
	<i>Ex-ante</i>	Prudential purpose	China's four AMCs (1997)	4 out of 50
Scope of action	Centralised	Large, single-window unit open to all or almost all the financial sector	DUTB (Slovenia, 2014)	15 out of 37 ad hoc bad banks schemes
	Decentralised	Smaller units dedicated to one or a handful of institutions	StabFund (Switzerland, 2009)	22 out of 37 ad hoc bad bank schemes
Ownership structure (initial equity injection)	Public	Full public participation	KAMCO (Korea, 1997)	28 out of 50
	Public-Private	Public-private partnership	Resolution Trust Corporation (USA, 1990)	14 out of 50
	Private	Full private participation	Propertize (Netherlands, 2013)	8 out of 50
(Re)Financing	Equity	Funding through equity issuance	Resolution Trust Corporation (USA, 1989-1995)	NA
	State-backed bonds	Issuance of guaranteed bonds	Arsenal (Finland, 1991)	NA
	Direct borrowing from the government	Government bestows a loan	FOBAPROA (Mexico, 1998)	NA
	Central Bank support	Long term loans	StabFund (Switzerland, 2010)	NA
Management strategy	Warehouse	Recovery of asset value through time (Passive rundown)	Sareb (Spain, 2012)	5 (+ 2 "Factories" that became "Warehouses") out of 50
	Factory – Liquidation	Quick sale of assets to more solid third parties	NAMA (Ireland, 2009)	
	Factory – Restructuring	Provision of restructuring services (maturity renegotiation, etc.)	NPART (Ghana, 1982)	45 (- 2 Factory that became "Warehouses") out of 50
	Factory Extinctive management	Organise the soft-landing of a non-profitable activity	UBS	
Incentive structures	Pricing – at book value	Ensure compliance	FMS (Germany, 2010)	21 out of 32*
	Pricing – below book value	Tame moral hazard	Royal Park Investment (Belgium & Luxembourg, 2009)	11 out of 32*
	Other approaches: Carrot-and-stick	Ensure compliance with burden sharing and severe write-off rules	Danaharta (Cambodia, 1998)	NA

*Data on pricing was only found for 32 bad banks
Source: Literature review by the authors

Table A2: A sample of Bad Bank schemes – Subsidiary BB

Bad Bank Name	Country Operating years	Ownership Governance	Centralised Decentralised	Equity Funding	Model	Pricing of purchased assets (Average)	Other incentive structures	Targeted Assets
Grant Street National Bank	US – 1988	Mellon Bank		Private	Factory	57% of book value		
Institutional Restructuring Unit	Germany – 2003-2005	Dresdner Bank		Private	Factory	100% of book value		
Phoenix	Ireland/Germany – 2008	WestLB (PPP)		Public-Private	Factory	100% of book value		
Financial Resolution & Recovery & Ektorner	Sweden – 2009	Swedbank	Irr.	Private	Factory	100% of book value	Irr.	All
Citi Holdings	US – 2009	Citi Bank		Public (38%)-Private (62%)	Factory	n.a		
Heta Asset Recovery	Austria – 2014	Hypo Alpe Adria Bank		Public	Factory	No transfer (institution created with their portfolio)		

"All" denotes Bonds, Equity, Loans and Complex products. "n.a" denotes "not available", and "Irr." stands for "Irrelevant".

Table A3: A sample of Bad Bank schemes – Spin-off BB

Bad Bank Name		Country Operating years	Ownership Governance	Centralised Decentralised	Equity Funding	Model	Pricing of purchased assets (Average)	Other incentive structures	Targeted Assets
Magyar Bank	Hitel	Hungary – 1996	Magyar Hitel Bank	Irr.	Public	Factory			Loans
BIH		Germany – 2006	BIH	Irr.	Public	Factory			
KA Finanz		Austria – 2013	KA Finanz	Irr.	Private	Factory	No transfer : institution created with their portfolio	Irr.	All
Reverta		Latvia – 2010	Parex	Irr.	Public	Factory			
UK Asset Resolution		UK – 2010	UK Asset Resolution	Irr.	Public	Factory			
Bank of America		US – 2011	Bank of America	Irr.	Private	Factory			
Dexia		Belgium – 2011	Dexia	Irr.	Private	Factory			
Banco Espírito Santo (BES)		Portugal – 2014	Banco Espírito Santo (BES)	Irr.	Private	Factory			

“All” denotes Bonds, Equity, Loans and Complex products. “n.a” denotes “not available”, and “Irr.” stands for “Irrelevant”.

Table A4: A sample of Bad Bank schemes – *Ad hoc* BB

Bad Bank Name	Country – Operating years	Ownership	Scope of action	Equity Funding	Model	Pricing of purchased assets (Average)	Other incentive structures	Targeted Assets
Danaharta	Malaysia – 1964-2005	State	Centralised	Public	Factory	56% of book value	Compulsory write-offs at loss if refusal of Daharta's bid	All
Fondo de Garantía de Depósitos	Spain – 1977-...	State	Centralised	Public	Factory	No transfer : Takeover	n.a	Loans
Asset Privatization Trust	Philippines – 1987-2000	State	Centralised	Public	Factory	100% of book value	n.a	Loans
Resolution Trust Corporation	US – 1989-1990	State	Decentralised	Public-Private	Factory	90% of book value	Ability to exert large control on failing institutions	Mortgages
Konsolidační Banka (1990-2001), then Česká konsolidační agentura (2001-2007)	Czech Republic – 1990-2007	State	Centralised	Public	Warehouse	n.a	n.a	Loans
NPART	Ghana – 1990-1997	State	Centralised	Public	Warehouse	100% of book value minus accruing interest	n.a	Loans
Securum	Sweden – 1992-1994	State	Decentralised	Public-Private	Factory	100% of book value	None	Debt
Retriva	Sweden – 1992-1994	State	Decentralised	Public-Private	Factory	100% of book value	None	Debt

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Bad Bank Name	Country – Operating years	Ownership	Scope of action	Equity Funding	Model	Pricing of purchased assets (Average)	Other incentive structures	Targeted Assets
Consortium de réalisation then Etablissement Public de financement et de restructuration	France – 1993-2006	Credit Lyon-nais, then French State	Decentralised	Public – Private	Factory, then Warehouse	100% of book value	None	All
Omaisuuudenhoitoyhtiö Arsenal	Finland – 1993-...	State State	Decentralised	Public	Warehouse	100% of book value	n.a	Mortgages Properties
Sponda	Finland – 1993-...	State State	Decentralised	Public	Warehouse	100% of book value	n.a	Mortgages Properties
FOBAPROA (1994-1998) then IPAB (1998-)	Mexico – 1994-...	State State	Centralised	Public-Private	Factory, then Warehouse	100% of book value (minus provisions)	Losses assumed up to 80%	All
KAMCO	Korea – 1997-...	State	Centralised	Public	Warehouse	40% of book value	None	Loans
BBC	Thailand – 1998	State	Decentralised	Public	Factory	> 100% of book value	None	Loans
Indonesian Bank Restructuring Agency (IBRA)	Indonesia – 1998-2004	State	Centralised	Public	Warehouse	100% of book value	Takeover of some banks and corporations	All
CINDA	China – 1999-...	State State	Decentralised	Public	Warehouse Preemptive action	100% of book value	Restriction to loans extended before end-1995	Loans
Oriental	China – 1999-...	State State	Decentralised	Public	Warehouse Preemptive action	100% of book value	Restriction to loans extended before end-1995	Loans

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Bad Bank Name	Country – Operating years	Ownership	Scope of action	Equity Funding	Model	Pricing of purchased assets (Average)	Other incentive structures	Targeted Assets
Great Wall	China – 1999-...	State State	Decentralised	Public	Warehouse Preemptive action	100% of book value	Restriction to loans extended before end-1995	Loans
Huarong	China – 1999-...	State State	Decentralised	Public	Warehouse Preemptive action	100% of book value	Restriction to loans extended before end-1995	Loans
UOBR	Thailand – 1998	State	Decentralised	Public	Factory	> 100% of book value	None	Loans
KTB	Thailand – 2000	State	Decentralised	Public	Factory	>100% of book value	None	Loans
Thai Asset Management Company (TAMC)	Thailand – 2001-...	State	Centralised	Public	Factory	33% of book value	Loss and profit-sharing agreements	All
BMB	Thailand – 2002	State	Decentralised	Public	Factory	> 100% of book value	None	Loans
SCIB	Thailand – 2002	State	Decentralised	Public	Factory	>100% of book value	None	Loans
Finansiel Stabilitet	Denmark – 2008-...	State	Centralised	Public	Warehouse	n.a	None	All
Parvalorem	Portugal – 2008-...	State	Decentralised	Public-Private	Warehouse	100% of book value	n.a	All
Parups	Portugal – 2008-...	State	Decentralised	Public-Private	Warehouse	100% of book value	n.a	All
Parparticipadas	Portugal – 2008-...	State	Decentralised	Public-Private	Warehouse	100% of book value	n.a	All

Continued on next page

Bad Bank Name	Country – Operating years	Ownership	Scope of action	Equity Funding	Model	Pricing of purchased assets (Average)	Other incentive structures	Targeted Assets
Royal Park Investments SA/NV	Belgium & Luxembourg – 2008-...	State	Decentralised	Public	Warehouse	83% of book value*	n.a	All
StabFund	Switzerland – 2008-2013	Central Bank	Decentralised	Public-Private	Factory	95% of book value	n.a	All
Erste Abwicklungsanstalt	Germany – 2009-...	State	Decentralised	Public	Warehouse	n.a	n.a	Structured Securities, Loans, Advances
National Asset Management Agency (NAMA)	Ireland – 2009-...	State	Centralised	Public (49%) – Private (51%)	Factory	43% of book value	n.a	Mortgages
FMS Wertmanagement	Germany – 2010-...	State	Centralised	Public	Warehouse	100% of book value	n.a	All
Sareb	Spain – 2012-...	State State	Centralised	Public (45%) – Private (55%)	Warehouse	53% of book value	n.a	Mortgages Properties
Propertize	Netherlands – 2013-...	State	Decentralised	Public-Private	Warehouse	63% of book value	n.a	All
DUTB	Slovenia – 2014-...	State	Centralised	Public	Factory	29% of book value	n.a	All
NARCL	India – 2021-...	State	Centralised	Public	Warehouse	n.a	n.a	All

Note: “All” denotes Bonds, Equity, Loans and Complex products. “n.a” denotes “not available”, and “Irr.” stands for “Irrelevant”.

Conclusion

The issue of low-carbon transition risks has become a burning topic for financial regulators and financial agents. Plagued with numerous uncertainties, either empirical, theoretical, or methodological, the field is in constant search for improvements for existing approaches and for openings towards other economic methods. In this manuscript, I have intended to propose several steps in this direction by primarily calling out to methodologies aimed at characterising transition risks over whole mitigation pathways. More precisely, this PhD was thought of as an interface between the transition risk literature proper, the Energy-Economy-Environment Integrated Assessment strand and the post-Keynesian stock-flow consistent methodology. After a literature review, I developed and applied a new model to the study of transition risks, with a special focus on scenario emulations. I also proposed some new theoretical and empirical insights on the issues of asset stranding and transition risks before exploring a radical policy proposal.

In this conclusion, I first summarise the contributions of this research and highlight its main takeaways (i). Then (ii), I discuss the limitations of this thesis before (iii) opening towards new research avenues and perspectives.

Contributions of the thesis

Chapter-wise summary

This thesis begins with a literature review (Chapter 1), which provides a comprehensive overview of the literature on transition risks. It notably brings together the literatures on asset stranding, financial transition risks and financial econometrics together within a consistent grid of analysis. The takeaways from this literature review are threefold. First, it called for a more encompassing use of scenarios within the transition-risk assessment literature, notably in studying transition risks over long-run mitigation pathways. Second, I highlighted the need for a better modelling of expectations. Finally, I showed that a crucial avenue was a better understanding of the financial sector, and, therefore, an improved representation of it within existing modelling frameworks to better capture the interactions between the real and the financial economy along transition scenarios. This thesis was organised along these three lines.

The first two chapters developed a methodology meant to study low-carbon transition risks over a large number of mitigation pathways while, at the same time, allowing for an integrated treatment of real-financial interactions.

This approach started with the development and presentation of a stock-flow consistent model in Chapter 2. This model offers a compact representation of the low-carbon transition while offering a disaggregation of the financial sector and interactions across financial agents. I applied this model to the scenario suite of the NGFS to provide the first climate-stress test powered by a stock-flow consistent model. I showed that, while banks are relatively shielded from transition risks, other financial agents are more vulnerable due to changes in asset prices occurring along the transition, with significant tensions arising in the medium to long run in the most stringent pathways. Furthermore, I took advantage of the model's ability to emulate different variants of scenarios to highlight differences across mitigation pathways with similar narratives but initially provided by different modelling frameworks. By doing so, I

demonstrated that meaningful differences can emerge from different variants of the same mitigation pathway, calling for caution in considering a reduced set of scenarios. In Chapter 3, I, together with Céline Guivarch, built upon the latter observation and expanded this methodology to a large ensemble of mitigation pathways, the first study of that kind to the best of my knowledge. The first contribution of this Chapter is a classification of all scenarios of the IPCC database into fifty clusters and a determination of a “best representative” amongst each cluster. Then, we replicated and expanded the methodology of Chapter 2 by applying FASM-ID on our set of best representatives, while accounting for parameter and macroeconomic uncertainty. We find again that non-bank financial agents are mostly affected, although tail-risk scenarios affect more the banking sector. These scenarios are characterised by a low efficiency of climate policy, in the sense that high carbon price levels must be implemented to reach a given decarbonisation target. We further find that in the majority of cases, low-carbon financial transition risks are contained, which represents an optimistic outlook on the feasibility of the transition from a transition-risk perspective. These feasible scenarios include mitigation pathways with high climate ambition if corresponding climate policies are not too stringent.

The two following chapters answered the two other concerns raised by the literature review, namely the modelling of expectations and a better understanding of the financial sector.

Chapter 4, co-authored with Louison Cahen-Fourot, Emanuele Campiglio, Michael Gregor Miess and Andrew Yardley, intends to provide a new way to model expectations in the context of the low-carbon transition. By building on the fact that the shape of the low-carbon transition cannot be predicted, the model assumes that agents have autonomous beliefs on future transition developments. These beliefs are not necessarily model-consistent and can lead agents to adopt heterogenous behaviours. We apply this intuition to a compact model of investment choice relevant to transition matters, in which agents decide to invest in high- or low-carbon capital depending on expected stranding. We find notably that an increase in expectation dispersion

can significantly affect low-carbon investment, notably if short-run developments are more uncertain. This paper illustrates that accounting for belief dispersion is a key element for the modelling of transition expectations. Furthermore, this approach could, in principle, be brought to larger-scale macroeconomic models and could be applied to a variety of economic agents.

Chapter 5 added an empirical note to the thesis by exploring how financial agents modified their exposures to the non-financial companies most exposed to low-carbon transition risks between the Paris Agreement and the Covid outbreak. This endeavour was motivated by the desire to provide a better understanding of how exposures have evolved and could evolve through time before the introduction of decisive climate policies. By disaggregating across financial agent types, regions and portfolio sizes, I was able to pinpoint what kind of agents were more prone to increase their exposures to high transition-risk companies between the Paris Agreement and the Covid outbreak. I notably find that the agents most prone to increasing their exposures were located in emerging economies and that Northern-economies Pension Funds, especially in Anglo-Saxon countries, showed a pervasive slant towards the most polluting companies in the world. I also document an increasing polarisation of the financial system in terms of exposure to high-carbon companies consistent with an increase in the concentration of exposures. These findings contribute to a better understanding of the dynamics of transition-risk exposures. They highlight, first and foremost, that the distribution of financial losses will get increasingly skewed towards emerging economies. Thus, higher attention should be paid to transition risks in emerging economies and how they could ripple off to central financial systems. More precisely, a greater focus on balance-of-payment and exchange rate dynamics linked to the transition would be in order. More broadly, this chapter highlighted that financial agents have very diverse expectations and stances with regard to transition risks. This finding calls for (i) a better surveying of these stances and (ii) a modelling of the financial sector doing full justice to this heterogeneity.

Finally, Chapter 6 offered an opening in the form of a policy discussion. Together with

Mathilde Salin, we examined the relevance and challenges associated with an emerging policy proposal: the setting up of a climate bad bank. Similarly to traditional bad banks, this institution would take on its balance sheet those assets most vulnerable to transition risks. This policy move could alleviate the balance sheet of financial agents most exposed to transition risks and avoid exposures being transferred to less solid and less regulated agents. Building on a historical review of past bad banks, we highlighted the challenges involved by a possible climate bad bank, and provided a tentative blueprint for the construction of such an institution.

Main takeaways from the dissertation

Overall, the takeaways from this dissertation across its six chapters can be summarised through the four following points.

Financial agents are not equally affected by transition risks. Furthermore, the latter extend far beyond short-run adjustments and depend to a significant extent on the pace and shape of the transition and on the corresponding climate policy stance. Notably, risks linked to asset devaluations are more susceptible to giving rise to long-run transition risks and larger shocks to financial agents. Credit risks, affecting banks, are generally relatively small, with only transitory adjustments. Banks are indeed able to stomach much of the losses on commercial loan defaults arising from the transition. On the other hand, non-bank institutions seem more fragile.

Looking at a wide array of scenarios, around 60% of representative mitigation pathways do not give rise to significant financial transition risks. This perspective is reassuring with regard to the financial-stability feasibility of the transition, all the more so since these pathways even include very climate-ambitious scenarios with relatively high climate policy pressure. However, it means that some 40% of mitigation pathways feature high risks for the financial sector, with a few leading to outright financial crises in the medium to long run. These scenarios are mostly characterised by

high carbon prices for mid-range decarbonisation targets, highlighting the efficiency of carbon prices as the main driver of transition risks. Given the relatively meagre results of carbon prices so far and their sheer lack of popularity, it calls for the design of less punitive climate policies and of sound financial stabilisation policies to hedge potential transition risks.

Accounting for agents' heterogeneity across a variety of variables, like expectations, regional origins or business model, is a key frontier in the improvement of transition risk assessments. Dispersion in future beliefs about the transition can lead to uncoordinated and possibly transition-adverse investment behaviours that certainly could have an impact on transition risks. **Furthermore, attention and importance given to transition risks by investors can vary significantly from one another. Hence, some agents will likely take transition-adverse bets and take on extra exposures. This thesis showed that some emerging countries and particular financial agent types may be more likely to increase said exposures.** It calls for a careful scrutiny of these agents and the design of sound policies. It also invites considering geographical and intra-financial heterogeneity seriously in model-based assessments of transition risks, with due representations of relevant interactions.

Finally, a climate bad bank could be a viable way to alleviate possible transition risks, although this policy poses acute distributional, efficiency and regulatory challenges. A pre-emptive bad bank could take on its balance sheets the assets most at risk of stranding, based on a careful taxonomy of dirty activities, by targeting the most financially fragile institutions. It would be organised as a network of bad banks gathered under an umbrella institution.

Limitations of the thesis

The approaches used in this PhD are, however, not without limits.

To start with, each chapter has limitations of its own. Chapter 1 did not build on a

systematic approach, which may have led to neglecting some articles. Furthermore, it left aside issues beyond climate-related financial risks, like biodiversity (Svartzman et al. 2021) or critical materials (Miller et al. 2023), two emerging concerns within the field. Neither did it discuss financial policies for the transition, although the topic has been increasingly burning over the course of the PhD. Chapter 2 developed a necessarily stylised model with strong assumptions and limits, like the absence of definite labour market dynamics or a world-level perspective. More work could also be done to improve the calibration of the model and its validation. Chapter 3, on top of similar caveats to Chapter 2, highlighted some of the limitations of using a unified modelling framework as a comparison platform. For instance, the real-economy structure of the model, based on the replacement of an Incumbent sector by a Challenger, although it gave rise to interesting insights, partly drove some counter-intuitive results. Furthermore, mitigation pathways featuring very high carbon prices were very difficult to simulate by the model, casting doubt on its ability to run any kind of scenario. The insights developed in Chapter 4, unfortunately, could not be ported to a larger-scale mode that could have allowed the study of the macroeconomic effect of the representation of expectations it proposes. In itself, the framework could benefit from further refinements, like being brought to dynamics and allowing for heterogeneity for more variables than the utilisation rate. Chapter 5 only offered a partial assessment of exposure changes by focusing only on equity investment on a reduced time period. Finally, Chapter 6 builds only a literature review and could benefit from a clearer theoretical and formal framework to study a potential climate bad bank, and a more systematic comparison with other financial climate policies, like current information-base measures or other radical steps, like green nationalisations. From a more general standpoint, this dissertation could but partly answer its overarching question. In particular, compared to regulatory exercises (T. Allen et al. 2020; Alogoskoufis et al. 2021), this PhD adopted an aggregated perspective by focusing on macro-financial risks. While this approach is more economical in terms of data and modelling effort, it necessarily provides a less detailed and less precise picture

of transition risks. Anchored in a prospective approach, the intention of the PhD was less to provide accurate quantitative estimates at a disaggregated level than to propose possible transition risk patterns. Furthermore, the theoretical and empirical insights drawn from Chapters 4 and 5 could not be brought to the model developed in the PhD. All these elements will be integrated into the model in further work. Finally, the PhD could not go to the end of one of its first intentions, namely the study of financial policies aimed to alleviate transition risks. The study of possible policies was confined to a literary and historical treatment, while FASM-ID could, in principle, accommodate financial policies. This will also be the object of further work.

Future Research and Perspectives

For future research, improving FASM-ID is a top priority. Several avenues could be envisaged. Bettering the representation of the labour market and including population dynamics would be a first step towards a better representation of transition dynamics, given the importance of demographics in mitigation pathways. On the more precise theme of transition risks, the model could benefit from a better representation of expectations and more disaggregation in three respects. On the one hand, a better geographical resolution would allow for a more precise picture of physical stranded assets, distributed very unequally around the globe (Daumas 2023, Chapter 2). Then, improving the disaggregation of the financial sector by including more agent types or building a fully-fledged agent-based financial sector module could represent an important step forward in better understanding transition risks. Finally, FASM-ID could become a more technology-rich model with a better sectoral disaggregation of the financial sector. Further add-ins could also better represent monetary, fiscal, and climate policies. These endeavours could certainly build upon the teachings of Chapter 4 and 5.

Following these leads could help emulate more aspects of mitigation pathways than

carbon price and emission schedules, like the precise deployment of low-carbon technologies. FASM-ID could thus be applied to more precise aspects of existing mitigation pathways and measure transition risks more precisely. Allowing for more elements from mitigation pathways could also improve their characterisation and clustering, as was done in Chapter 3, and therefore relate transition risks to more scenario features. The improvements above could also make FASM-ID amenable to simulating scenarios beyond existing mitigation pathways, incorporating little-explored dimensions, like geopolitics and critical materials.

On a more general level, this thesis has also highlighted a need for a better understanding of the dynamics of the financial sector and notably the possible evolution of exposures and vulnerability to asset stranding in high-carbon sectors. Chapter 5 presented a tentative step in this direction, but more data would be required to come up with a precise picture of such dynamics. Other methodological approaches could be considered. Notably, the financial and industrial network approaches represent two promising avenues to pinpoint possible transition risk developments. In particular, there is room to make current approaches to financial networks more dynamic, for instance, by building on statistical regularities in the evolution of exposures in observed financial networks.

However, this exciting research programme must come alongside a critical use of the transition risk notion. This term, coined by a central banker to match the *jargon* of financiers, is anything but innocent. On top of leaving aside key dimensions of the broader ecological transition, like adaptation, and besides reducing transition developments to yet another risk factor to be hedged, it also locks the understanding of the macro-financial consequences of the transition into a technical and ultimately a-politicised understanding. Let us not forget, however, that beyond the risks to the financial system – that, this dissertation has shown, may be small – the issue of asset stranding and asset losses is first and foremost distributional. In the end, it is a matter of political economy, a dimension that the transition risk term tends to make invisible.

Most importantly, financial instability should not be taken as a pretext to absolve the financial system from carrying its share of the burden of decarbonisation. It should not, either, exempt us from answering crucial questions. How to force powerful incumbents out and create new ways to organise our economies? How to make asset-holders accept possible losses or become agents of change? How to reallocate workers whose skills and jobs will be made redundant? How to ensure that we embark on sufficiently transformative paths? And, most of all, how to make sure that the scarecrow of possible financial disturbances does not lead to over-protecting those who probably need it least? Answering these questions is probably more pressing than worrying about a potential financial crisis. If only because they could lead to adopting much more ambitious – and protective – climate-finance policies than those proposed so far.

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Conclusion en français

La question des risques liés à la transition vers une économie sobre en carbone est devenue un sujet d'importance pour les régulateurs financiers et les agents financiers. En proie à de nombreuses incertitudes, qu'elles soient empiriques, théoriques ou méthodologiques, le domaine est en constante recherche d'améliorations des approches existantes et d'ouvertures vers d'autres méthodes économiques. Dans ce manuscrit, j'ai voulu proposer plusieurs étapes dans cette direction en faisant principalement appel à des méthodologies visant à caractériser les risques de transition sur l'ensemble des trajectoires d'atténuation. Plus précisément, cette thèse a été conçue comme une interface entre la littérature sur les risques de transition proprement dite, les approches en évaluation intégrée de la littérature Énergie-Économie-Environnement et la méthodologie stock-flux cohérente issue de l'école post-keynésienne. Après une revue de la littérature, j'ai développé et appliqué un nouveau modèle à l'étude des risques de transition, avec un accent particulier sur les émulations de scénarios. J'ai également proposé de nouvelles perspectives théoriques et empiriques sur les questions d'échouage d'actifs et de risques de transition avant d'explorer une proposition politique radicale.

Dans cette conclusion, je résume d'abord les contributions de cette recherche et j'en souligne les principaux enseignements (i). Ensuite (ii), je discute des limites de cette thèse avant (iii) d'ouvrir de nouvelles voies et perspectives de recherche.

Contributions de la thèse

Résumé par chapitre

Cette thèse commence par un état de l'art (Chapitre 1), qui fournit une vue d'ensemble de la littérature sur les risques de transition. Elle rassemble notamment la littérature sur l'échouage d'actifs, les risques de transition financière et l'économétrie financière au sein d'une grille d'analyse cohérente. Les conclusions de cette revue de la littérature sont triples. Premièrement, elle appelle à une utilisation plus large des scénarios dans la littérature sur l'évaluation des risques de transition, notamment dans l'étude des risques de transition sur des trajectoires d'atténuation à long terme. Deuxièmement, j'ai souligné la nécessité d'une meilleure modélisation des anticipations. Enfin, j'ai montré qu'une meilleure compréhension du secteur financier et, par conséquent, une meilleure représentation de ce dernier dans les cadres de modélisation existants étaient essentielles pour mieux saisir les interactions entre l'économie réelle et l'économie financière dans les scénarios de transition. Cette thèse a été organisée selon ces trois axes.

Les deux premiers chapitres ont développé une méthodologie destinée à étudier les risques liés à la transition vers une économie à faibles émissions de carbone pour un grand nombre de scénarios d'atténuation, tout en permettant un traitement intégré des interactions entre l'économie réelle et l'économie financière.

Cette approche a commencé par l'élaboration et la présentation d'un modèle stock-flux cohérent dans le Chapitre 2. Ce modèle offre une représentation compacte de la transition à faible émission de carbone tout en offrant une désagrégation du secteur financier et des interactions entre les agents financiers. J'ai appliqué ce modèle aux scénarios proposés par le NGFS afin de fournir le premier *stress test* climatique basé sur un modèle stock-flux cohérent. J'ai montré que, si les banques sont relativement protégées des risques liés à la transition, d'autres agents financiers sont plus vulnérables en raison des changements dans les prix des actifs qui se produisent tout au long de la transition, avec des tensions significatives à moyen et long terme dans les

transitions les plus disruptives. En outre, j'ai tiré parti de la capacité du modèle à émuler différentes variantes de scénarios pour mettre en évidence les différences entre les sentiers d'atténuation dont les narratifs sont similaires, mais qui sont initialement générés par des cadres de modélisation distincts. Ce faisant, j'ai démontré que des différences significatives peuvent émerger de différentes variantes de la même trajectoire d'atténuation, appelant à la prudence dans l'examen d'un ensemble réduit de scénarios.

Dans le Chapitre 3, avec Céline Guivarch, je me suis appuyé sur cette dernière observation et j'ai étendu cette méthodologie à un grand ensemble de sentiers d'atténuation, la première étude de ce type à ma connaissance. La première contribution de ce chapitre est une classification de tous les scénarios de la base de données du GIEC en cinquante groupes et la détermination d'un « meilleur représentant » dans chaque groupe. Ensuite, nous avons reproduit et élargi la méthodologie du Chapitre 2 en tenant compte de l'incertitude des paramètres et de l'incertitude macroéconomique, et en appliquant FASM-ID sur l'ensemble de nos meilleurs représentants. Nous constatons à nouveau que les agents financiers non bancaires sont principalement affectés, bien que les scénarios aux risques les plus élevés affectent davantage le secteur bancaire. Ces scénarios se caractérisent par une faible efficacité de la politique climatique, dans le sens où des niveaux élevés de prix du carbone doivent être mis en œuvre pour atteindre un objectif de décarbonisation donné. Nous constatons en outre que dans la majorité des cas, les risques liés à la transition financière vers une économie à faibles émissions de carbone sont maîtrisés, ce qui représente une vision optimiste de la faisabilité de la transition du point de vue des risques liés à la transition. Ces scénarios réalisables incluent des trajectoires d'atténuation avec une ambition climatique élevée si les politiques climatiques correspondantes ne sont pas trop strictes.

Les deux chapitres suivants répondent aux deux autres préoccupations soulevées par l'analyse documentaire, à savoir la modélisation des anticipations et une meilleure compréhension du secteur financier.

Le Chapitre 4, coécrit avec Louison Cahen-Fourot, Emanuele Campiglio, Michael Gregor Miess et Andrew Yardley, propose une nouvelle façon de modéliser les anticipations dans le contexte de la transition vers une économie sobre en carbone. En se basant sur le fait que la forme de la transition vers une économie sobre en carbone ne peut être prédite, le modèle suppose que les agents ont des croyances autonomes sur l'évolution future de la transition. Ces croyances ne sont pas nécessairement modèle-cohérentes et peuvent conduire les agents à adopter des comportements potentiellement contradictoires entre eux. Nous appliquons cette intuition à un modèle compact de choix d'investissement adaptés aux questions de transition, dans lequel les agents décident d'investir dans du capital à forte ou à faible intensité de carbone en fonction de l'échouage attendu. Nous constatons notamment qu'une augmentation de la dispersion des anticipations peut affecter de manière significative les investissements à faible intensité de carbone, notamment si les développements à court terme sont plus incertains. Cet article montre que la prise en compte de la dispersion des croyances est un élément clé de la modélisation des anticipations en matière de transition. En outre, cette approche pourrait, en principe, être appliquée à des modèles macroéconomiques à plus grande échelle et à une variété d'agents économiques.

Le Chapitre 5 a ajouté une note empirique à la thèse en explorant comment les agents financiers ont modifié leurs expositions aux entreprises non financières les plus exposées aux risques de transition à faible émission de carbone entre l'Accord de Paris et l'épidémie de Covid. Cette démarche a été motivée par le désir de mieux comprendre comment les expositions ont évolué et pourraient évoluer dans le temps avant l'introduction de politiques climatiques décisives. En désagrégeant les types d'agents financiers, les régions et la taille des portefeuilles, j'ai pu déterminer quels types d'agents étaient plus enclins à augmenter leur exposition aux entreprises à haut risque de transition entre l'Accord de Paris et l'épidémie de Covid. Je constate notamment que les agents les plus susceptibles à augmenter leur exposition sont situés dans les économies émergentes et que les fonds de pension des économies du Nord, en particulier dans les pays anglo-saxons, ont montré un penchant omniprésent pour

les entreprises les plus polluantes du monde. Je constate également une polarisation croissante du système financier en termes d'exposition aux entreprises à forte intensité de carbone, qui va de pair avec une augmentation de la concentration des expositions. Ces résultats contribuent à une meilleure compréhension de la dynamique des expositions aux risques de transition. Elles soulignent avant tout que la répartition des pertes financières sera de plus en plus déséquilibrée en faveur des économies émergentes. Il convient donc d'accorder une plus grande attention aux risques de transition dans les économies émergentes et à la manière dont ils pourraient se répercuter sur les systèmes financiers centraux. Plus précisément, il conviendrait de mettre davantage l'accent sur la dynamique des balances des paiements et des taux de change liée à la transition. Plus généralement, ce chapitre a mis en évidence le fait que les agents financiers ont des anticipations et des positions très diverses à l'égard des risques de transition. Cette constatation appelle à (i) un meilleur recensement de ces positions et (ii) une modélisation du secteur financier qui tienne pleinement compte de cette hétérogénéité.

Enfin, le Chapitre 6 propose une ouverture sous la forme d'une discussion politique. Avec Mathilde Salin, nous avons examiné la pertinence et les défis associés à une proposition politique émergente : la création d'une *bad bank* climatique. À l'instar des *bad banks* traditionnelles, cette institution prendrait dans son bilan les actifs les plus vulnérables aux risques de transition. Cette mesure pourrait alléger le bilan des agents financiers les plus exposés aux risques de transition et éviter que les risques ne soient transférés à des agents moins solides et moins réglementés. Sur la base d'un examen des *bad banks* historiques, nous avons mis en évidence les défis posés par une éventuelle *bad bank* climatique, et fourni un schéma provisoire pour la construction d'une telle institution.

5.1 Principaux enseignements de la thèse

Globalement, les enseignements tirés de cette thèse au long de ses six chapitres peuvent être résumés à travers les quatre points suivants.

Les agents financiers ne sont pas affectés de la même manière par les risques de transition. En outre, ces derniers vont bien au-delà des ajustements à court terme et dépendent dans une large mesure du rythme et de la forme de la transition ainsi que de l'orientation de la politique climatique correspondante. Notamment, les risques liés aux dévaluations d'actifs sont plus susceptibles de donner lieu à des risques de transition à long terme et à des chocs plus importants pour les agents financiers. Les risques de crédit, qui affectent les banques, sont généralement relativement faibles et ne donnent lieu qu'à des ajustements transitoires. Les banques sont en effet en mesure d'absorber une grande partie des pertes sur les défauts de paiement des prêts commerciaux résultant de la transition. En revanche, les institutions non bancaires semblent plus fragiles.

Si l'on examine un large éventail de scénarios, environ 60 % des trajectoires d'atténuation représentatives n'entraînent pas de risques significatifs liés à la transition financière. Cette perspective est rassurante en ce qui concerne la faisabilité de la transition sur le plan de la stabilité financière, d'autant plus que ces trajectoires comprennent même des scénarios très ambitieux sur le plan climatique, avec une pression relativement élevée en matière de politique climatique. Toutefois, cela signifie qu'environ 40% des scénarios d'atténuation présentent des risques élevés pour le secteur financier, certains d'entre eux conduisant même à des crises financières à moyen ou long terme. Ces scénarios se caractérisent principalement par des prix du carbone élevés pour des objectifs de décarbonisation moyennement ambitieux, ce suggère que l'efficacité des prix du carbone pourrait être le principal facteur de risque de transition. Étant donné les résultats relativement maigres des prix du carbone jusqu'à présent et leur manque de popularité, il est nécessaire de concevoir des politiques climatiques moins punitives et des politiques de stabilisation financière solides pour couvrir les risques de transition potentiels.

La prise en compte de l'hétérogénéité des agents à travers une variété de variables, telles que les anticipations, les origines régionales ou le modèle

d'entreprise, est une frontière clé dans l'amélioration des évaluations des risques de transition. La dispersion des croyances futures concernant la transition peut conduire à des comportements d'investissement non coordonnés et éventuellement défavorables à la transition, ce qui pourrait certainement avoir un impact sur les risques de transition. **En outre, l'attention et l'importance accordées aux risques de transition par les investisseurs peuvent varier considérablement d'un investisseur à l'autre. Par conséquent, certains agents sont susceptibles de prendre des paris défavorables à la transition et de s'exposer à des risques supplémentaires. Cette thèse a montré que certains pays émergents et certains types d'agents financiers peuvent être plus susceptibles d'augmenter ces expositions.** Elle appelle à un examen minutieux de ces agents et à l'élaboration de politiques adéquates. Elle invite également à prendre sérieusement en compte l'hétérogénéité géographique et intra-financière dans les évaluations des risques de transition basées sur des modèles, en tenant compte des interactions pertinentes.

Enfin, une structure de défaillance climatique pourrait être un moyen viable d'atténuer les risques de transition éventuels, bien que cette politique pose des problèmes aigus en termes de distribution, d'efficacité et de réglementation. Une structure de défaillance préventive pourrait inscrire à son bilan les actifs les plus exposés au risque d'échouage, sur la base d'une taxonomie minutieuse des activités polluantes, en ciblant les institutions les plus fragiles sur le plan financier. Elle serait organisée comme un réseau de bad banks regroupées sous une institution englobante.

Limites de la thèse

Les approches utilisées dans ce doctorat ne sont cependant pas sans limites.

Tout d'abord, chaque chapitre a ses propres limites. Le Chapitre 1 ne s'est pas appuyé sur une approche systématique, ce qui a pu conduire à négliger certains articles. En

outre, il a laissé de côté des questions autres que les risques financiers liés au climat, comme la biodiversité (Svartzman et al. 2021) ou les matériaux critiques (Miller et al. 2023), deux préoccupations émergentes dans le domaine. Il n'a pas non plus abordé les politiques financières pour la transition, bien que le sujet soit devenu de plus en plus pressant au cours de la thèse. Le Chapitre 2 a développé un modèle nécessairement stylisé avec des hypothèses et des limites fortes, comme l'absence d'une dynamique définie du marché du travail ou d'une perspective au niveau mondial. Des travaux supplémentaires pourraient également être réalisés pour améliorer la calibration du modèle et sa validation. Le Chapitre 3, outre des mises en garde similaires à celles du Chapitre 2, a souligné certaines des limites de l'utilisation d'un cadre de modélisation unifié comme plateforme de comparaison. Par exemple, la structure d'économie réelle du modèle, basée sur le remplacement d'un secteur en place par un secteur concurrent, bien qu'elle ait donné lieu à des aperçus intéressants, a en partie conduit à des résultats contre-intuitifs. En outre, les trajectoires d'atténuation comportant des prix du carbone très élevés ont été très difficiles à simuler par le modèle, ce qui pose la question de sa capacité à émuler n'importe quel scénario de decarbonation. Les idées développées dans le Chapitre 4 n'ont malheureusement pas pu être portées à une échelle plus grande qui aurait permis d'étudier l'effet macroéconomique de la représentation des anticipations qu'il propose. En soi, le cadre pourrait bénéficier de raffinements supplémentaires, comme être amené à la dynamique et permettre l'hétérogénéité pour plus de variables que le taux d'utilisation. Le Chapitre 5 n'a offert qu'une évaluation partielle des changements d'exposition en se concentrant uniquement sur l'investissement en actions sur une période de temps réduite. Enfin, le Chapitre 6 se limite à une revue de la littérature et pourrait bénéficier d'un cadre théorique et formel plus clair pour étudier une *bad bank* climatique potentielle, et d'une comparaison plus systématique avec d'autres politiques financières climatiques, telles que les mesures actuelles visant à réduire les asymétries d'information ou d'autres mesures radicales, telles que les nationalisations vertes.

D'un point de vue plus général, cette thèse n'a pu répondre que partiellement à sa

question principale. En particulier, par rapport aux exercices de réglementation (T. Allen et al. 2020; Alogoskoufis et al. 2021), cette thèse a adopté une perspective agrégée en se concentrant sur les risques macro-financiers. Si cette approche est plus économique en termes de données et d'effort de modélisation, elle fournit nécessairement une image moins détaillée et moins précise des risques de transition. Ancrée dans une approche prospective, l'intention du doctorat était moins de fournir des estimations quantitatives précises à un niveau désagrégé que de proposer des modèles possibles de risques de transition. En outre, les connaissances théoriques et empiriques tirées des chapitres 4 et 5 n'ont pas pu être intégrées au modèle développé dans le cadre du doctorat. Tous ces éléments seront intégrés au modèle dans des travaux ultérieurs. Enfin, le doctorat n'a pas pu aller au bout de l'une de ses premières intentions, à savoir l'étude des politiques financières visant à atténuer les risques de transition. L'étude des politiques possibles s'est limitée à un traitement littéraire et historique, alors que FASM-ID pourrait, en principe, accueillir des politiques financières. Cela fera également l'objet d'un travail ultérieur.

Recherches futures et perspectives

Pour les recherches futures, l'amélioration de FASM-ID est une priorité absolue. Plusieurs pistes peuvent être envisagées. Améliorer la représentation du marché du travail et inclure la dynamique de la population serait un premier pas vers une meilleure représentation de la transition, étant donné l'importance de la démographie dans les trajectoires d'atténuation. Sur le thème plus précis des risques de transition, le modèle pourrait bénéficier d'une meilleure représentation des anticipations et d'une plus grande désagrégation à trois égards.

D'une part, une meilleure résolution géographique permettrait d'obtenir une image plus précise des actifs physiques échoués, répartis de manière très inégale dans le monde (Daumas 2023, Chapitre 2). Ensuite, l'amélioration de la désagrégation du secteur financier en incluant davantage de types d'agents ou en construisant un mod-

ule de secteur financier à part entière basé sur les agents pourrait représenter un important pas en avant pour mieux comprendre les risques de transition. Enfin, FASM-ID pourrait devenir un modèle plus riche en technologies avec une meilleure désagrégation sectorielle du secteur financier. D'autres ajouts pourraient également mieux représenter les politiques monétaires, fiscales et climatiques. Ces efforts pourraient certainement s'appuyer sur les enseignements des chapitres 4 et 5.

En suivant ces pistes, il serait possible de reproduire d'autres aspects des sentiers d'atténuation que le prix du carbone et les courbes d'émissions, comme le déploiement précis de technologies à faible teneur en carbone. FASM-ID pourrait ainsi être appliqué à des aspects plus précis des voies d'atténuation existantes et mesurer plus précisément les risques de transition. La prise en compte d'un plus grand nombre d'éléments des voies d'atténuation pourrait également améliorer leur caractérisation et leur regroupement, comme cela a été fait dans le Chapitre 3, et donc relier les risques de transition à un plus grand nombre de caractéristiques des scénarios. Les améliorations susmentionnées pourraient également permettre à FASM-ID de simuler des scénarios au-delà des trajectoires d'atténuation existantes, en incorporant des dimensions peu explorées, telles que la géopolitique et les matériaux critiques.

D'une manière plus générale, cette thèse a également mis en évidence la nécessité de mieux comprendre la dynamique du secteur financier et notamment l'évolution possible des expositions et de la vulnérabilité à l'échouage d'actifs dans les secteurs à forte intensité de carbone. Le Chapitre 5 a présenté un premier pas dans cette direction, mais davantage de données seraient nécessaires pour obtenir une image précise de cette dynamique. D'autres approches méthodologiques pourraient également être envisagées. Notamment, les approches par les réseaux financiers et industriels représentent deux voies prometteuses pour identifier les évolutions possibles des risques de transition. En particulier, il serait possible de rendre les approches actuelles des réseaux financiers plus dynamiques, par exemple en s'appuyant sur des régularités statistiques dans l'évolution des expositions dans les réseaux financiers observés.

Toutefois, cet enthousiasmant programme de recherche doit s'accompagner d'un usage critique de la notion de risque de transition. Ce terme, inventé par un banquier central pour épouser le jargon des financiers, est loin d'être innocent. En sus de laisser de côté des dimensions essentielles de la transition écologique au sens large, comme l'adaptation, et de réduire les évolutions de la transition à un énième facteur de risque contre lequel se couvrir, il enferme la compréhension des conséquences macro-financières de la transition dans une compréhension technique et finalement dépolitisée. N'oublions pas cependant qu'au-delà des risques pour le système financier – qui, comme l'a montré cette thèse, pourraient s'avérer modestes – la question de l'échouage des actifs et des pertes au bilan est avant tout distributive. Il s'agit finalement d'une question d'économie politique, une dimension que l'expression risque de transition tend à rendre invisible.

Plus important encore, l'instabilité financière ne doit pas servir de prétexte pour dédouaner le système financier de sa part du fardeau de la décarbonisation. Elle ne doit pas non plus nous exonérer de réponses à des questions cruciales. Comment forcer les acteurs historiques à se retirer et créer de nouveaux modèles économiques ? Comment faire en sorte que les détenteurs d'actifs acceptent d'éventuelles pertes ou deviennent des moteurs du changement ? Comment réaffecter les travailleurs dont les compétences et les emplois seront supprimés ? Comment s'assurer que nous nous engageons sur des trajectoires suffisamment transformatrices ? Et surtout, comment faire en sorte que l'épouvantail des perturbations financières possibles ne conduise pas à surprotéger ceux qui en ont probablement le moins besoin ? Répondre à ces questions est probablement plus urgent que de s'inquiéter d'une éventuelle crise financière. Ne serait-ce que parce qu'elles pourraient conduire à l'adoption de politiques prudentielles beaucoup plus ambitieuses – et protectrices – que celles proposées jusqu'à présent.

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