'Bridging' human needs and carbon dioxide emissions reduction : the infrastructure dynamics at the core of the climate-development interplay

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Résumé de la thèse

’Faire le pont’ entre les besoins humains et la réduction des émissions de CO2 : la dynamique des infrastructures à l’interaction des enjeux de climat et de développement

Les enjeux de développement humain et de réduction du changement climatique sont liés et les infrastructures - bâtiments et ouvrages de génie civil - sont essentielles pour atteindre conjointement ces objectifs. Elles fournissent des services répondant aux besoins sociétaux mais cette fourniture est aujourd’hui insuffisante et intensive en émissions de CO_2 au niveau de leur usage et de leur construction. Toutefois, leur dynamique est soumise à des contraintes techniques, économiques et institutionnelles. Dans cette thèse, j’étudie la manière dont l’évolution des stocks globaux d’infrastructures peut permettre de concilier besoins de développement et réduction des émissions de CO_2. Je me concentre sur trois points de tension: (i) le verrouillage carbone - l’inertie sur la réduction des émissions futures - induit par le développement à court terme, (ii) le financement limité pour l’investissement et (iii) l’espace carbone pour un développement suffisant des infrastructures de base. Cette thèse apporte une contribution en mettant en lumière certaines conditions à assurer pour que les infrastructures ne limitent pas la faisabilité de la conciliation climat-développement.

Dans un premier temps, j’effectue une revue systématique de la littérature sur le verrouillage carbone induit par les infrastructures. J’utilise une approche d’apprentissage machine supervisé pour sélectionner les articles pertinents. Je synthétise selon les secteurs et zones géographiques les quantifications existantes de verrouillage carbone, les indicateurs utilisés pour le mesurer et les énoncés mentionnant des implications politiques pour en sortir. Je montre que les centrales électriques au charbon contribuent fortement au verrouillage carbone global et sont exposées au risque d’actifs échoués du fait du retrait anticipé. La répartition sectorielle et le montant des actifs échoués diffèrent selon les pays, avec potentiellement des montants importants pour les bâtiments dans les pays développés. Les actifs échoués sont réduits si les politiques climatiques sont mises en place rapidement. Il est nécessaire d’assurer la légitimité et la stabilité sur le long terme de ces dernières ainsi que la coordination entre les secteurs d’infrastructures. La tarification du carbone ne doit pas être le seul instrument utilisé et doit être complétée par la réglementation et un soutien financier au déploiement du capital bas-carbone.

Dans un deuxième chapitre, je quantifie les besoins d’investissements en infrastructures de transport au regard de différents niveaux d’ambitions climatiques. Je construis des scénarios socio-économiques avec un modèle d’évaluation intégré qui représente explicitement le secteur des transports. Je développe un module pour quantifier les besoins d’investissement en cohérence avec les scénarios de mobilité. J’applique une analyse de sensibilité globale pour identifier les

déterminants des besoins d'investissements. Je montre que les besoins d'investissements se réduisent avec l'augmentation de l'ambition climatique mais représentent des montants importants par rapport aux niveaux historiques et aux besoins dans les autres secteurs. Les niveaux d'utilisation du réseau ferré et les coûts de construction des routes sont des facteurs déterminants et pourraient être des leviers à activer pour favoriser les trajectoires bas-carbone à cout réduit.

Dans un troisième chapitre, j'évalue si un niveau élevé d'accès à 5 services essentiels- électricité, eau, habitat, assainissement et transport - peut être fourni à l'échelle mondiale sans compromettre les objectifs d'atténuation du climat. Je quantifie dans chaque pays les besoins en ciment et acier sur la base des tendances historiques. J'estime ensuite les émissions de CO_2 associées à la fabrication de ces matériaux en intégrant les facteurs d'influence tels que les technologies de production, la structure du commerce international et les mesures d'atténuation dans ces industries. Je montre qu'offrir un accès élevé à l'assainissement et aux transports peut entrer en conflit avec les trajectoires bas–carbone envisagées. Ces résultats suggèrent la nécessité d'une limitation de l'usage de ciment et d'acier et d'efforts supplémentaires de réduction des émissions dans les pays développés.

THESIS SUMMARY

'Bridging' human needs and carbon dioxide emissions reduction : the infrastructure dynamics at the core of the climate-development interplay

Human development and climate change mitigation are related, and infrastructure - buildings and engineered constructions - is essential to jointly achieve these objectives. Infrastructure provide services that meet societal needs, but this provision is currently insufficient and CO_2 emissions intensive in the use and construction. However, infrastructure dynamics is subject to technical, economic and institutional constraints. In this thesis, I investigate how the evolution of global infrastructure stocks can reconcile development needs with CO_2 emissions reduction. I focus on three points of tension: (i) carbon lock-in - the inertia on future emissions reduction - induced by short-term development, (ii) limited financing for investment, and (iii) the carbon space for sufficient basic infrastructure development. This thesis makes a contribution by highlighting some of the conditions that need to be met if infrastructure is not to limit the feasibility of climate-development reconciliation.

In a first chapter, I systematic review the literature on infrastructure-induced carbon lock-in. I use a supervised machine learning approach to select relevant articles. I synthesize according to sectors and geographical areas the existing quantifications of carbon lock-in, the indicators used to measure it and qualitative statements mentioning policy implications to get out of it. I show that coal-fired power plants contribute significantly to global carbon lock-in and are exposed to the risk of stranded assets due to early retirement. The sectoral distribution and amount of stranded assets differ between countries, with significant amounts for buildings sector in developed countries. Stranded assets are reduced if climate policies are implemented quickly. There is a need to ensure the legitimacy and long-term stability of these policies and coordination between infrastructure sectors. Carbon pricing should not be the only instrument used and should be complemented by regulation and financial support for the deployment of low-carbon capital.

In a second chapter, I quantify the investment needs in transportation infrastructures in relation to different levels of climate ambitions. I build socio-economic scenarios with an integrated assessment model that explicitly represents the transport sector. I develop a module to quantify investment needs in line with future mobility trends. I apply a global sensitivity analysis to identify the determinants of investment needs. I show that investment needs decrease with increasing climate ambition but represent significant amounts compared to historical levels and needs in other sectors. Rail utilization level and road building costs are determining factors and could be levers to be activated to promote low-carbon pathways with reduced costs.

In a third chapter, I assess whether a high level of access to five essential services - electricity, water, shelter, sanitation and transport - can be provided globally without compromising climate mitigation goals. I quantify in each country the needs for cement and steel based on historical trends. I then estimate the CO_2 emissions associated with the manufacture of these materials by taking into account influencing factors such as production technologies, international trade patterns and mitigation actions in these industries. I show that providing high access to sanitation and transport can conflict with the existing low-carbon trajectories. These results suggest the need to limit the use of cement and steel and for further efforts to reduce emissions in developed countries.

Mots clefs

Infrastructures Verrouillage carbone Emissions engagées Actifs échoués Revue systématique Besoins d'investissements Modèle d'évaluation intégré Analyse globale de sensibilité Besoins essentiels Accès aux infrastructures Émissions de dioxyde de carbone incorporées

KEYWORDS

Infrastructures   Carbon lock-in   Committed emissions   Stranded assets   Systematic map
Investment needs   Integrated assessment model   Global sensitivity analysis   Basic needs
Infrastructures access   Embodied carbon dioxide emissions

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List of articles from the thesis

Chapter 2 : Fisch-Romito, Vivien, Celine Guivarch, Felix Creutzig, Jan C Minx, and Max W Callaghan. 2020. Systematic Map of the Literature on Carbon Lock-in Induced by Long-Lived Capital. *Environmental Research Letters*. doi : 10.1088/1748-9326/aba660

Chapitre 3 : Fisch-Romito, Vivien, and Céline Guivarch. 2019. Transportation Infrastructures in a Low Carbon World: An Evaluation of Investment Needs and Their Determinants. *Transportation Research Part D: Transport and Environment* 72 (July): 203–19. doi: 10.1016/j.trd.2019.04.014.

Chapitre 4 : Fisch-Romito, Vivien. Embodied carbon dioxide emissions to provide universal high levels of access to basic infrastructures. *Under revision in Global Environmental Change.*

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LIST OF ACRONYMS

ASCE	American Society of Civil Engineers
AR	Assessment Report
BF	Blast Furnace
BOF	Basic Oxygen Furnace
BRT	Bus Rapid Transit
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
GDP	Gross Domestic Product
GHG	Greenhouse gas emissions
GNR	Getting the Numbers Right
HSR	High Speed Rail
IAM	Integrated Assessment Model
IPCC	Intergovernmental Panel on Climate Change
LLCS	Long Lived Capital Stocks
LMDI	Long Lived Capital Stocks
NDC	National Determined Contribution
OECD	Organisation for Economic Co-operation and Development
OHF	Open Hearth Furnace
QS	Qualitative Statements
RAI	Rural Access Index
SDG	Sustainable Development Goal
SSP	Shared Socioeconomic Pathways
SRC	Standard Regression Coefficients
USA	United States of America
WBCSD	World Business Council for Sustainable Development
WOS	Web Of Science

Chapter 1

Introduction

This thesis addresses the infrastructures as a key driver to unite human development and climate change mitigation. My motivations for approaching the infrastructures topic from this angle are multiple. Infrastructures here refer to buildings and engineered constructions which support human activities. They are essential so that the built environment meet societal needs. At the same time, they determine the climate impact of human well-being during their construction and operation stages. Understanding the constraints affecting the infrastructure dynamics is essential to enable decision-makers to make investment choices supporting the climate-development conciliation.

The objectives of this introduction are to show (i) how infrastructures are at the intersection of human development and climate change mitigation and (ii) how the evolution of infrastructure is subject to different constraints that make this conciliation challenging. In the first part of the introduction, I explicit the infrastructures definition used in this thesis and the capital goods considered as such (section 1.1). I then show how infrastructures contribute to human development (section 1.1.1) and play a role in greenhouse gas emission trajectories (section 1.1.2). In the second part of the introduction, I highlight three potential bottlenecks around the dynamics of infrastructures for the climate-development conciliation on which I focus in this thesis. First of all, I mention the risk of carbon lock-in as the short term infrastructures development hindering the emissions reductions later on (section 1.2.1). I then highlight the existing tension of financing investments needs and the future risks of crowding out investments, with a focus on the transportation sector (section 1.2.2). Finally, I question the carbon emissions space available under a climate constraint for a sufficient development of infrastructures in the short term, regarding the slow decarbonisation dynamics in the steel and cement sectors (section 1.2.3). I end this introductory chapter with a third part in which I present the thesis outline.

1.1 Infrastructures at the intersection of human development and greenhouse gas emissions reduction issues

1.1.1 A long-lasting exoskeleton

"How many of us could survive without the 4,000 tons of built environment and transformed habitat that belong to each of us? [...] Our human powers—of sheltering, feeding, communicating, connecting, creating, moving, and working—take place through vast built systems. That infrastructure has become the external body of humanity, and it is an exoskeleton [...] that

is not really optional for any of us." (Pardy, 2019). Our built environment support human activities through different stocks of infrastructures. Multiple definitions of this term coexist either describing the functions and characteristics of infrastructures, or compiling a set of goods considered as such, or doing both (Buhr, 2003; Prud'Homme, 2005; Fourie, 2006; Baldwin and Dixon, 2008; Fulmer, 2009).

Infrastructures have a primary role of providing services to meet societal needs. Fulmer (2009) argued that most of the existing definitions of infrastructures can be summarized as *"the physical components of interrelated systems providing commodities and services essential to enable, sustain, or enhance societal living conditions."*. In a discussion paper, Buhr (2003) used the term material infrastructures as *"the capital stocks that serve the function of mobilizing the economic potentialities of economic agents"*. Infrastructures are then considered as capital goods in opposition to consumption goods by producing service, such as the roads providing accessibility of certain locations to people and goods.

Infrastructures also play the role of intermediaries between social outcomes and biophysical resource use Brand-Correa and Steinberger (2017) presented physical infrastructures as integral part of the 'provisioning systems' which are *a set of related elements that work together in the transformation of resources to satisfy a foreseen human need* (Fanning et al., 2020). In the same manner, Pauliuk and Müller (2014) argued infrastructures have a role of 'consumption couplers' by linking the provision of service to energy and material flows.

One key characteristic to differentiate infrastructure stocks from other type of capital is their fixity. They are unmobile in opposition to other capital such as furnitures or machineries (Lanau et al., 2019) and stay in place for a long time (Baldwin and Dixon, 2008), from decades to more than a century (Table 1.1). They can be considered as long-lived capital stocks following the denomination of (Lecocq and Shalizi, 2014).

The list of capital goods considered as infrastructures can be narrow to broad depending on the definition considered. While some authors have only included the networked engineered construction (Fulmer, 2009) such as transportation, water, sanitation and communication systems, others have extended the definition beyond the physical elements including the established rules of a community as institutional infrastructure and the human capital as personal infrastructures (Buhr, 2003). Here I consider as infrastructures both buildings and engineered constructions, following Baldwin and Dixon (2008), because of their particular role at the intersection of human development and climate change mitigation. The compilation of capital goods I include is provided in figure 1.1 following the classification of Lanau et al. (2019).

1.1.2 A backbone for human development

Infrastructures are vectors of life quality and welfare improvements (Kessides, 1993; Prud'Homme, 2005). They provide services to households to fulfill their basic needs such as shelter, water, sanitation or food. Urban form affects the frequency of walking and bicycling which influence obesity (Papas et al., 2007). Infrastructures also protect people from hazards such as floods or disease from sewage (Thacker et al., 2019). Infrastructures development is a

Sector	Time scale (years)
Water infrastructures	30-200
Land-use planning	>100
Building and housing	30-150
Transportation infrastructure	30-200
Urban planning	>100
Energy extraction & transformation	20-70

Table 1.1 – Sample of infrastructures lifetimes in different sectors Hallegatte (2009).

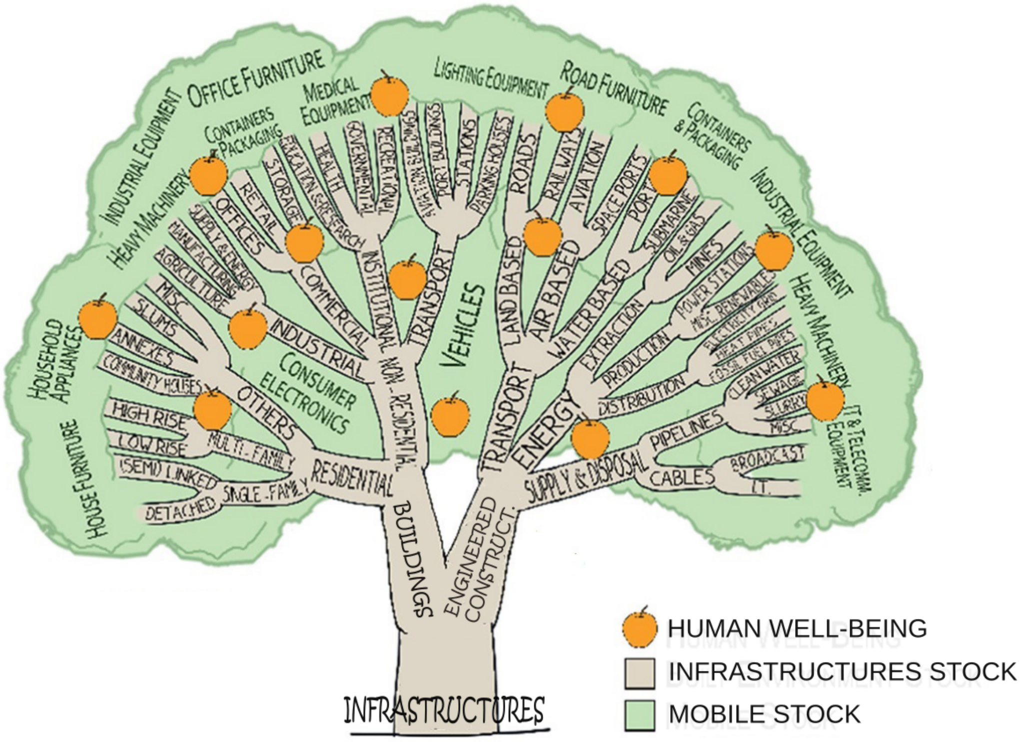

Figure 1.1 – Infrastructures stock categories as a tree. Adapted from Lanau et al. (2019)

significant determinant of poverty reduction (Akanbi, 2015; Chotia and Rao, 2017). Infrastructures create as well the capabilities to allow individuals to make choices between things they consider to be valuable and to actually attain them (Jakob et al., 2016; Clark et al., 2018). For instance, transportation and communication services allow for greater access to leisure, education or natural amenities (Kessides, 1993).

Infrastructures also foster economic growth. The interest of researchers in relating the investment in infrastructures to economic growth has been boosted since the late-1980's with the seminal work of Aschauer (1989) who found large positive impact of public capital investment on output on the 1949-1985 period in United States. Following this work, a first generation of studies have obtained similar result but this finding have been debated because of the wide range of values obtained (Munnell, 1992; Gramlich, 1994). Critics also have mentioned a spurious correlation because of omitted influencing variables or a chicken-egg problem because of uncertain direction of causality (Kessides, 1993; Gramlich, 1994). Several surveys (Romp and De Haan, 2007; Straub, 2011; Calderón and Servén, 2014) have highlighted a consensus from more recent empirical studies that the increase of infrastructure capital furthers economic growth but with a lower effect than found previously.

Different mechanisms can explain the positive impact of infrastructures investments on economic growth (Prud'Homme, 2005; Fourie, 2006). First of all, production costs are reduced as the services provided by infrastructures are intermediate inputs. For instance, investments can be made to improve a electricity network and reduce shortages which can damage a firm's electrical machines or result in the loss of perishable products that require energy to be conserved. Health of workers and their productivity are also improved with access to sanitation services. Secondly, long-lived capital stocks such as communication and transportation infrastructures expand the access to markets of goods and labour, notably in rural areas where they allow for an economy diversification. Transportation infrastructures increase the ability for a country to engage in interegional and international trade (Donaldson, 2018). Heterogeneous order of magnitude in terms of impact on economic growth have been obtained across countries, sectors and time (Straub, 2011; Calderón and Servén, 2014; Holmgren and Merkel, 2017). Straub (2011) justified this heterogeneity by the following reasons : capital investments may have only a transitory effect on growth; once the infrastructure is in place, maintenance investment can have as greater impact; productivity gains can only be felt when a certain infrastructure threshold of coverage is reached.

Yet, many regions have inadequate infrastructures both in terms of quantity and quality. In terms of quantity, this translates into insufficient access to some essential services. In several African countries, the majority of the population has no access to electricity, sanitation or communication technology and South Asia is also affected by a low access level to sanitation and communication technology (Fuss et al., 2016). More than 60 millions homes in India are not considered as decent living (Mastrucci and Rao, 2019). The quality of the built environment is also an element of concern. Indeed, even if access to services is ensured, service quality provided can be heterogeneous. For instance, several countries in South Asia, Africa or Latin America have more than 75% of their population with an access to a road within 2km but less than 50% of the overall network is paved which can limit accessibility in certain seasons (Wenz et al., 2020). Many households in Sub-Saharan Africa and India with access to electricity are subject to frequent outages because of insufficient generation capacities or poor transmission and distribution infrastructures (Aklin et al., 2016; Farquharson et al., 2018). This issue of quality is not limited to developing countries. The recent collapse of the Morandi highway bridge at Genoa (El-Faizy, 2018) has highlighted a situation of chronic under-investment in the maintenance of existing stocks in developed countries, leading to a certain obsolescence of some structures. Every four years, the American Society of Civil Engineers (ASCE) describes in the "Report Card for America's Infrastructure" the state and performance of the American infrastructure, taking into account the physical condition and the investments needed for improvement. The institution have given in 2017 and 2013 the grade of D+ (on a scale of A to F) on the overall infrastructures stock which is associated to poor to fair condition and significant deterioration (ASCE, 2017).

Since 2015, United Nations members agreed on a common framework for human development through 17 Sustainable Development Goals (SDGs) and 169 associated targets with infrastructures as essential parts. 5 categories of capital stocks- energy, transport, water, solid waste and digital communications- directly or indirectly influence 72% of these targets (Thacker et al., 2019). About half of SDG financing needs for developing countries are hence related to infrastructures. (Franks et al., 2018). The interdependence between the different capitals stocks, especially network infrastructures, extends their influence beyond the single service they provide (Clark et al., 2018; Adshead et al., 2019). Then, the global urbanization rate growth and population increase expected for the next decades (Jones and O'Neill, 2016) require at the global scale a rapid build-up of new stocks and an upgrade to existing ones.

1.1.3 A crucial role for climate change mitigation

Human activity and related greenhouse gas emissions are the cause of a global warming since the pre-industrial period. Any additional increase in temperature will be associated with increased risks to health, livelihoods, food security, water supply, human security and economic growth (Hoegh-Guldberg et al., 2018). Since 2015 and the Paris agreement, 197 countries have agreed to limit the global temperature increase to below 2°C and if possible to 1.5°C. This implies to reduce our greenhouse gas emissions in the coming years in order to reach zero net emissions during the second half of the century (Rogelj et al., 2018).

Infrastructures play a major role in this objective by shaping the patterns of energy demand & supply and the emissions associated. At first glance, infrastructures, by allowing the production of infrastructures services to be common, reduce greenhouse gas emissions compared to a system where, all other things being equal, services would be produced in an atomized manner. For instance, the construction of network infrastructures improved the energy efficiency of the manufacturing industry in China during the period 2003-2016 (Lin and Chen, 2019). Another example is the use of back-up diesel generators in 15 Sub-Saharan countries which is associated with higher fossil energy consumption compared to the central grid case (Farquharson et al., 2018). However, stronger actions are needed on the infrastructures stock to decarbonize the entire economic system.

On the energy supply side, electricity and heat generation contributed in 2018 to around 43% of global energy-related emissions (IEA, 2020). The reason is the sector's heavy dependence on fossil fuels power plants which represented in 2018 around two thirds of the total world electricity production with coal and gas power plants shares respectively equal to 39% and 22% (IEA, 2020). The energy demand side is also concerned with different end-use sectors. One third of global final energy consumption is attributed to buildings energy demand, with floor space as an important determinant (Levesque et al., 2018). The sector has a potential for reduction through the construction of new low-energy buildings and a high rate of energy refurbishment of existing buildings (Röck et al., 2020). Significant reduction of emissions is also necessary in the transportation sector with accounted for 26% of final energy use and 65% of oil consumption in 2015 (International Energy Agency, 2017). Transportation infrastructures have an important role to play in encouraging a modal shift towards less carbon-intensive modes of transport for both passengers and goods (Creutzig et al., 2016b; Kaack et al., 2018).

Yet, with the progress made in recent years on the operational energy consumption stage, it appears also necessary to go beyond and focus as well on the emissions associated with the manufacturing of construction products (Huang et al., 2018; Röck et al., 2020). The construction and maintenance of infrastructures are material-intensive making it the primary determinant of global material consumption (Miatto et al., 2017; Huang et al., 2017). Concrete is the second most consumed material after water in the world with an annual consumption of 30 billion tonnes (Monteiro et al., 2017). The manufacture of certain structural materials such as steel, concrete or aluminium are carbon-intensive and considered difficult to decarbonise in the current context due to technical constraints (Davis et al., 2018). The construction of new urban infrastructure could account for almost one third of total urban emissions between 2016 and 2030 (Creutzig et al., 2016a) and infrastructure development in developing countries could consume a significant part of the remaining carbon budget available to meet the Paris Agreement targets (Müller et al., 2013).

The interdependence between infrastructures means that the decarbonisation of one type of infrastructures will have an influence on the use of others and the associated emissions. For instance, the urban form can reduce emissions in both buildings and transportation sectors by reducing travel demand and building energy consumption and by fostering modal shift to non-motorized modes (Creutzig et al., 2016b). Also, if emissions reduction are targeted, the evolution of the demand for electric vehicles will differ depending on the decarbonisation rate of electricity sector. It will influence the structure of passenger transport and the associated infrastructures. The absence of decarbonisation actions on one type of infrastructures can then slow down the decarbonisation of others and, conversely the decarbonisation of one type of infrastructure can enable the greening of others (Figure 1.2).

1.2 Infrastructure dynamics as bottlenecks to climate-development combination

Sustainable Development Goals and the Paris Agreement agenda are intrinsically linked because the way in which the first are achieved affects the second and vice versa. Multiple synergies and trades offs exists and the combination of emission reduction and human development trajectories determines the distribution between these two coeffects and their extent (von Stechow et al., 2015). For instance the levels of warming targeted in the long term and the ambitions of emission reductions in the short term impact the risk levels of missing some SDGs related to food security, economic growth or job access. (Von Stechow et al., 2016; Bertram et al., 2018). The evolution of infrastructures must therefore be thought within this common

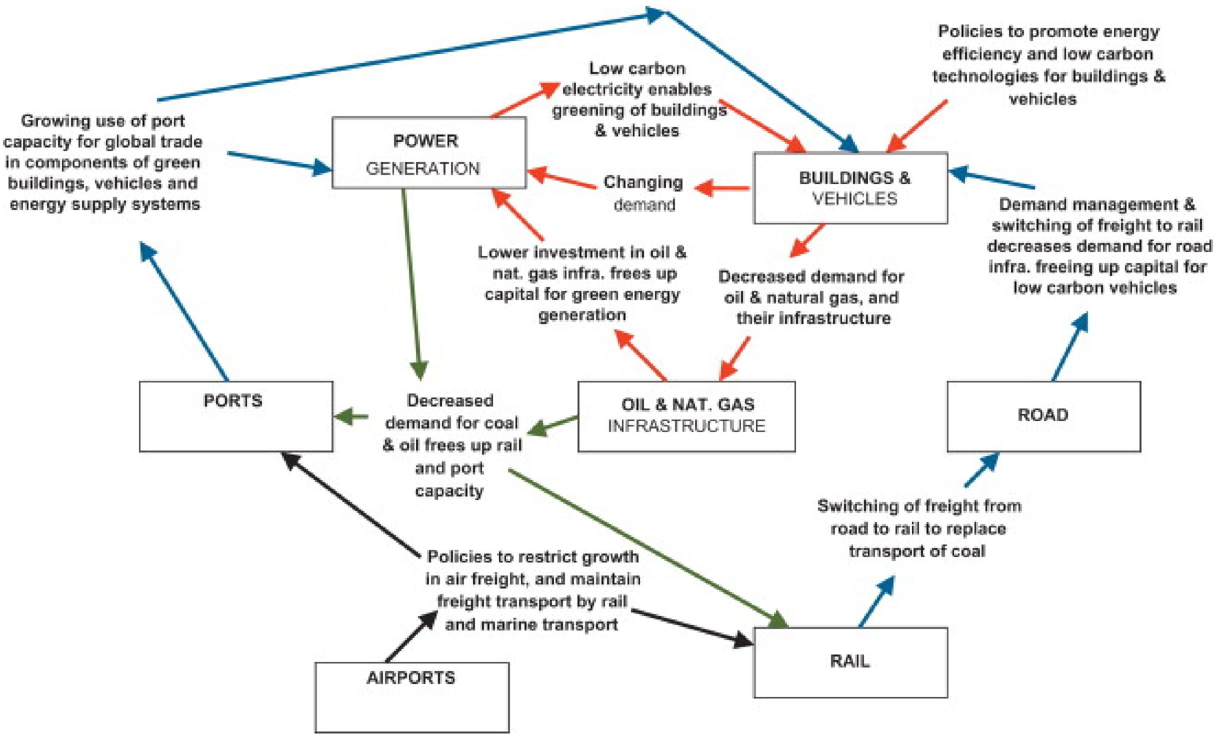

Figure 1.2 – Interdependence of the infrastructure systems in decarbonisation. Source : Kennedy and Corfee-Morlot (2013)

framework so that its expansion close the existing gap but also support the transition to carbon neutral economy.

However, infrastructures have characteristics that induce technical, economic and political constraints on their evolution. In the following sections, I present three potential bottlenecks arising from these constraints to the combination of human development issues and the reduction of greenhouse gas emissions : the risk of carbon lock-in as the short term infrastructures development hindering the emissions reductions later on; the existing tension of financing investments needs and the future risks of crowding out investments; the carbon emissions space available under climate constraint for a sufficient development of infrastructures in the short term. I chose to focus on these topics in this thesis because they are political economy issues that determine each country's margins of manoeuvre in achieving sustainable development. They therefore appear to be factors to monitor for the next international climate negotiations.

1.2.1 Carbon lock-in : the short term infrastructure development as a tragedy of the horizon

As we have shown previously, progress on SDGs by 2030 imply a development of the infrastructure stock and an upgrading of the existing one. However, this short-term development may contribute to the so-called "tragedy of the horizon" (Carney, 2015) where investment decisions do not integrate the long-term considerations of temperature limitation objectives. Infrastructures because of their lifespan are characterised by slow stock turnover and retrofit cycles. These act as bottlenecks to act on the carbon intensity of the energy used and energy efficiency (Ruth et al., 2004; Worrell and Biermans, 2005) which are essential levers for GHG reductions. Infrastructures let a legacy on emissions pattern well beyond the moment of their construction in both the energy production and energy demand sectors (Seto et al., 2016). Davis et al. (2010) in a seminal work introduced the concept of committed emissions as the cumulative CO_2 emissions that would occur over the remaining entire lifetime of an asset. Authors estimated the committed emissions associated with the infrastructures in place in 2010 would lead to a temperature increase of 1.3°C in 2060 compare to the pre-industrial period. Guivarch and Hallegatte (2011) extended this work integrating the influence of spatial patterns on transport demand and non-CO_2 greenhouse gas and obtained a 1.7°C warming. However, Lempert et al. (2002) cautioned *'capital has no fixed costs'* highlighting investment and capital retirement decisions depend much more on economic factors than on physical lifespan.

Infrastructures induce high upfront investments and concentrated in time. They are bulky because of their large units supply and capital intensity (Buhr, 2003). Network infrastructures are particularly concerned because they have high geographical extensiveness and limited divisibility (Baldwin and Dixon, 2008). This concentration of investments over time can be seen not only at the level of a particular construction project but also at the level of a broader investment program (Lecocq and Shalizi, 2014). For example, two-thirds of France's nuclear production capacity was installed between 1980 and 1990. Similarly, the interstate high mileage network in the United States was built in 20 years between 1965 and 1985. These initial investments are sunked as they cannot be recovered in the short term, thus inciting the owner to use his capital over a long time (figure 1.3).

Infrastructures also follow a path-dependent evolution where investment decisions determine upcoming decisions and then create inertia in the future trajectory. This is explained by four mechanisms of increasing returns in an infrastructure type adoption : scale economies, learning economies, adaptive expectations and network economies (Arthur, 1994; Unruh, 2000). Scale economies refers to the spread of fixed costs over the production volume decreasing the average production costs per unit. In the case of infrastructures, high fixed initial costs spread over the amount of services provided over time which incentives to use the capital installed. This also translates into unit level up-scaling (eg. coal power plant with higher production capacity) to decrease the average services costs (Wilson, 2012). Learning effects describe cost reductions over time through different processes such as product design improvements, material efficiencies or labour productivity (Argote and Epple, 1990). The unit production costs hence decrease with the cumulative production experience (eg. each new coal-fired power plant costs less than the previous one). Network economies result from the advantages of using a technology with wider adoption because of coordination effects between industries or through regulations and norms (Unruh, 2000). Hence, the benefits an individual receives from a particular technology increase as others follows the same option (Pierson, 2000). This mechanism is reinforced by the interdependence between the infrastructures such as the construction of nearby coal mines to supply these power plants. Adaptive expectations occur when the adoption of an infrastructure type decrease uncertainty and increase confidence in its usage (Unruh, 2000). This shapes behaviour patterns and induces projections of the future system bounded by habits. These 4 mechanisms are not specific to infrastructures (see for instance the QWERTY's keyboard lock-in in David (1985)) but are deeply set in place during the long operating time of infrastructures.

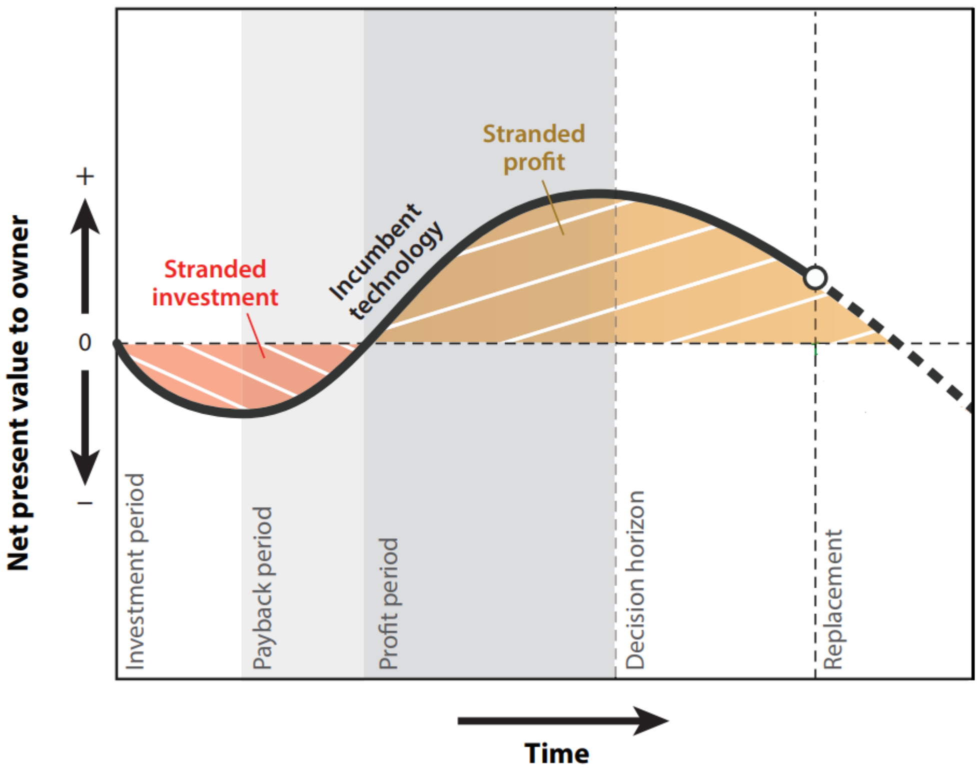

Figure 1.3 – Stylised investment cycle of an infrastructure. Here the net present value represents at a given moment in the life of an infrastructure the difference between the cumulative past expenses and the cumulative past revenues. Revenues can refers either to the sale of infrastructure product (e.g electricity sale produced by a power plant) or the avoided costs induced by the infrastructure build-up (e.g time and productivity gains from a transportation infrastructure). Source : adapted from Seto et al. (2016)

Infrastructures are also integrated in a 'techno-institutional complex' where public and private institutions influence their evolution (Unruh, 2000; Seto et al., 2016). Together with infrastructure systems, they form a feedback loop in which they create the conditions for the emergence of an alternative infrastructure-related technology or further contribute to the permanence of the existing one. The French nuclear program could not have been carried out so quickly without strong political support and a state-owned electricity monopoly (Grubler, 2010). In Poland, government supports the use of coal for electricity production by favouring in particular energy security before climate change concerns (Brauers and Oei, 2020). The co-evolution and mutual reinforcement of technical and institutional systems thus creates inertia in the renewal of infrastructures towards low carbon systems, a phenomenon known as carbon lock-in (Unruh, 2000, 2002; Unruh and Carrillo-Hermosilla, 2006).

Carbon lock-in has several notable consequences. Investing in the short term in assets supporting high carbon patterns reduces the flexibility of the system for emissions reductions. It increases the costs for achieving climate change mitigation goals (Bertram et al., 2015; Riahi et al., 2015) because in the long term there is a higher need to reduce emissions using expensive technologies such as negative emissions. Relying heavily on these technologies is all the more a risky gamble on the future in the sense that their maturation and therefore their scaling up is uncertain (Anderson and Peters, 2016).

Although it is necessary to act early to avoid going further into carbon lock-in, policymakers and investors face a decision dilemma. On one hand, they are confronted to major uncertainties regarding not only climate change which may impact infrastructures (Gersonius et al., 2013; Chester et al., 2020) but also the political and socio-economic context. For instance, the rapid decrease in the cost of renewable energy had not been anticipated by the experts (Metayer et al., 2015). It was also impossible to predict a shock like the Covid-19 pandemic we are experiencing, which dramatically altered patterns of energy demand (Le Quéré et al., 2020). This great uncertainty induces potential large opportunity costs - the cost of investing now rather than waiting - which incentive policymakers and investors to wait for more information to decrease uncertainty and investment risk (Dixit et al., 1994; Fuss et al., 2009).

On the other hand, in a rapid transition to low-carbon systems, a large part of the existing infrastructures stock would have to be retired. This would result in the creation of stranded assets which are capital *"suffering from unanticipated or premature write-offs, downward revaluations or are converted to liabilities"* (Caldecott et al., 2013). The retirement can be made either before the economic life necessary to make the investment profitable (stranded investments in figure 1.3) or before the end of the physical life limiting the expected profits (stranded profits in figure 1.3). Only in the electrical sector, the global financial impact could be high representing up to $500 billion of devaluation in cumulative until 2050 for emission pathways limiting global warming to 2°C (Johnson et al., 2015; Kefford et al., 2018). The drop in capital utilisation in one sector can have also a systemic impact as it can 'cascade down' to other related sectors creating as well stranded assets in the latter (Cahen-Fourot et al., 2019).

The question of when the infrastructure stock should be shifted to a low-carbon stock can't be separated from the question of how. In the electricity sector for example, the reduction of greenhouse gas emissions in the short term can be achieved by replacing coal-fired power plants either with gas plants or zero-carbon power generation. While the coal-to-gas switch may appear cheaper in the short term, the economic consequences will be more important in the long term to reduce emissions due to the greater inertia of the system (Vogt-Schilb and Hallegatte, 2014; Sachs et al., 2016).

Politicians and investors have then to be informed on the long term consequences of the short term infrastructures stock evolution. They have to be assisted as well in their decision making by indicators that allow them to assess the present and future carbon lock-in risks induced by their investment choices. Multiple indicators should be used in order to be able to assess political, economic and technical carbon lock-in as in (Erickson et al., 2015). They also need to identify windows of opportunity in the different sectors for infrastructures transition and the political levers to create them.

In this context, I ask in this thesis to what extent the existing stock of infrastructures and its expected evolution is compatible, or not, with long-term climate objectives, and what are the levers available for policy makers to make this stock "climate compatible". The chapter 2 brings a contribution by reviewing comprehensively for the first time the case studies in the literature about carbon lock-in related to infrastructures. I first highlight what sectors and geographic areas have been studied, and where there are research gaps. I then identify how carbon lock-in have been quantified in the literature and what findings emerge from it. I finally analyze the policy implications of carbon lock-in avoidance or escape.

1.2.2 Providing investment needs under financial constraint as a crowding out risk

In the previous section, I have recalled the need for a rapid change in the trajectory of the global infrastructure stock in order to avoid a reinforcement of the existing carbon lock-in. This requires to shift investment away from carbon-intensive capital stocks towards low-carbon capital stocks. At the same time, many investments will be needed, not only in developing countries for the construction of new infrastructure to meet growing urbanisation and population growth, but also in developed countries for the renovation and maintenance of the existing stock. Yet, both developed and developing countries have known in the last years chronic and substantial investments shortcomes, resulting in infrastructure inadequacies. The transport sector is particularly concerned. More than 50% of the population still resides within more than an hour of a city in low income countries (Weiss et al., 2018). 14% of the total population does not have access to a road within 2km of their home and this proportion exceeds 25% in many sub-Saharan and Southeast Asia countries. 68 countries have seen the quality of their transport infrastructure decreases between 2010 and 2017 (WEF, 2017).

Securing the necessary investments is challenging due to the combination of expenditures needs scale and financing issues. The public sector plays a key role in financing infrastructure. Although the private sector can also be involved, his ability to mobilize resources on a sufficient scale is limited. Transportation infrastructure creates positive externalities (i.e. benefits that go beyond the users) which are by definition difficult to capture in a price for the private sector (Lecocq and Shalizi, 2014; Granoff et al., 2016). For instance the construction of a train line between two cities will allow, in addition to the mobility service offered, to reduce congestion on the road network and improve air quality. Private investors are also reluctant to finance infrastructures projects in developing countries because of higher investment risks than in developed countries (Bhattacharya et al., 2012; Schmidt, 2014). This effect is reinforced by the current Covid-19 pandemic which has plunged private funding to developing countries (OECD, 2020). However governments also under-invest in infrastructures. Infrastructure development can be funding by end-users through fees, by tax payers through taxes that pay for subsidies or by some mix of the two. However, relying solely on these financing levers is impossible for reasons of acceptability. Especially in developing countries, the number of infrastructure users is more limited and the level of wealth does not allow for sufficient tax revenues (Bhattacharya et al., 2012; Granoff et al., 2016). Most of the infrastructure projects in transportation worldwide therefore have relied on public borrowing (Ang and Marchal, 2013) which is limited by available savings or credit-worthiness (Mercure et al., 2019). Beyond these economic mechanisms, the bad institutional quality in some countries (such as corruption level, administrative quality or regulatory quality) reduces efficiency in use of expenditures which further limits the available fiscal space (Kyriacou et al., 2019).

If the divergence between available financing and spending needs is prolonged or amplified, it might require a trade-offs between investments scaling-up for human development or investment in low-carbon capital to escape carbon lock-in. Yet, the impact of climate policies on infrastructure investment is ambiguous and could exacerbate the investment gap in some countries or release tension in others. With regard to rail infrastructure, for instance, investment needs would, on the one hand, be stimulated by a modal shift in freight transportation from road to rail. On the other hand, investment needs could be driven down by decreasing demand for coal transportation (Kennedy and Corfee-Morlot, 2013). It is then essential to anticipate the evolution of global transport infrastructure investment needs induced by the implementation of climate policies in order to ensure their financing. This can be done for instance through greater mobilisation of the private sector (Ang and Marchal, 2013) or through the introduction of new taxes on CO_2 emissions (Franks et al., 2018), land rent (Mattauch et al., 2013) or natural ressource rent(Fuss et al., 2016).

The majority of existing assessments of infrastructure investment needs at the global or multicountry scale are based on reports from international organisations or financial institutions. Recently, Mirabile et al. (2017) and Woetzel et al. (2016) have compiled multiple sectoral estimates of infrastructures needs, including transportation infrastructures, from different sources to provide an estimation of global infrastructure investment needs. Their analyses highlighted comparing the existing estimates is difficult because of the heterogeneity in the study framework and the various methods used for estimation. Time scales and types of infrastructures included in a sector can differ between sector (Ruiz-Nuñez and Wei, 2015). Infrastructure needs can be estimated for different goals or targets such as providing universal access to an infrastructure service (Pachauri et al., 2013), maximising the resulting economic growth (Crafts, 2009), or being consistent with a given level of economic development. Some studies have considered further climate action while others imply a continuation of current climate ambitions (Mirabile et al., 2017)

The indicators used to measure the infrastructure stock impact also the estimation of investment needs. Some authors have estimated the existing capital stock on the basis of past public investment flows and assuming a depreciation rate. However, Romp and De Haan (2007) has pointed out several limitations from this approach: the share of public expenditures allocated to infrastructures can vary over time and between countries; private sectors expenditures are excluded; public spending effectiveness and infrastructure construction costs differ between countries. There is therefore a risk of under- or overestimation of the infrastructure stock. Other studies have used physical measures such as the number of kilometres of paved roads for transportation infrastructures. Although they do not integrate the quality of the service delivered, using physical measures avoids the pitfalls mentioned above with monetary measures.

Among these studies using physical measures, several methods coexist. Following the seminal work of Fay and Yepes (2003), a first group of studies has relied on a 'top-down' approach where authors analyzed empirically the combined evolutions of GDP and transportation infrastructures stocks (Stevens et al., 2006; Kohli and Basil, 2011; Perrotti and Sánchez, 2011; Ruiz-Nuñez and Wei, 2015). Authors have then projected infrastructure demand using economic growth forecasts. However, this presupposes a continuation of historical investment trends, which does not allow to take into account major structural changes induced by the implementation of climate policies, such as a modal shift towards rail.

Another group of studies has relied on a 'bottom-up' approach to quantify the costs associated with achieving explicit targets for levels of transportation infrastructure. These approaches disaggregate the stock of infrastructure according to the different types of capital (road, rail, airports, etc.) and represent the differences in construction costs between regions and between types of infrastructure. Some studies have focused on the costs to provide basic access level to transportation infrastructures. Investment needs have been quantified to pave all the existing non paved lanes (Jakob et al., 2016; Fuss et al., 2016) or to provide a quasi-universal road access in less than 2km (Wenz et al., 2020). However, these articles has focused only on the essential services delivered to households by transport infrastructure without integrating the role of infrastructure as a support to the economy in particular the freight transport sector. Other studies have used sectoral transport models to estimate the investments needed to meet projected mobility demand over several years (Dulac, 2013; IEA, 2016). However, these models have omitted socio-economic determinants of mobility demand external to the transport sector, such as fuel price or urban form which play an important role in shaping transport behaviour over time (Javaid et al., 2020).

A third group of studies has estimated investment needs in infrastructures using detailed process integrated assessment models (IAM) (Weyant, 2017). Detailed process IAMs have been traditionnally used to study the energy–economy impacts of climate change mitigation policies. This type of model models the overall economy using separate but linked modules for each sector of energy production or demand. An economic module is also present in order to integrate the socio-economic determinants of energy demand or production but also to represent the impact of technical choices on economic development. These tools make it possible to analyse how the implementation of climate policies spreads throughout the economy and in particular influences the demand for passenger and freight transportation (Edelenbosch et al., 2017). The existing assessments of infrastructures investments using this model type have mainly focused on the energy production sector (Tavoni et al., 2015; McCollum et al., 2018). Transportation infrastructures are not typically included in global estimates of emissions mitigation costs (Creutzig et al., 2015). The only contribution on the transportation sector is from Broin and Guivarch (2017) who focused on the investment needs induced by passenger activity but omitted the freight sector.

A common feature of all the above-mentioned studies is that they all have estimated the investment needs in transportation infrastructure by providing a single number, either as an absolute cumulative amount or in relation to the GDP of the region studied. However, the evolution of the determinants of transport activity trajectories and infrastructure needs are very uncertain whether they are external to the sector (e.g. fuel price or income) or internal (e.g. vehicle occupancy rate or electric vehicle costs). This is a situation of radical uncertainty in the sense that we do not know the probability distribution of possible cases in the future (Knight, 1921). Some studies, at a more local scale, have integrated this deep uncertainty in transportation planning by using the 'robust decision making' framework where they assess thousands of plausible futures to identify robust investments plans (Lempert et al., 2020).

The chapter 3 of the thesis makes a contribution by quantifying the investment needs in transportation infrastructures induced by the evolution of both passenger and freight transport activity under climatic constraints. I base my analysis on a detailed process IAM to represent the determinants of transport activity inside and outside the transport sector. Rather than denying the uncertainty, I integrate it into infrastructure expenditures estimates in order to have robust results but also to understand what pushes those needs along low-carbon pathways. Detailed process IAMs are particularly adapted for uncertainty analyses because of their capacity to produce a wide variety of global low-carbon scenarios.

1.2.3 The carbon emissions space for sufficient infrastructures development under climate constraints

To engage countries in the process of global climate action, the distribution of emissions reduction efforts between them must be fair so that the human well-being of some is not favoured to the detriment of others. This is why global climate regime has relied on the principle of "common but differentiated responsibilities and respective capabilities", present since 1992 in the United Nations Framework Convention on Climate Change (Brunnée and Streck, 2013). Its consideration has evolved over time in order to enable development pathways and the associated build-up of infrastructures in developing countries.

Initially, global climate action has followed a top-down approach by capping global emissions through national binding commitment targets. Following the Kyoto Protocol in 1997 which only included industrialised countries, a universal agreement was supposed to emerge including as well emerging and developing countries . However, it has been difficult to agree on a burden sharing scheme, as the failure of the Copenhagen negotiations showed in 2009. Indeed, several principles of equity exist (e.g. equality, ability to pay or capacity, responsibility or historical contribution) with for each principle several emissions reduction sharing possibilities (Robiou du Pont et al., 2016; van den Berg et al., 2019; Leimbach and Giannousakis, 2019). Also, the costs distribution resulting from a emissions reductions sharing scheme is uncertain and can lead ex-post to a much less acceptable distribution of effort (Méjean et al., 2015). Low-carbon energy could be more expensive in the short term in developing countries than fossil fuels, leading to higher capital costs and therefore delaying the build-up of basic infrastructures in developing countries (Jakob and Steckel, 2014).

Subsequently, there has been a gradual paradigm shift in the international climate regime towards a more bottom-up approach (Vandyck et al., 2016) with the aim to ensure 'equitable access to development' (Winkler et al., 2013). Thus, for the Paris agreement, the parties have chosen their level of ambition for emission reductions by providing national determined contributions (NDC). The aggregation of these commitments, regularly evaluated, should enable global emissions to be reduced in line with national contexts. However, NDCs are currently inconsistent with the Paris Agreement objective of limiting global average temperature increase to well below 2°C (Höhne et al., 2020) and should then be enhanced during the 2023 global stocktake. This 'ratcheting-up' process will most likely include some evaluation of fairness where the question of carbon emissions spaces to allow 'sufficient' development in developing countries should be of concern.

The idea of a development threshold to be reached for human well-being has emerged with Sen (1990) and Nussbaum (2003) who have proposed a set of capabilities to ensure in order to enable people live as they would choose, or Doyal and Gough (1991) and Max-Neef (1992) who have proposed a set of human needs to satisfy. Following these approaches, some authors have interpreted the principle of equitable access to sustainable development by proposing a set of material conditions that are universal, irreducible and essential to achieve regardless of climate constraints. The emissions associated with the achievement of these conditions have been defined in the literature as the Subsistence Emissions (Shue, 1993), the Decent Living Emissions (Rao and Baer, 2012), the greenhouse development rights (Baer, 2013) or the 'Safe and Just Operating Space '(so-called 'Doughnut') (Raworth, 2012).

The carbon emissions required to satisfy human needs tend to decrease over time (Steinberger and Roberts, 2010) but this trend is limited by the accumulation of infrastructure that constitutes a 'carbon floor' difficult to compress in the short and medium term. Infrastructures are capital intensive and bulky. The emissions resulting from chemical reactions involved to manufacture materials are difficult to eliminate without carbon capture and storage technologies (Davis et al., 2018). Steel production is challenging and expensive to decarbonise due to it demand for high-temperature heat (Sharmina et al., 2020). The long technical lifetimes of the capital used in the heavy industries create inertia in the renewal of technologies and slow possibilities to reduce emissions (Erickson et al., 2015).

The SDGs set the objective of universal access to infrastructure services such as water, sanitation or transport by 2030 (United Nations, 2015). I question the coherence between reaching a level of infrastructure consistent with the attainment of these objectives and the emission reduction trajectories envisaged. The accumulation of infrastructure by 2050 could consume a significant part of the carbon budget available to respect the Paris Agreement target (Müller et al., 2013). Conversely, current mitigation scenarios could be too optimistic with respect to energy consumption and carbon emissions necessary for infrastructure development in developing countries (Steckel et al., 2013).

A first literature strand has assessed the carbon impact of providing high access levels to different infrastructure services but without considering the role played by the carbon intensity of construction materials production (Chakravarty and Tavoni, 2013; Pachauri et al., 2013; Pachauri, 2014; Rao et al., 2014; Lamb and Rao, 2015; O'Neill et al., 2018). Another literature strand has projected the global CO_2 emissions from both cement and steel sectors but without monitoring the evolution of the access level to infrastructures (Steckel et al., 2013; Müller et al., 2013; Van Ruijven et al., 2016).

The chapter 4 goes beyond the existing literature by estimating the cement and steel needs and the CO_2 emissions impact for achieving five sustainable development goals related to infrastructures by 2030. I differentiate between countries the factors of emissions related to cement and steel consumption such as trade structure and carbon intensity of material production. I also apply different decarbonisation scenarios for the cement and steel industries to disentangle the contributions to emissions pathways from changes in the carbon intensity of materials production and in the materials demand.

1.3 Thesis outline

In the first part of this introduction, I have shown how infrastructures are at the core of the climate-development interplay. I have first clarified the definition of the polysemous term "infrastructure" I use in this thesis (section 1.1.1). Infrastructures - buildings and engineered constructions - have the primary role of providing services to meet societal needs but also have the function of intermediaries between social outcomes and biophysical resource use. Their specific characteristic is their fixity as they are immobile and have long life spans. I then argued infrastructures are a pillar of human development (section 1.1.2) by contributing to life quality and welfare improvements and by fostering economic growth. I have pointed out many regions have currently inadequate infrastructure stocks both in terms of quantity and quality. I have then emphasised the crucial role of infrastructures evolution in reducing greenhouse gas emissions (section 1.1.3). They shape pattern of emissions in energy demand and supply sectors and their construction is carbon-intensive. Moreover, infrastructures are interdependent so that the decarbonisation rate of one type of infrastructure will influence the decarbonisation rate of other types.

After having reminded the interconnection between climate and development issues and the need to assess infrastructures dynamics in a framework encompassing both, I have highlighted in the second part three bottlenecks of infrastructures dynamics on which I focus in this thesis. First of all, I have mentioned the risk of carbon lock-in as the short term infrastructures development can hinder the emissions reductions later on because of technical, economical and institutional constraints (section 1.2.1). I then highlight the existing tension of financing investments needs and the risks of future crowding out investments (section 1.2.2). I have focused on the transportation sector because there is currently insufficient investment in this sector and the effects of mitigation policies on these investment needs are ambiguous. Finally, I have questioned the space that the climate constraint allows for a sufficient development of infrastructures in the short term, regarding the slow decarbonisation rate in the steel and cement sectors (section 1.2.3). On one hand the short term infrastructure accumulation could consume a significant part of the cumulative emissions available to respect climate mitigation targets. On the other hand, overly restrictive climate policies could hamper essential short-term infrastructure development.

Throughout this thesis, I would like to bring elements of answer to the following questions : How the dynamics of the global infrastructure stocks can enable to unite human development and climate change mitigation ? What are the levers that make it possible to unite these issues ?

In the second chapter, I review the literature about carbon lock-in induced by infrastructures. I provide a systematic map by using supervised machine learning allowing to deal with the high amount of the scientific literature on the topic. I find literature has mainly focused on power generation. I also identify a bias toward developed countries, which represent the majority of our sample. I show how the literature has quantified carbon lock-in, which indicators have been used and how carbon lock-in 'strength' differs between sectors and geographical areas. Synthesizing the policy implications mentioned to escape carbon lock-in, I highlight that carbon pricing should be implemented but complemented with additional measures, notably a financial support for low-carbon capital deployment. However, this appears to be a challenge given that there is currently a tension on infrastructure investment financing as show in the introduction.

In the third chapter, I analyse if this tension would be amplified or release by the implementation of climate policies, with the case of transportation infrastructures. I estimate the investments needs for transportation infrastructures and their determinants in low-carbon pathways. To do so, I build socioeconomic scenarios with an integrated assessment model, combining alternatives for model parameters that determine mobility patterns. I then developed a module to quantify the investment needs consistent with the passenger and freight transportation trends in the different scenarios with and without climate policy. I finally used a global sensitivity analysis to identify the determinants of investments in low-carbon scenarios. I show that, contrary to the energy production sector, investment needs decrease with increasing climate ambition both at the global and regional scale. However, these investments could still represent significant amounts compared to historical levels. Rail utilization rates and road construction costs are determining factors for investment in all regions and can be policy levers to favor low investment needs pathways. Modal shift from road to rail can be also a lever to reduce investment needs only if combined with action on rail infrastructure occupancy.

Actions can be done to reduce the expenditures allocated to low-carbon infrastructures transition and increase the financing space available for basic infrastructures development. However, the climate constraint also question the carbon emissions space available for basic infrastructures development. I address this question in the fourth chapter where I assess if high level of access to 5 basic infrastructure services - electricity, water, shelter, sanitation and transportation - can be provided at the global scale in 2030 and maintained until 2050 without compromising climate mitigation targets. Following historical patterns, I first quantify the cement and steel requirements in each country associated with providing high access levels. I then estimate the production-based carbon dioxide emissions related to manufacturing the cement and steel needs. To do so, I model influencing factors such as national production technologies mix, trade structure and mitigation actions in the cement and steel industries. Most of the cement and steel demand are concentrated in Asia, Middle-East and Africa. I show for all infrastructures services that achieving high access level in 2030 and keeping it until 2050 induces cumulative carbon dioxide emissions below the carbon budgets related to Paris Agreement targets. However, I find providing high sanitation and transportation access conflicts with existing low-carbon pathways. This calls for on one side implementing material efficiency and substitution towards less carbon-intensive construction materials, and on the other side building scenarios that leave more 'carbon space' for infrastructure development in emerging countries.

Finally, I present the conclusions of my thesis in a fifth chapter. I interpret the results of the three core chapters to highlight the conditions under which infrastructures can enable the conciliation between human development and emissions reduction. I place my results in a broader perspective before proposing avenues for improvement and future research.

Chapters 2, 3 and 4 are written in the format of research papers which necessarily leads to some overlap between their respective introductions and the introductory chapter of this thesis. It should also be noted that the use of the "I" and the "we" changes between the chapters if there are co-authors on the associated study. All three chapters have resulted in research articles published or under review in peer-reviewed journals (Table 1.2). These articles have also been presented in multiple conferences and seminars both in France and internationally.

Chapter	Publication	Conferences
2	Fisch-Romito, Vivien, Celine Guivarch, Felix Creutzig, Jan C Minx, and Max W Callaghan. 2020. "Systematic Map of the Literature on Carbon Lock-in Induced by Long-Lived Capital." *Environmental Research Letters.* doi : 10.1088/1748-9326/aba660	
3	Fisch-Romito, Vivien, and Céline Guivarch. 2019. "Transportation Infrastructures in a Low Carbon World: An Evaluation of Investment Needs and Their Determinants." *Transportation Research Part D: Transport and Environment* 72 (July): 203–19. doi: 10.1016/j.trd.2019.04.014.	Fifth GGKP Annual Conference (Washington); Third International Workshop : The Energy Transition In Land Transportation (Paris); Scenarios Forum (Denver)
4	Fisch-Romito, Vivien, "Embodied carbon dioxide emissions to provide universal high levels of access to basic infrastructures". Under revision. *Global Environmental Change.*	IEW (Paris), ISIE-SEM (Berlin)

Table 1.2 – Research articles from the thesis

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Chapter 2

Systematic map of the literature on carbon lock-in induced by long-lived capital

2.1 Introduction

The objective of the Paris Agreement on climate change to 'hold the increase in the global average temperature to well below 2°C above pre-industrial levels' requires reaching net zero emissions globally during the second half of the 21^{st} century. This implies a fast reduction of global emissions in the next decades (Rogelj et al., 2018) and one pillar of this transition is a rapid replacement of polluting capital by clean capital (Rozenberg et al., 2018). Polluting capital is that whose use directly emits CO_2, such as fossil fuel power plants and internal combustion engine vehicles, but also capital that indirectly induces emissions, such as building shells, roads and urban forms because of their influence on energy demand and mitigation possibilities (Guivarch and Hallegatte, 2011).

Most of the capital concerned by this transition can be qualified as 'long-lived capital stock' (LLCS), which has specific characteristics that may hinder rapid transitions (Lecocq and Shalizi, 2014). First, by definition LLCS has long life spans, from around 15 years for personal vehicles to more than 50 years for buildings (Reyna and Chester, 2015; Erickson et al., 2015), and to centuries if not millennia in the case of road networks (De Benedictis et al., 2018). A second key characteristic of LLCS is the lumpiness of capacity installation (Lecocq and Shalizi, 2014). While lock-in builds on the long life spans of infrastructures and capital stocks, lumpiness refers to the concentration in a short period of time of investments in specific capital stocks or infrastructures. Examples are railroads in the 19^{th} century, nuclear power plants between 1960 and 1990, and (Chinese) high-speed railways since 2008. This lumpiness leaves a short window of opportunity to influence the capital stock characteristics and whether it locks in high carbon patterns or not.

Moreover, the dynamics of LLCS are driven by path-dependent evolution induced by four intertwined and mutually reinforcing mechanisms: scale economies, learning effects, network economies and adaptive expectations (Arthur, 1994; Unruh, 2000). Scale economies refers to reduced unit production costs over time due to the spread of fixed costs over increasing production volume (Kalkuhl et al., 2012; Klitkou et al., 2015). Learning effects describe how knowledge accumulation from a technology results in decreasing costs over time. This has been observed for power generation plants in the past (McDonald and Schrattenholzer, 2001), with higher learning rates for more granular technologies, such as photovoltaics (Creutzig et al., 2017; Nemet, 2019; Wilson et al., 2020), and lower if not zero (or even negative) learning rates for large-scale technologies, such as nuclear (Grubler, 2010). Network economies result from the advantages of using a technology with wider adoption because of coordination effects between industries or through regulations and norms. For example, a road portion increases in value as the network expands because of new possible destinations (Unruh, 2000). Adaptive expectations are due to the adoption of a technology reducing uncertainty, and hence increasing confidence in using this technology. This mechanism shapes preferences and cultural norms such as habits for travel behaviors (Lanzini and Khan, 2017).

LLCS therefore induces inertia that prevents or delays transitions towards low-carbon systems, a phenomenon called carbon lock-in (Unruh, 2000). The capital built today will influence the paths of future emissions for several decades. The transition to low-carbon capital can therefore only be made by taking into account the existing stock and its economic and technological characteristics. LLCS is also embedded in broader institutional context that can keep promoting the high-carbon capital in place or create the conditions for the emergence of an alternative low-carbon technology (Seto et al., 2016).

It is therefore essential to understand to what extent this existing stock of long-lived capital and its expected evolution is compatible, or not, with long-term climate objectives, and to identify levers available to make this stock "climate compatible". A certain level of lock-in associated with existing carbon-intensive capital is inevitable but its depth can be problematic and hinder a low carbon transition (Bjørnåvold and Van Passel, 2017). This raises the questions of how to quantify carbon lock-in and how its 'strength' differs between sectors or geographical areas. Answering those questions is a crucial condition for policies and decisions which avoid creating or exacerbating carbon lock-in. This article contributes to this by reviewing the literature about carbon lock-in related to long-lived capital stock. Our goal is to describe the current state of knowledge, and to show what evidence there is of the (in)compatibility of the existing LLCS and its expected evolution with the long term climate objectives. Specifically, we aim to (i) highlight what sectors and geographic areas have been studied, and where there are research gaps, (ii) identify how carbon lock-in has been quantified in the literature and what findings emerge from it, and (iii) analyze the policy implications of carbon lock-in avoidance or escape.

In a previous traditional literature review, Seto et al. (2016) synthesized the causes and types of carbon lock-in. Authors conceptualized three major types: "(a) lock-in associated with the technologies and infrastructure that indirectly or directly emit CO_2 and shape the energy supply; (b) lock-in associated with governance, institutions, and decision making that affect energy-related production and consumption, thereby shaping energy supply and demand; and (c) lock-in related to behaviors, habits, and norms associated with the demand for energy-related goods and services". This review also identified conditions which reinforce carbon lock-in and some strategies for escaping it. However, to our knowledge, no study to date has comprehensively synthesized case studies and associated results on carbon lock-in. The rapid expansion of the scientific literature on the topic (Cui et al., 2019) calls for scalable methods to deal with large numbers of articles (Tsafnat et al., 2014; Minx et al., 2017; Beller et al., 2018; Westgate et al., 2018; Nakagawa et al., 2019; Callaghan et al., 2020).

Our article hence complements the review by Seto et al. (2016) by providing a systematic map of the literature about carbon lock-in. We collected, described and catalogued the available literature based on a systematic review methodology (James et al., 2016). The screening process was streamlined using a machine learning approach (O'Mara-Eves et al., 2015; Lamb et al., 2019). We map out the distribution of existing studies across sectors, geographic areas and spatial scales and identify mature areas of research as well as research gaps. We further describe the different methodologies and indicators used to quantify carbon lock-in and provide a synthesis of those estimates. In particular, we analyze how evaluations of global stranded assets depend on the temperature objective of the scenarios and on whether action in scenarios is early or delayed. We study how global committed emissions evaluations have evolved over time, and also provide a comparison of the results for our indicators between sectors and geographical areas. Finally, we offer a synthesis of existing qualitative statements in the publications about policies to escape or avoid carbon lock-in. The rest of this article is structured as follows : section 1.2 details our methodology, section 1.3 presents and discusses our results and section 1.4 concludes.

2.2 Methodology

We apply systematic mapping and subsequent synthesis to understand what the evidence is of the (in)compatibility of the existing LLCS and its expected evolution with the long term climate objectives. Systematic mapping (Haddaway et al., 2016; James et al., 2016), and evidence gap mapping (McKinnon et al., 2015; Snilstveit et al., 2016), have their roots in the social sciences (Oakley et al., 2005; Bates et al., 2007). Systematic maps provide an open-framed inquiry related to the state-of-evidence in a particular field by systematically collating, describing and cataloging the relevant evidence (James et al., 2016). Like other evidence synthesis methods, systematic mapping approaches provide formal procedures that aim to minimize different sources of bias during the review process and promote a comprehensive, rigorous, transparent and objective overview of the available evidence. We describe in detail the process of constructing and analyzing our systematic map of the literature on carbon lock-in across five discrete methodological stages (see Figure 2.1) and subsequent synthesis below. We close this section by describing our approach to the thematic analysis of policy implications identified in the various papers.

2.2.1 Steps 1 & 2 - Review design, scope and search query

To operationalise our review question, we scope our review in the following way: we consider long-lived capital across three categories identified by Seto et al. (2016), namely (i) carbon-emitting infrastructure, such as power plants and vehicles, (ii) carbon emissions-supporting infrastructure, such as fossil fuel distribution network, and (iii) energy-demanding infrastructures,

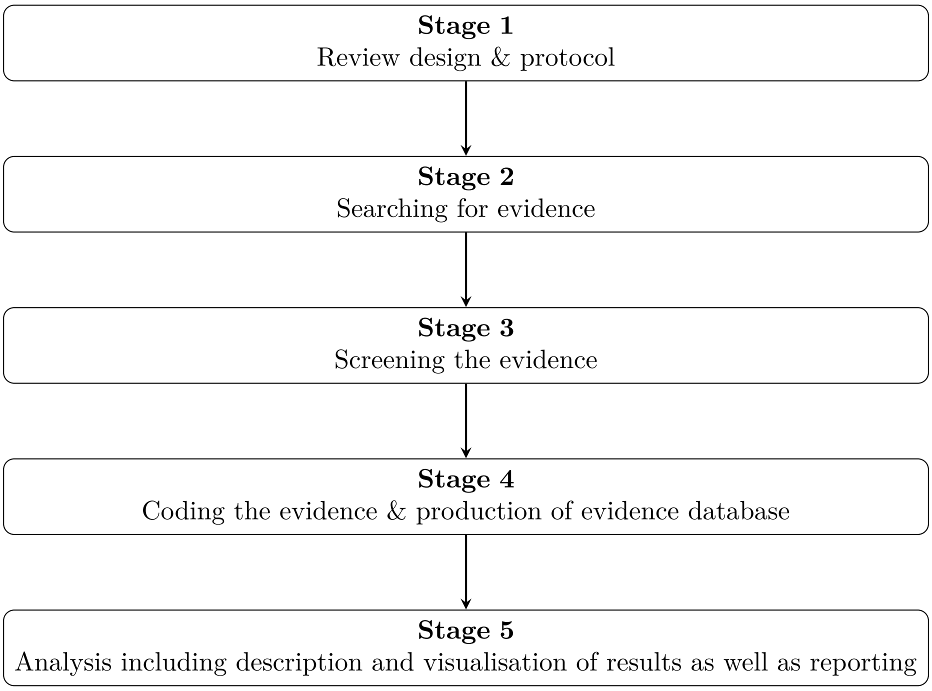

Figure 2.1 – Systematic mapping procedure (James et al., 2016)

such as building shells, roads and urban forms. Our focus is on studies that analyse the capital built to extract, transport and transform the fossil fuel resources, but not fossil fuels themselves - even though these can contribute to lock-in as well. We also limit the scope of our inquiry to articles that explicitly study carbon lock-in, and not only lock-in of a specific technology with no consideration of the greenhouse gases emissions implication of the technology use. From the three types of carbon lock-in conceptualized by Seto et al. (2016) - namely (a) technological and infrastructural, (b) institutional and (c) behavioral - we limited our analysis only on the first two. Behavioural lock-in is a much less mature scientific concept and would require a lot more groundwork before starting any synthesis that would mainly rest on highly disciplinary evidence from sociology, behavioural economics or psychology (Beretti et al., 2013; Stoknes, 2014). This is beyond what can be provided here. So we leave it to a dedicated future effort that would need to involve additional scientific expertise.

We constructed a transparent keyword-based query and search both the Web of Science (WOS) and Scopus. Our search string consists of synonyms related to climate change, LLCS and lock-in. The keywords were initially chosen on the basis of the authors experience. We then developed and tested a series of alternative search strings against a sample of 30 key articles available on WOS compiled a priori by the authors (see the test list in Appendix B). We selected the search string presented in Table 2.1, which could retrieve 29 of the 30 articles (notably the one article was only not retrieved because the associated abstract was not available on WOS). In this query we included the generic keywords "scenario", "pathway" and "integrated assessment" in the LLCS and lock-in keywords category to also include articles using integrated assessment model and/or climate change mitigation scenarios. Some articles from this literature have addressed carbon lock-in induced by LLCS among other topics without necessarily mentioning related keywords explicitly in the abstract (see for instance Creutzig et al. (2016) or Luderer et al. (2018)). To limit the number of results obtained, we also included keywords combined with the Boolean NOT to exclude articles about forest and agriculture because they do not fit the definition of LLCS we used. Overall, our query yielded an initial total of 34002 unique publications on WOS and Scopus in June 2019. We chose this rather extensive search string over more focused alternatives for matters of comprehensiveness and given the availability of a machine learning pipeline for streamlined evidence screening and selection (see below).

Climate keywords	**LLCS keywords**	**Lock-in keywords**
((carbon NEAR/3 (emission* OR budget)) OR (CO2 NEAR/3 (emission* OR budget)) OR decarboni*ation OR (degree* NEAR/3 ("1.5" OR "2")) OR (climat* NEAR/3 (mitig* OR policy OR policies OR goal)) OR (energy NEAR/2 (consum* OR use)))	(infrastructure* OR transport* OR fossil OR industry OR electricity OR shipping OR building* OR gas* OR coal* OR power OR "built environment" OR "building stock*" OR urban* OR cities OR city OR "integrated assessment")	(lock* OR "stranded" OR retirement OR divest* OR "inertia" OR "path dependen*" OR "pathway*" OR "scenario*" OR "earlier" OR "early" OR (commit* NEAR/3 (emission* OR CO2)))
Keywords for exclusion : (*forest* OR agric* OR agro*)		

Table 2.1 – Description of search query.

Although the search string is extensive, we recognize several shortcomings of our search strategy. First, we focused on English publications only, but recognise the existence of relevant articles on carbon lock-in in other languages. Second, we focused on the two bibliographic databases WoS and Scopus, but these do not cover the entire academic literature and miss grey literature entirely. To partially compensate for the second and third point, additional documents were identified by "snowballing" (Sayers, 2007) - extracting references from relevant publications on carbon lock-in including grey literature. Overall, whilst not being fully exhaustive, we feel that our approach provides an extensive view of the available literature.

2.2.2 Step 3 - Screening and selecting the evidence

A growing challenge for rigorous evidence synthesis methodologies is that many search strings return tens of thousands of results - particularly in an open-framed context like systematic mapping. Here, the selected search string returned a total of 34,002 publications in June 2019 after deleting duplicates. Available guidelines for systematic evidence mapping (Snilstveit et al., 2016; Collaboration for Environmental Evidence., 2018; Saran and White, 2018) require the comprehensive screening of all search results - ideally by two independent screeners. It is our observation that due to the rapid expansion of scientific literature, authors tend to artificially restrict their search queries in order to keep the number of articles for screening manageable, even though this may substantially limit the analysis.

An alternative way to approach this is to relax the stringency of screening in exchange for building a comprehensive search query that yields a number of search results greater than that which can be screened by hand. Machine learning can be used to assist the screening and selecting articles by training an algorithm with the screening decisions made by humans (O'Mara-Eves et al., 2015; Westgate et al., 2018; Lamb et al., 2019; Nakagawa et al., 2019). Only the subset of remaining articles predicted to be most likely to be relevant are then screened manually. We set out the screening process we followed in detail below, and summarise in figure 2.2.

First, to ensure screening consistency between reviewers and a common understanding of inclusion/exclusion criteria, four authors screened the same set of 100 articles independently at the beginning of the process. The screening results were compared and reviewers jointly discussed consistency in the light of inclusion/exclusion criteria (Table 2.2).

Include/Exclude	**Reason**
Include	Publication using scenarios in the energy demand or supply sectors must include keywords related to carbon lock-in, investments dynamic or stock renewal in the abstract
Exclude	Publications only focusing on lock-in but not related to climate change mitigation or GHG emissions induced by long-lived capital
Exclude	Publications only about carbon lock-in induced by fossil fuels themselves or natural resources
Exclude	Publications only analysing behavioural carbon lock-in

Table 2.2 – Inclusion/Exclusion criteria

After the consistency check, the reviewers screened a further 508 records independently, resulting in an initial random sample of 608 documents. We added 41 articles identified a priori as pertinent for our topic in order to provide more "relevant" labels in our training dataset. These articles were extracted from the test list we built and from the references list of Erickson (2015) and Seto et al. (2016). We justify the choice of these two articles by the fact they are highly cited and fit our topic perfectly through their analysis of different types of carbon lock-in in different sectors.

We then started an iterative process where at each iteration, we 1) trained a machine learning model to predict the relevance of a document given its title and abstract; 2) predicted the relevance of the unseen documents; and 3) assigned the next set of documents to be screened by the authors by selecting the documents predicted to be most relevant. We went through three iterations of machine learning prioritized screening and each had decreasing proportions of relevant documents in the set of screened articles. In the first iteration of 494 documents, 35% of records were relevant. In the last iteration of 300 documents - only 5% documents were relevant, suggesting that the returns to additional screening would be small.

We then added 4,093 further documents by repeating the queries in February 2020, and by searching for documents citing the article on lock-in by Unruh (2000). We screened the 97 documents predicted most likely to be relevant from these additional documents, finding a further 28 relevant documents.

We performed full text screening on the 335 documents included during the screening process. Only articles with full text available and in English were kept. 184 of these articles

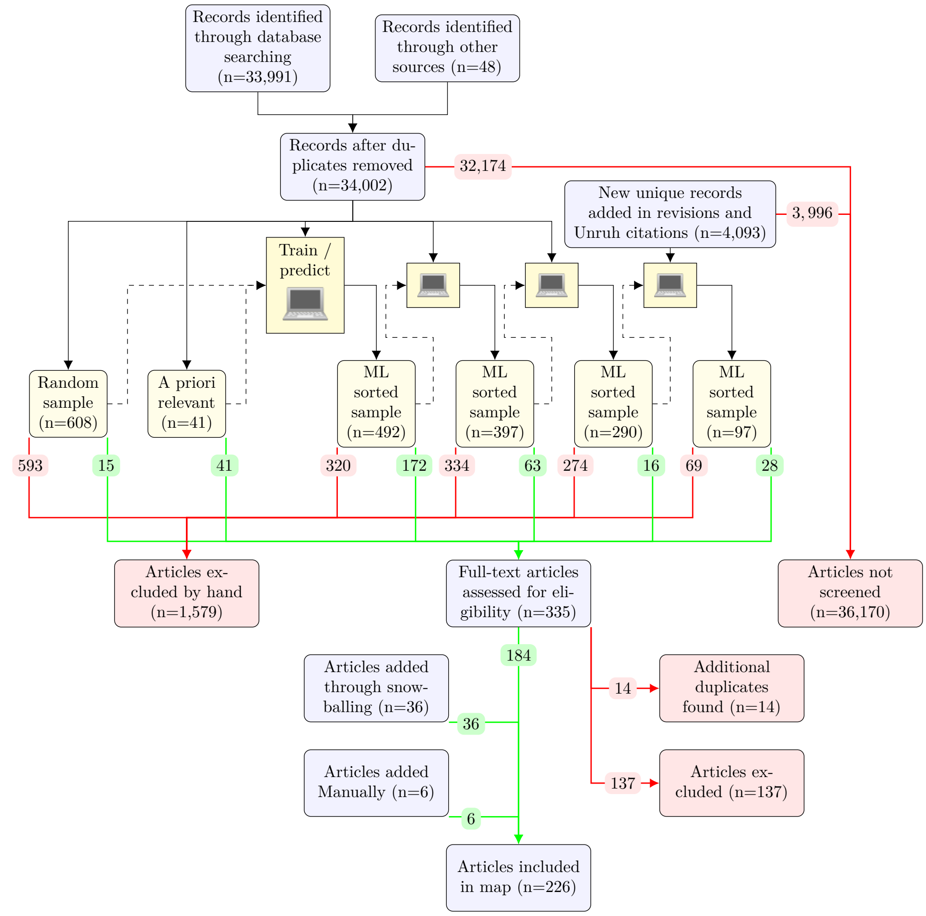

Figure 2.2 – Screening process

were kept, to which we added 6 further documents identified manually and 36 documents identified through the aforementioned snowballing procedure. A total of 226 documents were finally included for our map and review.

2.2.3 Step 4: Coding the evidence & production of evidence database

We developed a codebook (included as Supplementary material to the online published article associated with this chapter) for systematic extraction of information. In our codebook we reported results for each study in rows. We define a study as an instance where geographical and/or sectoral carbon lock-in is reported (either qualitatively or quantitatively). Overall, we found a total of 431 studies across the 226 included publications. For each study we extracted the meta-data (Authors, Title, Date, Doi) of the corresponding publication. We further recorded qualitative data on the study context such as the scale of analysis, the geographic areas and the sectors studied. For each quantification of carbon lock-in, we also extracted the numerical indicators related to carbon lock-in and their corresponding values. Overall, we found 286 quantifications of carbon lock-in from 92 publications. A common table with limited choices was constructed in order to ensure consistent information extraction between the authors.

2.2.4 Thematic analysis of qualitative statements

We used thematic synthesis to systematically analyse policy implications and options for avoiding carbon lock-in mentioned in our final sample of studies. Widely used in psychology, thematic synthesis is a method for identifying, analysing and highlighting themes within qualitative studies (Braun and Clarke, 2006). It also enables a tractable and easily updatable synthesis of extracted statements (Thomas and Harden, 2008; Hilaire et al., 2019). Thematic synthesis allows us to identify a list of possible policy interventions for avoiding carbon lock-in and characterize the appropriateness of these interventions and the factors influencing their implementation.

Overall, we manually extracted 136 qualitative statements (QS) on policy implications from abstract, conclusion or discussion sections of our final set of articles, assuming that most of the statements on policy implications would be in these sections. To be included, QS had to explicitly refer to policy action or instruments to escape or avoid carbon lock-in. We classified QS into broad groups of policy instruments, following Goulder and Parry (2008), namely: incentive-based instruments, regulatory instruments, technology policies and others. QS from the 'others' category were then reassessed to highlight the most frequently mentioned specific features associated with these policies to avoid or escape carbon lock-in.

2.3 Results

2.3.1 Literature mapping

We first analyzed the literature distribution across sectors, geographic areas studied, and scales of analysis. We find that carbon lock-in has been mainly analyzed in the electricity generation sector (figure 2.3a) with 98 related publications representing 43% of our sample.

Publications remaining at an aggregated sectoral level or analyzing carbon lock-in in a generic way also account for a significant portion of our sample with 66 publications representing 29 % of our sample. Conversely, the industry and fossil fuel production & distribution sectors have been little studied with respectively 13 and 14 related articles representing a combined 11% of our sample. This focus on the power sector can be explained by its large contribution to annual global CO_2 emissions, representing between 30 and 40% of total emissions from 2005 to 2018 (Crippa et al., 2019). However, while in the electricity sector the observed operational lifetimes of capital vary between 30 and 60 years (Rode et al., 2017), capital in other sector such as buildings, fossil fuels extraction facilities, or urban form can remain in place longer and could present a larger potential source of long-term carbon lock-in (Reyna and Chester, 2015; Bos and Gupta, 2018). Moreover, the shares of global emissions in sectors other than power generation will tend to increase in the coming decades due to the faster decarbonisation of the power sector (Méjean et al., 2019) and the harder-to-mitigate emissions in sectors such as aviation or industry (Davis et al., 2018).

Carbon lock-in has been studied at different scales, from subnational to global, but unevenly in the literature (figure 2.3b). Global/Generic and national scales represent the majority of existing publications with respectively 46% and 33% of our sample. There are on the other hand only 16 publications in our sample analyzing carbon lock-in on a multi-country scale, 8 of which are related to the European Union. These low numbers are partially compensated by the fact that several quantitative studies at the global level also include results for different world regions, such as Johnson et al. (2015). 32 publications, or 14% of our sample, specifically analyzed the subnational scale. As for the multi-country scale, some analyses at the national scale also include specific results at lower scale, such as Jiang et al. (2017) at the Chinese provinces level. Urban settlements account for nearly 70% of today's global carbon emissions (Acuto and Parnell, 2016) and subnational mitigation policies are specific and differ from larger scale policies (Creutzig et al., 2015). Carbon lock-in is also a 'fractal trap' in the sense that its occurrences at different scales tend to reinforce each other (Bernstein and Hoffmann, 2019). This calls for a greater emphasis on the regional and city scales for future research.

To analyse the geographical distribution of the literature, we used two different indicators: 1) the number of publications related to a country or a world region (independent of the scale of analysis; e.g., an article focusing on a particular city in a country was counted as related to that country); and 2) the number of different sectors analysed per country/world region. The chosen sectors are the same as those presented on figure 2.3.

The literature has investigated 45 countries, but with uneven focus (figure 4a). China and the United States are the most studied countries, with 29 and 27 publications respectively, covering 5 sectors (figure 2.4b). The UK has been widely studied as well with 19 publications covering 4 different sectors. In contrast, 13 countries have been analyzed by only 1 publication each. More than 9 publications are related to Australia, Germany and India, but for only 3 sectors each. Even if publications are more numerous for those countries compared to others, future studies on the missing sectors would be relevant. 26 publications provide carbon lock-in analysis for world regions. A large part of this sub sample (17 articles) is about the European

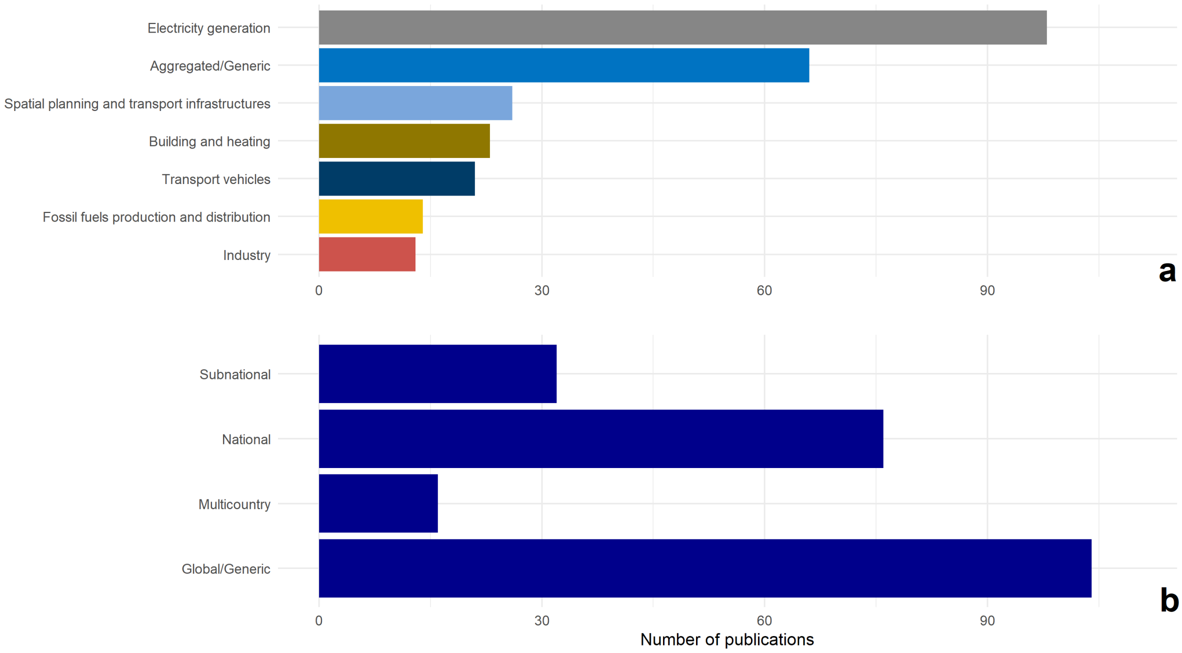

Figure 2.3 – Literature distribution between sectors (a) and scales (b) of the analysis. A publication with multiple studies about several sectors is counted in each corresponding category. The scale corresponds to the territorial level concerned by the analysis, which may differ from the geographical unit which is the disaggregation level used for quantification. For instance an estimation of carbon lock-in at the global scale with results disaggregated by countries is considered here in the global scale category.

Union, which makes sense because it is the only world region studied that forms a political union with climate policies formulated at this level.

Our results reveal a literature bias towards developed countries. That can be seen in the aggregated number of publications associated with five world-regions (IPCC categories): Developed Countries, Asia & Developing Pacific, Africa & Middle East, Latin America & Caribbean and Eastern Europe & West-Central Asia (region definitions are presented in Appendix C). 92 publications are associated with Developed Countries, 38 with Asia & developing Pacific, 10 with Africa & Middle East, 10 in Latin America & Caribbean and 8 in Eastern Europe and West-Central Asia. Even though developing countries (excluding China and India) are not major contributors to global CO_2 emissions at the moment, they may contribute to a high proportion of future emissions growth, which calls for more research in those countries. Among the Developed Countries publications, some countries are over-represented compared to their contribution to global emissions, particularly the United Kingdom, but also to a lesser extent Germany, Sweden and Australia (Figure 2.5). Russia contributes significantly to global CO_2 emissions but has been proportionally less studied, with only 5 publications. Although China has been the most studied country, the share of associated publications is still lower than its share of emissions in 2018 (Figure 2.5).

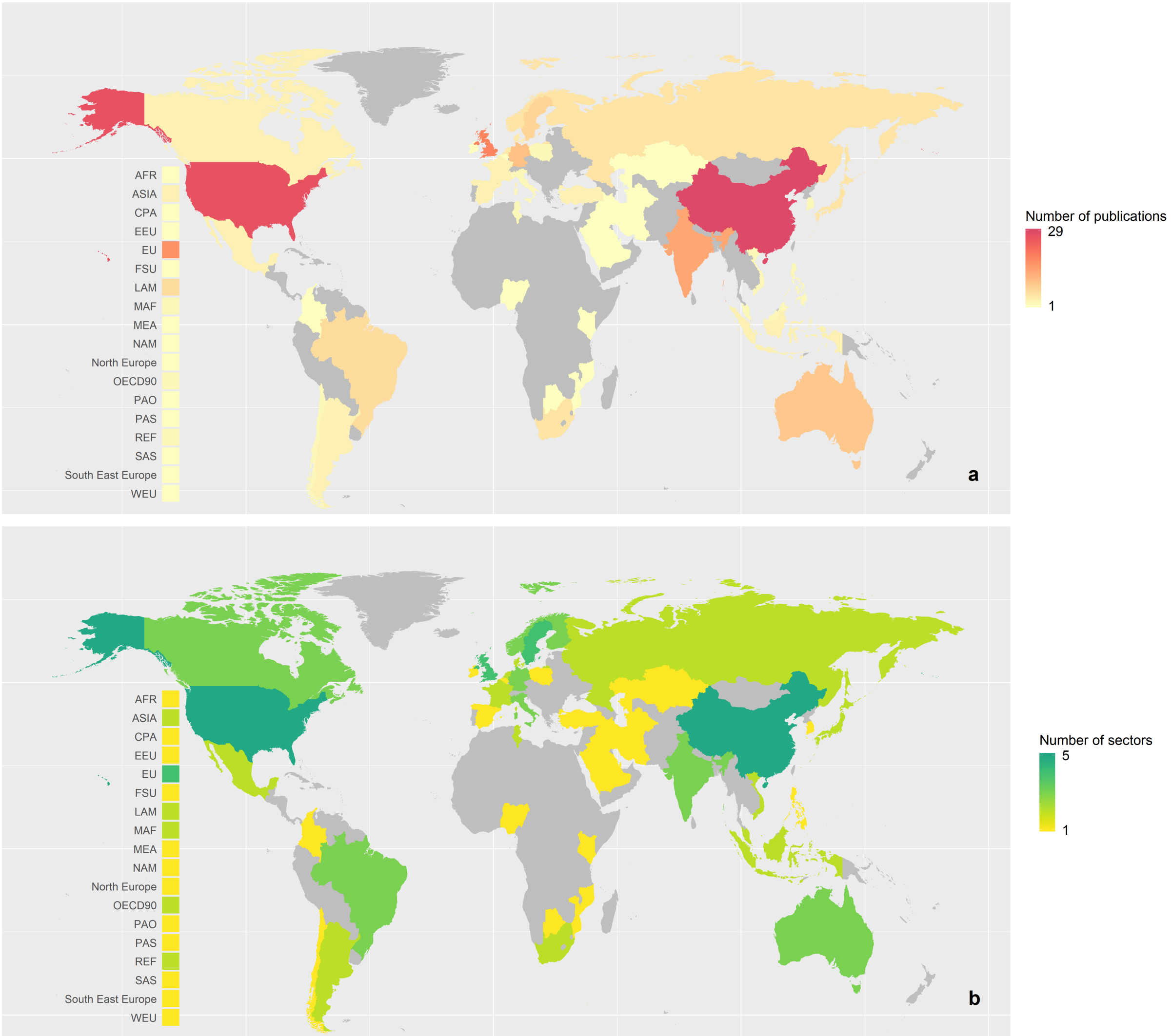

Figure 2.4 – Geographical distribution of the literature by numbers of publications (a) and numbers of sectors analyzed (b). The maps present the results for countries analyzed, with all scales of analysis combined. For instance publications focusing on a particular city in a country will we counted as related to that country. The bar plots show the geographical distribution among world regions of publications with global or multi-country scales of analysis. The codes for world regions are given in the Appendix C table 2.7.

2.3.2 Review of carbon lock-in quantifications

Carbon lock-in indicators

In our analysis of the literature, we find 92 publications that contain 286 quantitative estimations of carbon lock-in. We sort them according to geographical scope (subnational, national, multicountry, and global), and sector (electricity, building, spatial planning, transport vehicles, fossil fuel production, industry).

The electricity sector has received the most quantifications, with 170 estimations in 60 publications, which represents 65 % of the subsample of quantitative studies. This result is valid as well for all geographic levels, except for cities (figure 2.6 and Appendix A figure 2.1). On the

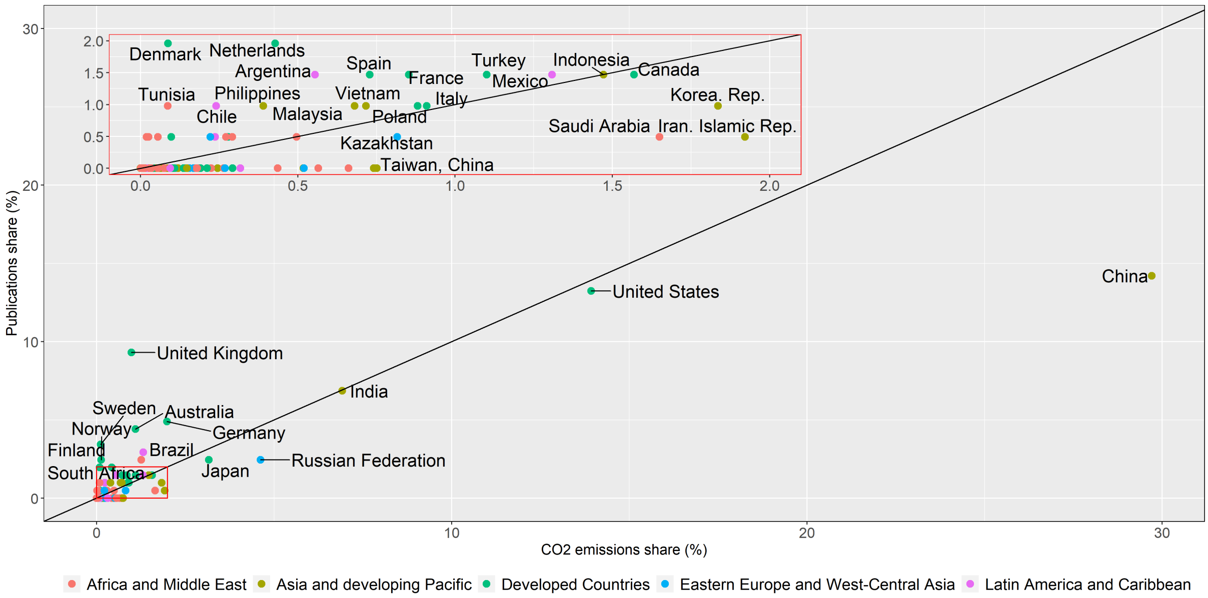

Figure 2.5 – Shares of publications against shares of 2018 CO_2 emissions for each country. The black line corresponds to the points where the share of publications equals the share of CO_2 emissions. Data used for CO_2 emissions come from (Crippa et al., 2019)

other hand, publications containing quantifications for transport vehicles and spatial planning represent each less than 10% of the quantitative studies. Few quantifications (3) for cities have been done compared to other geographical units. More city case studies would be needed to quantify the impact of different policies on CO_2 emissions in the long term and give insights for local planning choices.

We identified 11 indicators used in the literature (Table 2.3). These have been applied for different time frames of analysis that can be classified as backward-looking, static for a given year, or forward-looking using scenarios. Backward-looking analyses study periods in the past over a certain time frame. Static analyses provide a snapshot at a given year, often just a few years before the date of publication of the study, corresponding to the latest year for which data is available. Forward-looking analyses construct scenarios of future evolutions and analyze those trajectories. Few articles (7) have carried out quantitative retrospective analyses on carbon lock-in compared to static (30) or prospective (63) analyses. In the next paragraph, we describe each of the different indicators used and summarize the common trends in results where publications numbers are sufficient.

Studies have focused on the evolution of *installed capacity*, corresponding for example to the electricity output for a power plant or the traffic volume for a road. Installed capacity, as projected over time, is used as a measure of carbon lock-in in the electricity generation and fossil fuel production & distribution sectors. Articles have highlighted the risk of a rapid increase in high-carbon installed capacity by 2030 if climate policies are further delayed (Bertram et al., 2015b; Turhan et al., 2016; Kefford et al., 2018; McGlade et al., 2018). However, these studies could potentially overestimate the carbon lock-in induced by LLCS evolution by not considering low carbon retrofitting such as carbon capture and storage integration for power plants. This

Indicator	Time frame		
	Backward	*Static*	*Forward*
Installed capacity		2	4
Age of existing stock		4	
Committed emissions	5	13	8
Capital costs intensity		1	1
Stranded assets		5	31
Mitigation costs		1	10
Emissions/Energy gap			12
Residual emissions			2
Elasticity related to LLCS variables	3		1
Technology scale	1	2	2
Employment		2	

Table 2.3 – Indicators used in the literature by time frame of analysis. The number of publications is indicated in each cell

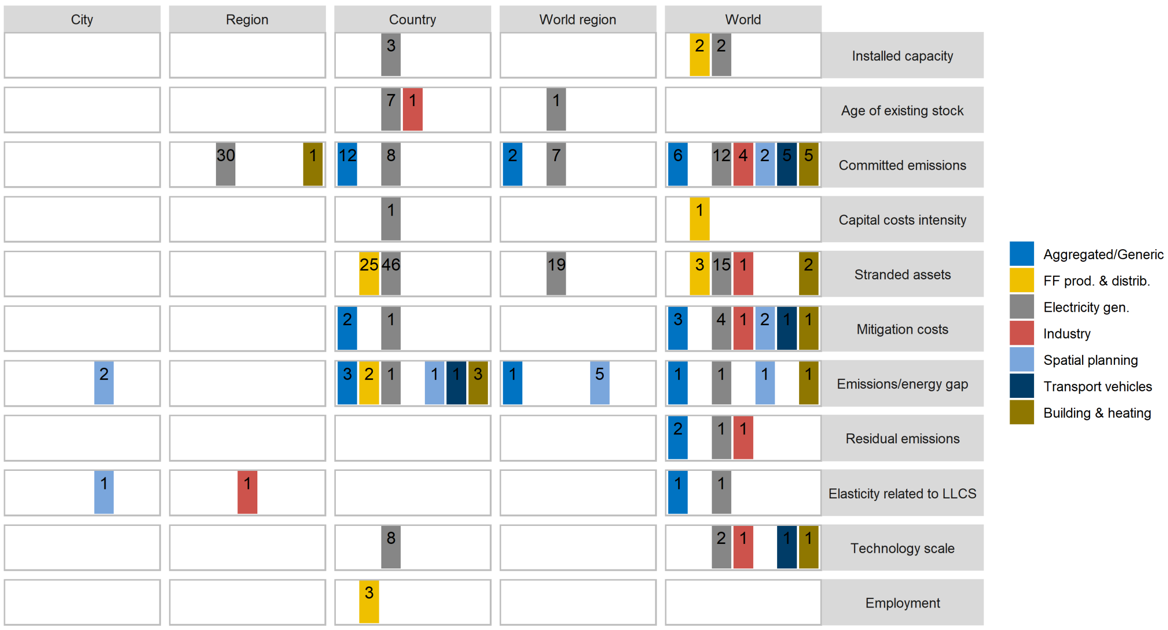

Figure 2.6 – Distribution of carbon lock-in quantifications by geographical unit, sector studied and indicator used. The numbers in each color bar give the number of publications for the corresponding geographical unit, sector and indicator combination. Note that a publication can contain multiple quantifications.

is shown by Li et al. (2011) which quantifies in a static manner the share of power generation capacity existing at a given year in China that could be retrofitted with carbon capture and storage.

Other studies quantified carbon lock-in in relation to the lifetime of the capital considered. Some authors referred to the *age* of the existing infrastructure stock, analyzing either its distribution or its average value. The younger the stock, the lower the probability to replace this capital in the short term. This indicator has been used mainly in the electricity generation sector (figure 2.6). The global age distribution tends to be bimodal between OECD and non OECD countries. For instance, in China a large part of industrial and electricity sector capital is younger than 10 years (Lane et al., 2016; Zheng et al., 2018) whereas in the EU and the US an important part of electricity generation capital is more than 30 years old. (Lane et al., 2016; Rode et al., 2017).

The concept of *committed emissions* has also been used to quantify the cumulative emissions that would occur over the remaining entire operation lifetime of an asset (Davis et al., 2010). This indicator has been mainly applied in static and forward-looking frameworks (table 2.3). Past committed emissions over a given period have also been analysed, but to a lesser extent (Davis and Socolow, 2014; Jiang et al., 2017; Pfeiffer et al., 2018; Tong et al., 2019). In a static framework, the committed emissions calculated can be compared with carbon-budgets associated with a temperature target to quantify the potential (in)consistency of the existing stock with the temperature goal. Whereas most of the indicators are used for one or two time frames, committed emissions have been used for backward-looking, static and forward-looking analyses.

The operational life of infrastructure does not only depend on its age. Indeed, any infrastructure project is based on an investment plan with an expected long-term profitability. A change in the regulatory and economic context (for example the implementation of a carbon tax) can thus modify the operational costs, rendering the continued use of an infrastructure uneconomical. This is why other indicators also include economic aspects to quantify carbon lock-in. Two publications have quantified the *capital costs intensity* as the level of capital investment required for extraction or production of given unit (Shackley and Thompson, 2012; Erickson, 2015). The assumption behind is that the more capital-intensive an investment, the more it may be isolated from price fluctuations and hence the more operators will be likely to keep using this capital.

In the same manner, carbon lock-in literature has made extensive use of the *stranded assets* indicator. It is defined as the premature retirement/retrofitting or under-utilization of existing assets in relation to a potential reference capital (Saygin et al., 2019). This indicator measures the implications - the assets lost - if the carbon lock-in is to be escaped from. Stranded assets can be either the stranded investments or the stranded profits depending on the reference lifetime chosen. Indeed, the reference lifetime considered can be the 'physical' one over which the capital can be used or the 'economic' one over which capital investment costs are recovered. Making this distinction is important because it can have significant impact on the results obtained as the difference between those two lifetimes can be of several decades (Kefford et al., 2018). The majority of existing estimations are about the electricity generation and fossil fuel production & distribution sectors (figure 2.6). Two distinct methodologies have been used. For the first one, some authors have used the age distribution of the existing stock for a given year based on unit-level assessments to project its evolution, assuming all capital stock is used until the end of its potential lifetime. This evolution is then compared (i) either in a static manner to the capital stock targeted for a future year (Pfeiffer et al., 2016; Farfan and Breyer, 2017a,b) or (ii) with a forward looking approach to the capital stock evolution extracted from a low-carbon scenario (CTI, 2014b,a; Lane et al., 2016; Kefford et al., 2018; Cui et al., 2019; Saygin et al., 2019). The second approach is to quantify the stranded assets using models with an endogenous evolution of capital stock (Mercure et al., 2014; Iyer et al., 2015; Johnson et al., 2015; Luderer et al., 2016; van Soest et al., 2017; Coulomb et al., 2019). In this case, capital can be retired early because new economic conditions make its use unprofitable. Results obtained are expressed either in terms of electricity capacity/production retired or in monetary terms to quantify the loss of expected revenue. Given the numerous quantifications for these two indicators - committed emissions and stranded assets - the synthesis of the results is presented in a subsection below.

Mitigation costs is also an indicator which has been used to quantify the transition costs induced by the inertia of long-lived capital. It represents the potential macroeconomic costs associated with the transition to a low-carbon system for different levels of short-term climate policy ambition. Mitigation costs have been quantified as the variation of an economic indicator between a "reference" scenario (either with no mitigation policies or with only current policies) and a mitigation scenario or a scenario considered as 'optimal' to reach a long term temperature target. It is an indicator widely used in the integrated assessment literature to compare the macroeconomic costs of different scenarios. We extracted only the studies using specifically this indicator to quantify carbon lock-in. The economic variables chosen to represent the mitigation costs have been GDP losses (Ha-Duong et al., 1997; Richels et al., 2009; Waisman et al., 2012; Lucas et al., 2013; Riahi et al., 2015; Luderer et al., 2016) or consumption losses (Lecocq et al., 1998; Kalkuhl et al., 2012; Bertram et al., 2015b). The literature has mainly used mitigation costs to quantify carbon lock-in at the global scale. A common result with this indicator is that when mitigation policies are nonexistent or when their stringency is low in the short term, overall mitigation costs increase, reflecting short-term inertia and path-dependency. We considered as mitigation costs as well the unlocked costs calculated by Erickson et al. (2015) as the carbon price needed to retire an existing investment in 2015 at half its economic lifetime and replace it with a corresponding low-carbon alternative.

Other studies have evaluated the contribution of infrastructure stock evolution to CO_2 emissions by dynamically taking into account both technical and economic factors. To do so, some authors calculated the *emissions/energy gap* at a given future year between different scenarios of infrastructure stock evolution. Another approach has been to compare *residual emissions* – the amount of CO_2 emissions whose abatement remains uneconomical or technically infeasible in the long term (Kriegler et al., 2015; Luderer et al., 2018) – between scenarios. Models used in these publications have projected an increase of global residual emissions when the strengthening of mitigation efforts is delayed. While former indicators have been applied only for forward-looking studies, *elasticities related to capital stock variables* allows authors to retrospectively isolate the contribution of capital stock evolution to increases in CO_2 emissions. Correlations have been estimated between CO_2 emissions from coal capital & economic growth, CO_2 emissions

& material stock or CO_2 emissions & industrial agglomeration index (Steckel et al., 2015; Lin et al., 2017; Zhang et al., 2018). Avner et al. (2014) have also used this type of approach in a forward looking framework, looking at fossil fuel price elasticity of CO_2 emissions for different scenarios of public transport supply.

A last group of indicators, used more marginally, relates to institutional and political factors that influence the transition rate of LLCS. This concerns first of all *employment*, with analyses of the distribution of jobs between low and high carbon sectors or the regional concentration of jobs in carbon-intensive sectors (Bjørnåvold and Van Passel, 2017; Spencer et al., 2018). The issue of employment is not just a question of social acceptability in case of rapid transition. One of the conditions for the emergence of a capital-intensive low-carbon technology in the face of a dominant technology is the rapid reduction of cost through learning effects. These learning effects depend on the production process of the technology and therefore on the skills of the workers (Bjørnåvold and Van Passel, 2017). The second institutional indicator is the *technology scale* expressed as the market share of given technologies (Erickson et al., 2015; Spencer et al., 2018; Skoczkowski et al., 2018). The hypothesis here is that widespread adoption of a technology induces significant carbon lock-in through confidence in the technology (adaptive expectations) and coordination between sectors (network effects).

The indicator statistics reveal that the majority of existing estimations have used committed emissions or stranded assets as metrics (figure 2.6 and table 2.3). Those indicators have been used at a diversity of geographical levels compared to other indicators and in multiple sectors. However, more retrospective analysis could be carried out for stranded assets, in particular in order to analyse which policy instruments triggered these premature closures and what the associated economic impacts were. The majority of indicators used refer to technical and economic dimensions of carbon lock-in. Conversely, few analyses have been carried out to quantify institutional carbon lock-in.

Synthesis of results concerning committed emissions and stranded assets

10 studies in the literature have estimated cumulative committed emissions for a given year and at the global scale (figure 2.7). These articles differ by the sectors included in the analysis. From the four studies that include all sectors, a slight increase over time of committed emissions seems to emerge. However, this result is to be taken with care since it comes from a very small number of studies, and part of the result may come from different methodologies, data sources or assumptions, in particular on capital lifetimes and utilization rates. No clear trend over time emerges for the electricity sector, but again this may be due to different methodologies and assumptions across studies. One study (Tong et al., 2019) recently analyzed, with the same methodology, data sources and assumptions, the evolution in committed emissions over time and finds an increase in total committed emissions from just above 400 $GtCO_2$ in 1998 to 658 in 2018, with the majority of the increase in the power generation sector and in China.

The existing infrastructure contributing the most to global committed emissions are power plants, accounting for between 48% and 54% of the total (Smith et al., 2019; Tong et al., 2019).

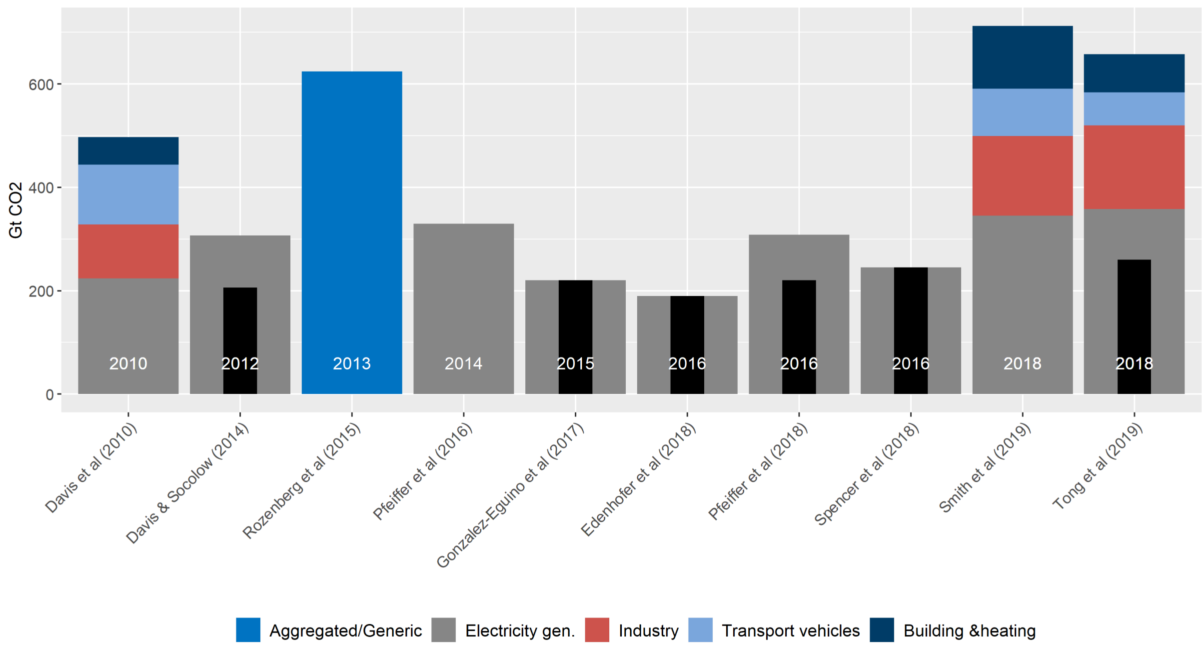

Figure 2.7 – Global committed emissions (central values) for existing stock of energy infrastructures. The black bar represents the committed emissions related to coal power plants when available. The year used to calculate committed emissions is indicated at the bottom of each bar.

This high contribution of the electricity sector is also found at the national level for the 5 countries with the highest CO_2 emissions. For all 5 countries, the share of the electricity sector in total committed emissions is above 45% (figure 2.9). Industry is the second largest source of committed emissions, particularly in emerging countries such as China and India with shares close to 30%.

Existing evaluations of stranded assets have also highlighted the carbon lock-in induced by the power generation sector. Coal-power plants constitute the electricity generation capital with the highest risk of stranded assets. For scenarios consistent with a 2°C target, cumulative global early retired capacities by 2060 would represent less than 50 GW for oil, a maximum of around 600 GW for gas and up to 1700 GW for coal (Iyer et al., 2015; Kefford et al., 2018). This large difference justifies the greater emphasis of the stranded assets literature on coal power plants. Estimations are sensitive to modelling hypothesis (figure 2.8). The later the climate policy is implemented, the higher the expected stranded assets are. Even if the climate policy is implemented before 2020, the short-term level of stringency is a determining parameter. Compared to the scenarios assuming a strong emissions reduction as early as 2015 and consistent with a 2°C target, global cumulative stranded coal power assets are expected to be higher by a factor 2-3 for National Determined Contributions (NDC) pathways (those NDC pathways correspond to scenarios where mitigation policies until 2030 correspond to the NDCs from Paris Agreement on Climate Change and where emissions reductions accelerate after 2030 to meet the long term temperature target). This estimation of the additional stranded assets induced by NDCs comes from a single publication (Iyer et al., 2015) and therefore could be refined by

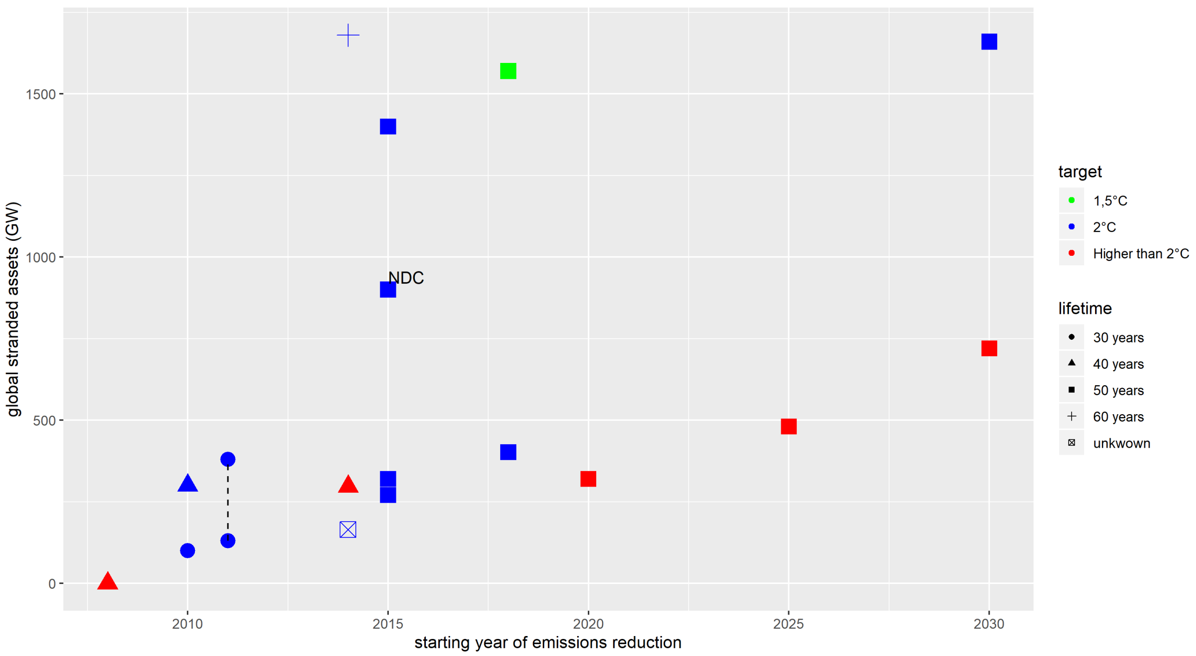

Figure 2.8 – Global cumulative stranded capacities of coal power plants by 2060. Each marker corresponds to one quantification, either one scenario or one static analysis. The marker's shape codes the assumption on plants lifetimes, and the colors code the temperature target of the scenario. Temperature target refers to the maximum temperature increase expected in 2100 (50% chances minimum) extracted from the scenarios. The X-axis corresponds to the year when emissions reduction starts. It is the year in the mitigation scenario when emissions start to be different from emissions in the baseline scenario (i.e. the scenario with no climate policy). For static analyses based on retirement schedules of the existing stock, we considered the year of the dataset as the starting year of emissions reduction. The NDC scenario refers to a trajectory of emissions reductions consistent with the national determined contributions until 2030 and accelerated emissions reductions after 2030 to meet the long term temperature target.

further research. Results are very sensitive to the assumed operational lifetime for stranded assets calculation especially for lifetimes higher than 50 years. Only one study (Cui et al., 2019) has quantified stranded assets for 1.5 °C scenario obtaining results significantly higher than other studies with similar coal power plants lifetime and year of climate policy implementation.

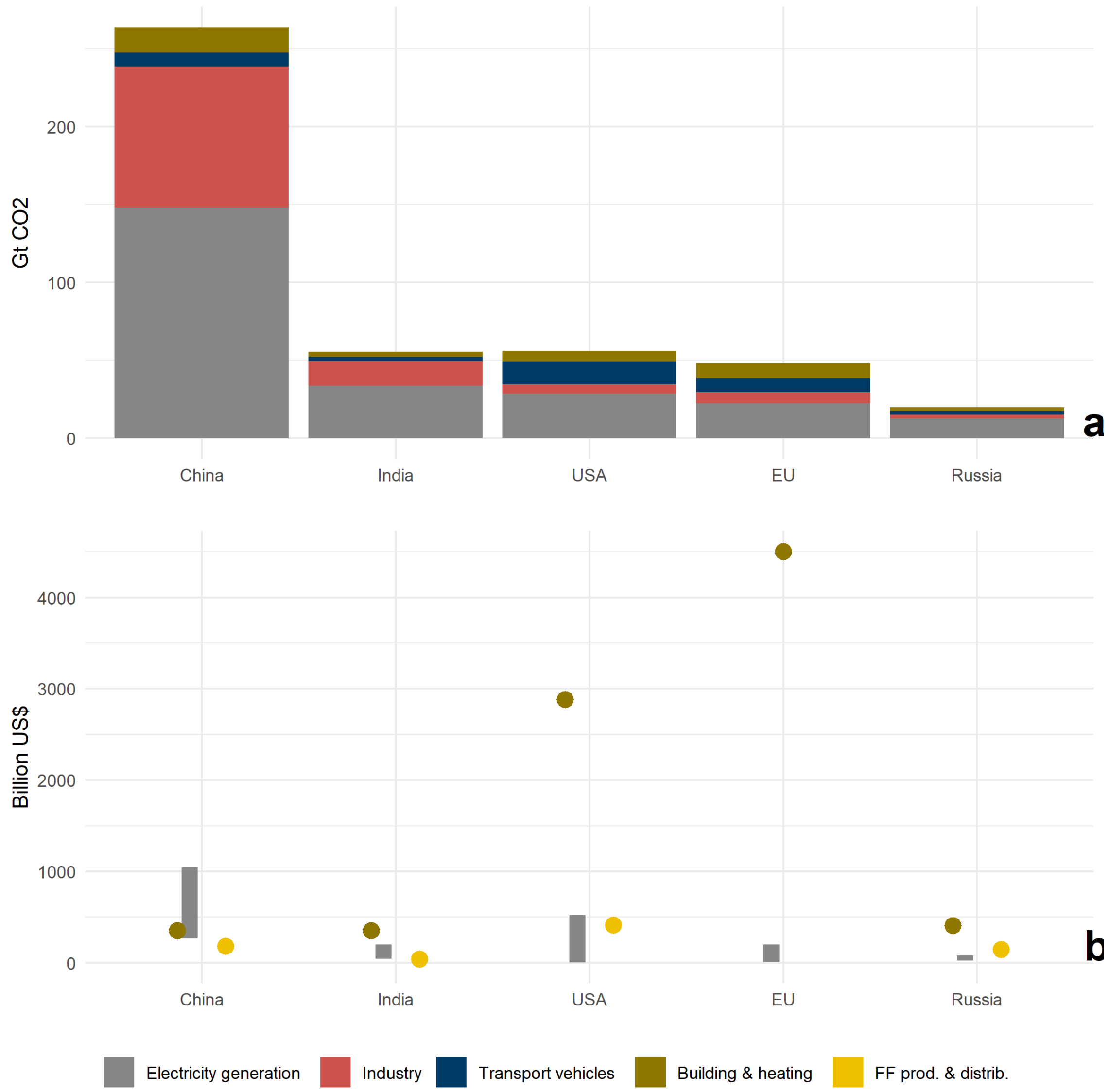

Figure 2.9 – Quantifications of committed emissions and stranded assets for the five most CO_2-emitting countries in 2018. Panel (a) shows committed emissions in 2018 from existing infrastructures and panel (b) stranded assets (stranded investments) by 2050 for a 2°C consistent pathway. Dots correspond to a single quantification, bars give the range when there are multiple quantifications. The order of magnitude for stranded assets in the buildings sector have been estimated by graphical reading from IRENA (2017). Values are not referenced in the codebook we used in this review. Sources : CTI (2015); IRENA (2017); Kefford et al. (2018); Saygin et al. (2019); Tong et al. (2019)

However, some publications have suggested that stranded long-lived assets may be even more important outside of the power sector. While stranded power sector assets by 2050 could reach up to $1.8 trillion in scenarios consistent with a 2°C target, Saygin et al. (2019) found a range of $5-11 trillion in the buildings sectors. Muldoon-Smith and Greenhalgh (2019) have even estimated a potential value at risk for global real estate assets up to $21 trillion. CTI (2015) has also quantified $2.2 trillion of unnecessary capex in fossil fuel production and distribution from 2015 to 2025.

The sectoral distribution and amount of stranded assets differ across countries (figure 2.9). Capital for fossil fuel production and distribution represents a larger share of potentially stranded assets in fossil fuel producing countries such as the United States and Russia. Electricity generation would be a larger share of total stranded assets in emerging countries because this capital is relatively new compared to its operational lifetime. Conversely, buildings could represent a larger part of stranded capital in more developed countries such as the United States, EU or even Russia because of high market value and low turnover rate.

The contrasting results between the two indicators for the buildings sector can be explained by the methodology used to calculate committed emissions. Estimation in global studies tend to underestimate carbon lock-in outside the electricity sector as they do not take into account additional inertia induced by building shells, conditions, asset locations or transport infrastructures (Guivarch and Hallegatte, 2011). More research is needed about stranded assets outside of the power sector given their potential magnitude.

2.3.3 Synthesis of policies to break out carbon lock-in

Here we summarize identified policy implications suggested to escape or avoid carbon lock-in (Table 2.5). The qualitative statements (QS) we found emphasize that three governance dimensions need to be integrated regardless of the instruments used: stability, coordination and legitimacy. *Long-term stability* of climate policy orientations is referred to in 20 QS. When the policy implementation appears certain and credible, stakeholders are confident and invest early in low-carbon LLCS (Bento, 2010; Nam et al., 2013; Shahnazari et al., 2014; Wang et al., 2014; Vogt-Schilb et al., 2015) to adapt to the future regulatory context and to avoid sunk investments in high-carbon LLCS. The predictable evolution of climate policies leads to investments more consistent with the long term target, limiting carbon lock-in extension or stranded assets due to unanticipated shock in climate policy (Lazarus et al., 2015; Bergen and Muñoz, 2018; Kalkuhl et al., 2019).

The transition of LLCS towards low-carbon systems cannot be done without assuring its *legitimacy*. This idea appears in the qualitative statements we extracted through different channels such as the transparency and emphasis on co-benefits and avoided costs (11 QS) or the creation of participatory processes (11 QS). Carbon lock-in is at the intersection of political, economic and institutional constraints among a multitude of actors. There is hence the need to ensure the largest possible consensus and support around the rapid transition of existing capital and the associated policy instruments.

Policy packages should also create the space for the *coordination* between actors and sectors (12 QS), counterbalancing existing coordination effects between 'dirty' sectors. Those three aspects - stability, legitimacy and coordination - are not independent and influence each other: creating legitimacy between different actors of LLCS transition policies reinforce the long term stability, and policies that appear stable and credible to stakeholders lead to more coordination.

Topic	Counts	Sources
Supporting low-carbon technology deployment	#22	Greene and Plotkin (2001); Sandén and Azar (2005); Delrio and Unruh (2007); Ahman and Nilsson (2008); Bento (2010); Lehmann et al. (2012); Kalkuhl et al. (2012); Avner et al. (2014); Mercure et al. (2014); Lecocq and Shalizi (2014); Aglietta et al. (2015); Bertram et al. (2015b); Steckel et al. (2015); Fouquet (2016); Wesseling et al. (2016); Hansen et al. (2017); Schmidt et al. (2017); Bos and Gupta (2018); Leibowicz (2018); Tvinnereim and Mehling (2018); Edenhofer et al. (2018); Szabo et al. (2019)
Carbon pricing should be introduced	#21	Greaker and Heggedal (2010); Lehmann et al. (2012); Hood (2014); Lecocq and Shalizi (2014); Mercure et al. (2014); Shahnazari et al. (2014); Bertram et al. (2015b); Erickson (2015); Fay et al. (2015); Hermwille et al. (2015); Mattauch et al. (2015); Steckel et al. (2015); Aghion et al. (2016); Pfeiffer et al. (2016); IRENA (2017); Jiang et al. (2017); Edenhofer et al. (2018); Zheng et al. (2018); Wilson and Staffell (2018); Rosenbloom et al. (2019); Wang et al. (2020)
Climate policies orientation needs to be stable over time	#20	Delrio and Unruh (2007); Bento (2010); Greaker and Heggedal (2010); Nolden (2012); Chignell and Gross (2013); Nam et al. (2013); Hood (2014); Shahnazari et al. (2014); Wang et al. (2014); Lazarus et al. (2015); Pfeiffer et al. (2016); Hansen et al. (2017); IRENA (2017); Bergen and Muñoz (2018); Spencer et al. (2018); La Viña et al. (2018); Skoczkowski et al. (2018); Wilson and Staffell (2018); Kalkuhl et al. (2019); Rosenbloom et al. (2019)
Carbon pricing if introduced needs to be complemented with other instruments	#17	Sandén and Azar (2005); Delrio and Unruh (2007); Maréchal (2007); Avner et al. (2014); Lecocq and Shalizi (2014); Mercure et al. (2014); Bertram et al. (2015b); Fay et al. (2015); Jotzo and Mazouz (2015); Steckel et al. (2015); Mattauch et al. (2015); Pfeiffer et al. (2016); Tvinnereim and Mehling (2018); Kalkuhl et al. (2019); Meyer and Schwarze (2019); Rosenbloom et al. (2019); Lamperti et al. (2020)
Implementing technology mandates	#13	Gül and Turton (2011); Shackley and Thompson (2012); Chignell and Gross (2013); Mercure et al. (2014); Bertram et al. (2015b); Erickson (2015); Jotzo and Mazouz (2015); Steckel et al. (2015); Shearer et al. (2017); Pfeiffer et al. (2018); Rozenberg et al. (2018); Tvinnereim and Mehling (2018); Li and Strachan (2019)
Coordination between sectors and actors	#12	Frantzeskaki and Loorbach (2010); Carley (2011); Gül and Turton (2011); Lehmann et al. (2012); Malekpour et al. (2015); Mäkinen et al. (2015); Sachs et al. (2016); Wesseling et al. (2016); Karakaya et al. (2018); Gadre and Anandarajah (2019); Gross and Hanna (2019); Tozer (2019)

Highlighting co-benefits and avoided costs	#11	Delrio and Unruh (2007); Briggs et al. (2015); Steckel et al. (2015); Kriegler et al. (2015); Clausen et al. (2017); Martínez Arranz (2017); Edenhofer et al. (2018); Skoczkowski et al. (2018); de Macedo and Jacobi (2019); Meyer and Schwarze (2019); Rosenbloom et al. (2019)
Creating participation processes	#10	Praetorius (2009); Lehmann et al. (2012); Briggs et al. (2015); Vandevyvere and Nevens (2015); Sachs et al. (2016); Schmid et al. (2016); Wesseling et al. (2016); Schmidt et al. (2017); Spencer et al. (2018); Skoczkowski et al. (2018)
Implementing performance standards	#10	Bento (2010); Li et al. (2010); Shackley and Thompson (2012); Verbruggen (2012); Zaid et al. (2014); Fay et al. (2015); Pfeiffer et al. (2016); Edenhofer et al. (2018); Pfeiffer et al. (2018); Rozenberg et al. (2018)
Setting a compensation scheme	#5	Odenberger and Johnsson (2007); Kefford et al. (2018); Edenhofer et al. (2018); Jotzo and Mazouz (2015); Rentier et al. (2019)
Supporting low-carbon R&D	#4	Gül and Turton (2011); Mattauch et al. (2015); Aghion et al. (2016); Tvinnereim and Mehling (2018)
Not picking any technology as 'winners'	#4	Marechal and Lazaric (2010); Shackley and Thompson (2012); Bjørnåvold and Van Passel (2017); Hansen et al. (2017)
Implementing tax on high-emitting capital	#3	Barrington-Leigh and Millard-Ball (2017); Rozenberg et al. (2018); Kalkuhl et al. (2019)

Table 2.5 – Findings from the thematic analysis on qualitative statements about policy implications to escape carbon lock-in. The 136 qualitative statements extracted from our sample are available in the Supplementary Material 3 of the online version of the published article related to this chapter

A variety of different policy instruments are mentioned in our sample (Table 2.5). *Incentive-based instruments* include emissions taxes, tradable allowance systems, subsidies to emissions abatement or taxes on goods associated with emissions. 21 documents refer to the implementation of carbon price instruments through taxes or allowances with the objective to provide incentives making high-carbon LLCS less attractive. However, some qualitative statements highlight limitations of carbon pricing with regard to the constraints on the LLCS such as the difficulty to assure commitment and stability over time (Pfeiffer et al., 2016; Kalkuhl et al., 2019), the legitimacy of this instrument (Pfeiffer et al., 2016; Rosenbloom et al., 2019) or the fact that it does not prevent sunk costs and stranded assets (Tvinnereim and Mehling, 2018; Meyer and Schwarze, 2019). 17 QS highlight the need to integrate carbon pricing in a broader policy package. Other incentives instruments are mentioned with 3 QS related to taxes on high-emitting capital.

The second category of instruments considered are *regulatory instruments* with technology mandates and performance standards. Technology mandates refer to a specific requirement regarding the production process such as making the use of a given technology or equipment mandatory. Performance standards impose conditions regarding the output but do not impose any technology. We obtained 13 and 10 QS related to technology mandates and performance standards respectively. For performance standards, the buildings and heating sector is more represented, with 50 % of the statements compared to other instruments. One explanation is the very slow turnover of building stocks. This means that some choices about energy performance attributes such as the building orientation or its compactness for instance are irrevocable. This calls for immediately choosing the highest energy performance which can be assured with performance standards (Fay et al., 2015; Verbruggen, 2012). Limiting further sunk costs because of long capital lifetimes also justify the usage of technology mandates especially in the electricy sector with several mentions of moratoria for new coal power plants (Mercure et al., 2014; Bertram et al., 2015b; Steckel et al., 2015; Pfeiffer et al., 2018; Rozenberg et al., 2018).

Technology policies include R&D support and support to technology deployment. Few QS (4) are related to support for R&D contrary to support for technology deployment with 22 QS. One approach is to decrease investment risks in new low-carbon capital (Aglietta et al., 2015; Mercure et al., 2014; Edenhofer et al., 2018). Another approach is to subsidize low-carbon capital to create niche emergence and compensate for the lower costs of fossil fuel capital induced by past cumulative learning effects (Mercure et al., 2014; Fouquet, 2016; Bos and Gupta, 2018; Szabo et al., 2019).

2.4 Conclusion

Long-lived capital-stocks, such as infrastructure and buildings, induce path-dependent evolution and therefore constitute a constraint for the rapid reduction of greenhouse gas emissions. Here, we systematically map the literature about carbon lock-in. To do so, we use machine learning to identify 226 relevant publications for a set of 38095 articles from the Web of Science and Scopus databases. We extracted qualitative and quantitative informations for each publication. The synthesis of this information reveals common analytical approaches, as well as geographical or sectoral specificities.

We find that research on carbon lock-in has mainly focused on power generation. We also identify a bias toward developed countries, which represent the majority of our sample. Comparing the share of global emissions in 2018 and the share of publications for each country, we also highlight understudied countries such as Russia or China (even though the latter has been the most studied country in the literature, it represents a smaller share of publications than its share in global emissions) and overstudied countries such as the United Kingdom, Australia, Sweden or Germany.

We also scrutinized publications that quantify carbon lock-in. We identify 11 types of indicators used : installed capacity, age of existing stock, committed emissions, stranded assets, capital costs intensity, mitigation costs, emissions/energy gap, residual emissions, elasticity related to long-lived capital stock, technology scale and employment. The majority of quantitative studies have evaluated carbon lock-in with forward-looking indicators. Committed emissions and stranded assets are the two most widely used indicators. The literature indicates that global committed emissions of existing energy infrastructure increased slightly since 2010. However, this result is to be taken with care since it comes from a very small number of studies. Stranded assets have mainly been quantified for the power generation sector. Coal-power plants are the most important and most investigated stranded assets in the electricity sector. In scenarios consistent with a 2°C target, coal-power plants represent on average about 70% of cumulative early retired capacity. Studies also demonstrate, unsurprisingly, that the later climate policies are implemented, the higher the expected stranded assets are. In scenarios consistent with a 2°C target, stranded coal power assets are evaluated to be higher by a factor 2-3 for pathways that assume relatively low-ambition policies following National Determined Contributions until 2030 compared to pathways assuming ambitious climate policies starting in 2015. However, recent literature suggests that stranded long-lived assets may be even more important outside of the power sector - notably for the buildings sector in developed countries due to its high market value and low turnover rate.

We finally synthesized qualitative statements related to policies to escape carbon lock-in. They highlight the need to assure (i) the stability of climate policy orientations, (ii) the coordination between actors and sectors and (iii) the legitimacy of targets and instruments used. Although the carbon price is the most mentioned policy instrument, it is also regularly pointed out that it cannot prevent carbon lock-in if used alone. Carbon pricing therefore needs to be complemented with other instruments, such as fiscal support for low-carbon capital deployment and technical regulations.

Our work has some limitations related to the systematic review methodology. First of all, some abstracts may use keywords or synonyms other than those used in our search query. Although we also analysed the references of each article to limit this omission, the terminology used for the same subject can vary significantly between organizations and research domains, in particular for transdisciplinary research topic such as sustainable development (Glavič and Lukman, 2007). In addition, although the authors defined commonly criteria for publications inclusion/exclusion, the manual filtering of articles can be subject to a certain amount of subjectivity as to whether or not these criteria are met. One way of limiting this potential bias would have been to jointly check all the excluded articles, but this would have led to a much greater amount of work time allocated to the filtering stage. We also conclude from the results of our machine-learning assisted screening that the returns to additional screening would be low, but not zero. It is therefore unlikely that we identified 100% of relevant studies returned by our queries.

Despite these limitations, we identify different knowledge gaps. First, more analyses in non-electricity sectors are required. The two reasons are that (i) the rates of capital renewal can be slower than in the electricity sector but also that (ii) the contribution of sectors other than electricity is likely to increase in the coming decades, as the electricity sector is the 'easiest' sector to decarbonise. Secondly, studies at urban scale are lacking, although cities are called upon to play an increasing role in the implementation of mitigation policies in the future. Thirdly, although developed countries are large contributors to global emissions with the majority of the physical stock already built, future development pathways will need to be analyzed in developing countries in order to disentangle the factors contributing to carbon lock-in (Lee and Koski, 2014). In addition, although some of the countries not studied may not contribute significantly to global emissions, they may have specific characteristics of interest for the analysis of carbon lock-in and mitigation policies. This is notably the case for islands, including small island developing states (SIDS), which are geographically confined, are limited in outward sprawl, and display a smaller number of power plants and gasoline stations. These characteristics make them ideal candidates for escaping carbon lock-in (Soomauroo et al., 2020). Finally, carbon lock-in depends not only on techno-economic factors but also on institutional factors, and the increasing use of indicators integrating this latter dimension seems necessary to assess more precisely lock-in risks.

Multiple possible low-carbon transition pathways involving rapid transitions of capital exist. However, decisions concerning the transitions cannot avoid the question of feasibility and the underlying political and economic constraints. Identifying existing or future socio-technical and institutional barriers is crucial to informing policy makers on the realistic implementation of public policies (Lamb and Minx, 2020). The measures of carbon lock-in strength induced by LLCS delineate the "dynamic political feasibility space" (Jewell and Cherp, 2020). Multidimensional monitoring can allow the iterative readjustment decarbonization targets in different sectors or regions and the implemententation of policy packages consistent with the dimensions highlighted in this review. Some of the indicators that quantify carbon lock-in could support efforts to track progress towards the Paris Agreement targets and to inform the next 'global stocktakes' (Peters et al., 2017).

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2.A Appendix A - Supplementary results

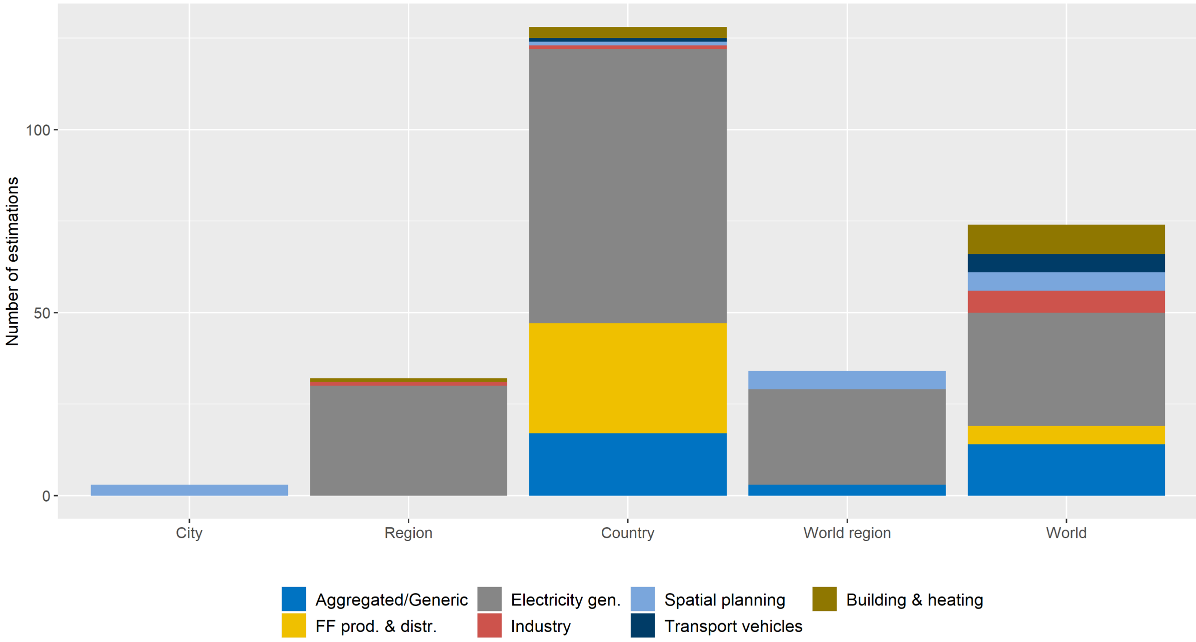

Figure 2.10 – Distribution of carbon lock-in quantifications by geographical unit

2.B Appendix B - Test list used for the calibration of the search query

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2.C Appendix C - Definitions of world regions

Code	Definition
AFR	**Sub-Saharan Africa**: Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Cote d'Ivoire, Congo, Democratic Republic of Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Saint Helena, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe
ASIA	**Asia**: CPA, PAS and SAS
CPA	**Centrally Planned Asia**: Cambodia, China (incl. Hong Kong), Korea (DPR), Laos (PDR), Mongolia, Viet Nam
EEU	**Eastern Europe**: Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, The former Yugoslav Rep. of Macedonia, Hungary, Poland, Romania, Slovak Republic, Slovenia, Estonia, Latvia, Lithuania
EU	**European Union**: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden
FSU	**Former Soviet Union**: Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
LAM	**Latin America and the Caribbean**: Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guyana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Santa Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela
MAF	**Middle-East and Africa**: MEA and AFR
MEA	**Middle East and North Africa**: Algeria, Bahrain, Egypt (Arab Republic), Iraq, Iran (Islamic Republic), Israel, Jordan, Kuwait, Lebanon, Libya/SPLAJ, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria (Arab Republic), Tunisia, United Arab Emirates, Yemen
NAM	**North America**: Canada, Guam, Puerto Rico, United States of America, Virgin Islands

North Europe	**North Europe**: Denmark, Finland, Germany, Norway, Sweden and United Kingdom
OECD90	**OECD countries in 1990**: NAM, PAO and WEU
PAO	**Pacific OECD**: Australia, Japan, New Zealand
PAS	**Other Pacific Asia**: American Samoa, Brunei Darussalam, Fiji, French Polynesia, Gilbert-Kiribati, Indonesia, Malaysia, Myanmar, New Caledonia, Papua, New Guinea, Philippines, Republic of Korea, Singapore, Solomon Islands, Taiwan (China), Thailand, Tonga, Vanuatu, Western Samoa
REF	**Reforming Countries** : FSU and EEU
SAS	**South Asia** : Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka
South East Europe	**South East Europe**: Albania, Bosnia and Herzegovina, Bulgaria, Greece, Kosovo, former Yugoslav Republic (FYR) of Macedonia, Montenegro, Romania, Serbia
WEU	**Western Europe**: Andorra, Austria, Azores, Belgium, Canary Islands, Channel Islands, Cyprus, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Isle of Man, Italy, Liechtenstein, Luxembourg, Madeira, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom

Table 2.7 – Definitions of world regions

Chapter 3

Transportation infrastructures in a low carbon world : an evaluation of investment needs and their determinants

3.1 Introduction

Transportation is one of the fastest growing GHG emitting sectors, having undergone the highest growth in greenhouse gas emissions since 1970 (Sims et al., 2014), reaching 7.5 GtCO_2 eq in 2014 (IEA, 2017a). In 2015, global transportation activity accounted for 26% of final energy use and 65% of oil consumption (IEA, 2017b). Significant reductions in emissions from the transportation sector will therefore be needed to keep global temperature rise below 2°C.

Transportation mode choices and the resulting emissions are influenced by transportation infrastructures. Infrastructure planning can be a lever for a shift to low-carbon modes not only in developed countries (Henao et al., 2015) but also in emerging countries (Tiwari et al., 2016). Conversely, transportation infrastructures can cause lock-in on high carbon emissions because of their very long lifespans (Guivarch and Hallegatte, 2011). Transportation infrastructure planning is therefore an essential aspect of any strategy to reduce greenhouse gas emissions.

At the same time, transportation activity will rise over the coming decades, especially in developing countries as demographic and economic growth drive increasing per capita mobility (Schäfer, 2009). In the next four decades, global passenger and freight travel is expected to double over 2010 levels (Dulac, 2013). This future increase in mobility demand requires a rapid build-up of new infrastructure and an upgrade to existing stock.

These changes to the existing stock demand major investments, whereas some regions such as Latin America (Perrotti and Sánchez, 2011) or the USA (OECD, 2017a) have already experienced shortfalls in this area in recent decades. The impact of climate policies on infrastructure investment is essentially ambiguous and could exacerbate the investment gap in some countries or release tension in others. With regard to rail infrastructure, for instance, investment needs would, on the one hand, be stimulated by a modal shift in freight transportation from road to rail. On the other hand, investment needs could be driven down by decreasing demand for coal transportation (Kennedy and Corfee-Morlot, 2013).

Therefore, transportation infrastructure stands at the intersection between climate and development imperatives, and the question of the investment needs for transportation infrastructure to achieve transitions to low-carbon modes while pursuing development goals worldwide is part of the broader question of the finance needed to achieve climate and sustainable development objectives. This article seeks to contribute to this discussion by quantifying the investment needed for transportation infrastructure that promotes low-carbon pathways and analyzing how it differs (or resembles) the investment needed for high-carbon pathways.

Several analyses have already been carried out on the issue of global investment in transportation infrastructure. OECD (2006) forecasted investment needs in rail and road capital stock between 2005 and 2030 using the econometric relationship between infrastructure capital stock and per capita GDP. OECD (2012) updated the figures on rail and extends the analysis to other infrastructures, such as ports and airports. Dobbs et al. (2013) estimated transportation-specific spending (road, rail, airports, and harbors) through two different approaches, respectively based on historical spending on transportation infrastructures, and on the historical value of infrastructure stock compared with GDP. However, all these studies have in common the fact that they do not take climate policies into account in their assessments and have a short time horizon compared with the timeframe for the implementation of climate policies. Dulac (2013) compared the land transportation infrastructure required to support transportation activity projections built with the IEA Mobility Model (MoMo) for a baseline scenario and for a low-carbon scenario – the IEA '4DS' and '2DS' scenarios (IEA, 2012). IEA (2016) updated the figures with new assumptions on costs and calculations and a more fine-grained disaggregation of passenger rail infrastructure into high-speed, intercity, and metro/urban rail.

The issue of investment needs for low-carbon pathways has also been addressed using integrated assessment models (IAM), which have the advantage of taking into account the major interactions between energy, land-use, economic, and climate systems, but the assessments undertaken through this approach focus mainly on the energy sector Bosetti et al. (2009); Carraro et al. (2012); Tavoni et al. (2015); McCollum et al. (2018). Most of the models do not take investment in transportation infrastructures into account in their global estimation of costs (Creutzig et al., 2015) although the amounts of investment involved are of the same order of magnitude or higher than total investments in the energy sector. The only contribution is from Broin and Guivarch (2017), where the authors incorporated the costs of the construction and maintenance of transportation infrastructure into an IAM and compare a baseline scenario with a low-carbon scenario. The authors showed that the investment required is lower if climate policies implemented for low, medium, and high income countries.

Few studies have focused on specific regions, such as Perrotti and Sánchez (2011) for Latin America and Bhattacharyay (2010) for Asia. These studies are limited to estimates of investment needs only for scenarios with no climate policies, and for short-term time horizons. Moreover, the approaches are too different to allow a rigorous comparison of results between regions. In our paper, we followed a two-step modelling approach. In the first step, we developped a set of socioeconomic scenarios using an integrated assessment model, Imaclim-R. From this set of scenarios, we extracted the trends in future transportation activity as well as modal share for both passengers and freight. In the second step, we evaluated the investment needs corresponding to the transportation activity scenarios built in the first. By contrast with the methodology followed by Broin and Guivarch (2017), the two-step approach with Imaclim-R allows us to take the freight sector into account in the evaluation as an important driver of investment, and to disaggregate the transportation sector at a more granular scale. In our study, we did not include the investments associated with alternative fuel charging and delivery infrastructures or energy efficiency in order to be complementary to existing studies about the energy sector investments (see McCollum et al. (2018) for instance where those categories of infrastructures are included).

Our study goes beyond the existing literature in a number of respects. First, to facilitate comparison between regions and with historical values, we used the same framework to analyze the global and regional scales, and provide figures for investment needs relative to GDP in addition to estimates in absolute terms. Second, because there are many uncertain factors that might affect both future transportation activity and investment needs, such as changes in household motorization levels and structures, or building costs, we took a "what if. . . " approach to this quantification, based on the construction and analysis of a number of scenarios. Rather than following a single projection, as in most previous studies, we therefore explored the uncertainties involved, assess possible ranges of results, and highlight those that are robust. Third, we conducted a global sensitivity analysis to identify the influence of uncertain factors on investment needs, so that our approach addresses the question of what pushes those needs along low-carbon pathways. The main factors of uncertainty that determine the assessment of investment needs can be interpreted as possible policy levers to avoid directions likely to lead to stress over infrastructures investments.

The rest of this article is structured as follows: Section 3.2 describes our methodology, Section 3.3 presents our results, and Section 3.4 provides a summary and conclusion.

3.2 Methodology

Our methodology proceeds in two steps. In the first, we constructed a set of socioeconomic scenarios from which we extracted the results in terms of trends in future transportation activity as well as mode shares for both passengers and freight. Subsection 3.2.1 describes Imaclim-R, the integrated assessment model used, as well as the combinations of model parameters considered in constructing all the scenarios. In the second step, we evaluated the investment needs corresponding to the transportation activity scenarios built in the first step. Subsection 3.2.2 details the modelling approach used in this step. In the results section, we analyzed the range of results obtained from these two steps. We used a global sensitivity analysis to identify the main factors of uncertainty affecting the results. Subsection 3.2.3 details the method we use for the global sensitivity analysis.

3.2.1 Constructing a set of socio-economic scenarios to explore the determinants of transportation pathways

To explore a range of future transportation pathways, we constructed a set of socioeconomic scenarios using the Imaclim-R model (Waisman et al., 2013). This is a multi-sector and multi-region model of the world economy. It models the interwoven development of technical systems, energy demand behavior, and economic growth. It has a hybrid and recursive dynamic architecture that combines a Computable General Equilibrium (CGE) framework with bottom-up sectoral modules. Compared to other hybrid integrated assessment models, its specificity is to represent second-best mechanisms, including market imperfections, partial use of production factors, and imperfect expectations. The main exogenous assumptions are demography and labor productivity growth, the learning rates that reduce the cost of technologies (electric vehicles, renewable power generation, carbon capture and storage. . .) and their maximum potentials, fossil fuel reserves, the parameters of the functions representing energy efficiency in end-uses, the parameters of the functions representing energy-demand behaviors and lifestyles (motorization rate, residential space...). A detailed description of the model is available at http://themasites.pbl.nl/models/advance/index.php/Model_Documentation_-_IMACLIM.

The Imaclim-R model includes a representation of passenger and freight transportation. Passenger transportation is disaggregated into four modes: non-motorized, private vehicles, land transit, and air transportation. Freight transportation is disaggregated into three modes: land transportation (including both road and rail), maritime transportation, and air transportation. Imaclim-R represents both the technological and behavioral determinants of transportation trends.

Changes in passenger transportation volumes and modal shares result from households maximizing current utility under two constraints – a standard budget constraint and a time budget constraint. The four transportation modes are differentiated by their respective costs and speed. Access to the automobile mode in household choices is determined by the motorization rate, which is related to disposable income per capita in each region, with a variable income elasticity that is a function of income levels. This representation captures two stylized facts about passenger transportation: (1) the shift to faster (and more expensive) modes when household revenues increase, (2) the rebound effect of distances travelled following improvements in energy efficiency. Energy efficiency and the use of alternative fuels in private vehicles are determined by the turnover in vehicle stocks and household decisions on new vehicle purchases: standard vehicles (i.e. those that only consume liquid fuels), plug-in hybrid electric vehicles (i.e. those that consume both electricity and liquid fuels), and electric vehicles (i.e. those that only consume electricity). Technologies are differentiated by their unit fuel consumption and their capital costs (which decrease endogenously through the learning-by-doing process). Production possibilities in all sectors are described using a Leontief function with fixed intensity of labor, energy, and other intermediate inputs in the short term (but with a flexible rate of use of installed production capacities). Thus, at a given point in time, the intensity of production in each of the three freight transportation modes (air, water, and land) is measured by the input–output coefficients.

The input–output coefficients implicitly capture the spatial organization of the production process (in terms of production unit specialization/concentration) and the constraints imposed on distribution (in terms of distance to the markets and just-in-time processes). Both mechanisms drive the modal breakdown and intensity of freight transportation. Energy efficiency for freight transportation is not represented through explicit vehicle technologies but is implicitly captured through the evolution of the input–output coefficients of the energy requirements for the production of final transportation goods for each mode (water, air, and land transportation). The coefficients are responsive to energy price variations, which means that they can capture the incentive for technical progress in relation to market conditions.

Further details about the representation of the transportation sector and an analysis of typical results for this sector and its interaction with the rest of the economy can be found in Waisman et al. (2013). A comparison of results for passenger transportation from eleven global IAMs, including Imaclim-R, is described in Edelenbosch et al. (2017).

Imaclim-R is disaggregated into 12 regions (United-States, Canada, Europe, Pacific-OECD, Commonwealth of Independent States, China, India, Brazil, Middle-East, Africa, Rest of Asia, Rest of Central and Latin America). The results in this report were aggregated at the global level, or into 5 regions: OECD, CIS, MAF, ASIA and LAM. The definitions of the regions are summarized in Table 3.1.

Region	**Definitions**
OECD	United States, Canada, Europe, Pacific-OECD
ASIA	China, India, Rest of Asia
MAF	Middle-East, Africa
CIS	Commonwealth of Independent States
LAM	Brazil, Rest of Central and Latin America

Table 3.1 – Description of regions used for the analysis

We used a method previously developed in Rozenberg et al. (2014) to explore the multidimensional space affected by uncertain model input. In a first step, we identified the parameters that could in principle have an impact on results in terms of passenger and freight transportation pathways. The identified parameters were then gathered into parameter sets, seven in total, as presented in Table 3.2. For each parameter set, two or three alternatives were constructed, with contrasting parameter values. Two groups were chosen in order to relate to the Shared Socioeconomic Pathways (SSP) framework (O'Neill et al., 2017). They match the model parameters used to reproduce the different SSP, as in Marangoni et al. (2017). The transportation-specific parameters were collected into four groups using the ASIF decomposition (Schipper et al., 2000), depending on their a priori impact on (1) the Activity or volume of transport activity, (2) the Structure of transportation, i.e. changes in modal share, (3) the Intensity, i.e. the energy efficiency of transport modes, (4) the Fuels, i.e. the use of alternative fuels in the transportation

<table>
<tr><th colspan="2">Sets of parameters</th><th>Alternatives</th><th>Parameter set names</th></tr>
<tr><td colspan="2">Demography and productivity</td><td>SSP1, SSP2 and SSP3</td><td>Growth drivers</td></tr>
<tr><td colspan="2">Determinants of mitigation challenges (fossil fuels reserves and markets, energy demand, low carbon technologies except in the transportation sector)</td><td>SSP1 (low challenges) or SSP3 (high challenges)</td><td>Mitigation challenges</td></tr>
<tr><td rowspan="4">Transportation sector parameters</td><td>Determinants of activity (volume of passenger and freight transportation)</td><td>Low or high transport demand</td><td>Transport activity drivers</td></tr>
<tr><td>Structure (mode shares)</td><td>Individual mobility dominated trend or shared-mobility oriented trend</td><td>Transport structure drivers</td></tr>
<tr><td>Intensity (energy efficiency)</td><td>Low or high energy efficiency</td><td>Transport intensity drivers</td></tr>
<tr><td>Fuel (alternative fuels)</td><td>Low or high availability of alternative fuels</td><td>Transport fuel drivers</td></tr>
</table>

Table 3.2 – Description of parameter alternatives

sector. It should be noted transport-specific parameters do not directly prescribe the ASIF factors of transport sector emissions, the latter being also influenced by other determinants such as economic growth or energy prices. The description of the parameters in each set and their respective values are provided in Appendix A.

The combinations of these parameter alternatives produced 96 baseline scenarios, i.e. scenarios in which no climate policy was implemented. In addition, in each of these 96 "future worlds", we implemented two types of mitigation policies, making a total of 288 scenarios in all. Both types of mitigation policies were represented through a constraint on the global CO_2 emission trajectory maintained in the model through an endogenous uniform carbon price. The two policy cases, "High mitigation ambitions" [1]. and "Low mitigation ambitions" [2] differ in the stringency of the emissions constraint. In the rest of this text, the two mitigation scenarios will be referred to respectively as HMA and LMA. We considered results over the 2015-2080 timeframe because some mitigation scenarios appeared to be "not feasible" [3] beyond 2080. To be able to consider the whole set of scenarios, therefore, we restricted our analysis to the period

1. The case of "High mitigation ambitions" corresponds to an emission pathway between RCP 2.6 (Vuuren et al., 2011) and RCP 4.5 (Thomson et al., 2011). Cumulative CO_2 emissions from 1870 to 2100 add up to 3800 Gt CO_2. This is between (i) the 3300 Gt CO_2 value associated with a 33% probability of not exceeding 2°C and (ii) the 4200 GtCO_2 value associated with a 66% probability of not exceeding $3 \circ$C (Pachauri et al., 2014). We do not consider the more stringent constraint of an emission pathway following RCP2.6, because with such constraint a large number of scenarios were "not feasible" (see footnote 3 below)

2. The case of "Low mitigation ambitions" corresponds to the RCP4.5 (Thomson et al., 2011) emission pathway. Cumulative CO_2 emissions from 1870 to 2100 add up to 4600 Gt CO_2. Global temperature is projected to increase by a range of 1.7-3.2°C from 1870 to 2100 with a median value of 2.4°C (Pachauri et al., 2014).

3. We consider here that scenarios are "not feasible" in modelling terms when the endogenous carbon price increase from one year to another required to match the emissions trajectory is higher than 20%. The scenarios that are "not feasible" are essentially scenarios with parameters corresponding to the high mitigation challenges alternative.

2015-2080.

To disentangle the underlying dynamics that lead to direct CO_2 reduction, we applied index decomposition analysis for two years (2050 and 2080) between each mitigation scenario and the corresponding baseline and averaged the results over all scenarios. The factors analysed are the activity (pkm/capita), the mode shares, the energy intensity (EJ/pkm) and the fuel mix (g/EJ). We used the additive LMDI-I methods which is recommended because of multiple desirable properties in the context of decomposition analysis (see Ang (2004) for a review of the different existing methods and their properties).

The alternative assumptions explored to construct the set of scenarios were designed to cover a relevant portion of the uncertainty space: the SSP framework is used to cover socio-economic uncertainties relating to demography, growth, and challenges to mitigation, the ASIF framework to focus on transportation-specific dynamics. However, even though this approach creates a wide range of scenarios, only part of the total uncertainty space is explored and the future might in reality bring changes that diverge from all 96 scenarios in this study. In particular, major global geopolitical developments might influence international transportation in ways that do not match any of the SSPs. Similarly, the spread of disruptive technologies such as autonomous vehicles, could potentially shape transportation behaviors outside the boundaries considered in this study (Fagnant and Kockelman, 2015). As with any modelling study, the results depend on the model structure used and on which sets of parameters are chosen to vary and on the alternative values tested. Obviously, the impact of an uncertain driver on the results depends on the numerical assumptions chosen for each state of the driver. Furthermore, scenarios cannot be associated with some objective probabilities. We are in a case of uncertainty, not a case of risk where the objective probabilities of parameters are known (Grübler and Nakicenovic, 2001; Cooke, 2015). Therefore, the distribution of results cannot be interpreted as an objective distribution of outcome probabilities and would have to be interpreted as subjective, in the Bayesian sense. In the results section, the mean of the distribution of results is plotted to make the figures more readable, but this mean is to be interpreted as implying a (subjective) equiprobability of all scenarios.

The results of the socioeconomic scenarios in terms of transportation activity serve as input for the second step of the methodology, which quantifies the investment needs that are consistent with these transportation activity pathways. The next subsection describes the method and data used in this second step.

3.2.2 Quantifying the investment needs for transportation infrastructure underpinning the transportation activity scenarios

The second step of the methodology consists in an ex-post analysis of the transportation activity scenarios produced. It is used to evaluate the investment needs, i.e. investment that would be consistent with the given transportation activity scenarios, with certain target infrastructure utilization rates and adequate infrastructure maintenance. This is not the same approach as predicting future investment, which may be too small or too large relative to the levels required, resulting either in congestion and a deterioration in infrastructure quality in the first case, or in infrastructure underutilization and sunk costs in the second case.

The following transportation modes were considered: private vehicles, buses, bus rapid transit (BRT), rail, high-speed rail (HSR), and air transport for passengers; trucks and train for freight. Sea and air freight were not considered because of lack of data. The method used to compute investment needs proceeds in four steps: (1) compute mode share scenarios if they are not explicit, or not at the required disaggregation level, in input scenarios; (2) calibrate existing transportation infrastructure; (3) calculate the new construction required to fit the mobility scenarios; (4) calculate associated costs for construction, upgrade, operation, and maintenance of transportation infrastructure. Steps 2 to 4 are partly based on an approach to modelling infrastructure expansion in relation to scenarios for increases in transportation activity presented by Dulac (2013), with modifications and extensions as presented in the following subsections.

The quantifications were aggregated at the level of 5 world regions (OECD, CIS, Africa and Middle-East, Asia and Latin America). The transportation activities supplied by the Imaclim-R results were thus aggregated for these 5 regions for use as input into the analysis. We also incorporated the uncertain factors that determine investment needs by introducing alternative assumptions into the main parameters that play an a priori role in the four steps described above.

Modal share scenarios for passengers and freight

The transportation activity scenarios produced by running the Imaclim-R model were disaggregated into three modes for passengers (car, air, and other land modes) and into three modes for freight (air, sea, and land transportation). We made further assumptions to produce a more granular disaggregation of modes corresponding to the different infrastructures considered. To do this, we calibrated the respective shares to their 2015 values (see Appendix B, Table 3.15) and we considered two alternative scenarios for changes over time. In the first case, we considered the splits to remain constant over time. In the second case, we assumed that they evolve (linearly) towards levels in 2050 that are based on existing scenarios that represent a modal shift towards rail and BRT:

- Bus rapid transit share reaches 5% of bus share (Dulac, 2013);
- Rail freight share is 50% greater than road freight (UIC, 2016), i.e. rail accounts for 60% of land freight transportation and trucks for 40%;
- Rail passenger share reaches 40% of public transport (IEA, 2012);

In the reports cited, these target mode shares were given at global scale. We applied them in the different regions of our model, assuming convergence between all regions. Modal shares were assumed to remain constant after 2050.

3.2.3 Calibration of existing transportation infrastructure capacity

The different types of infrastructures considered and the associated units of measurement are summarized in Table 3.3. The values for transportation infrastructure capacities calibrated in 2015 for the 5 regions of our model are also presented.

Mode	**Unit of stocks**	ASIA	CIS	MAF	LAM	OECD
Road	thousand lane.km	16172	3108	2290	1489	24000
BRT	thousand trunk.km	1.24	0	0.309	1.8	2.05
Rail	thousand track.km	187	159	57.1	84.5	663.7
High speed rail	thousand track.km	36.43	0	0	0	24.77

Table 3.3 – Calibration of infrastructure stock for the year 2015 from different databases [4]

Following Dulac (2013), five, three and two lanes were assigned respectively to highways, primary road networks, and other roads, when complete data on different types of road were available. Otherwise, five and two lanes were assigned respectively to highways and the rest of the road network. Technically, BRT infrastructure was considered to be roadway. However, BRT systems require their own investment and involve high-capacity buses running in separate lanes isolated from other road traffic. For rail infrastructure, both urban and non-urban rail were considered and aggregated, with the exception of high-speed rail infrastructure, which was considered separately. Airports were included in this study but were not considered as a stock but as a fixed cost per unit of air passenger travel, following Broin and Guivarch (2017).

New build needs underlying the mobility scenarios

First, we aggregated private vehicles, buses, and trucks to evaluate the rate of utilization of the road infrastructure. To do so, we converted the data in passenger.kilometer (pkm) and tons.kilometer (tkm) to vehicle.kilometers (vkm) using vehicle occupancy factors [5].

Then, we defined a "desirable" infrastructure utilization rate and the speed at which it could be achieved from the current utilization rate. The current road utilization rate as reflected in data for distances travelled and infrastructure capacities varies greatly between world regions, from 150,000 vkm/paved lane.km for India to more than 1,000,000 vkm/paved lane.km for Latin America (Dulac, 2013). A first possible explanation for this heterogeneity is traffic structure. In freight activity, for example, 79% of goods are transported by truck in Latin America (ITF, 2017), whereas 41% are transported by rail in India (Dhar and Shukla, 2015). This mode structure has an influence on road occupancy. A second possible explanation is that the road quality defined as paved differs between countries (Klaus Schwab and Xavier Sala i Martin, 2016).

There is uncertainty about what utilization rate can be considered as "desirable". Indeed, high road utilization rates are a source of congestion, which is associated with financial costs and welfare losses caused by (i) vehicle delays, (ii) greater capital depreciation, (iii) congestion-related accidents, and (iv) the negative impact of congestion on the location of economic activities in

4. UIC (2015, 2017); CIA (2017); EMBARQ (2017) for ASIA, CIS and MAF; EMBARQ (2017); BID (2016) for LAM; UIC (2015, 2017); IRF (2009) for OECD

5. The average payload for a truck is assumed to be 13 tons (IEA, 2009). The average passenger occupancy for a bus used is 20 (Schipper et al., 2010). For car occupancy, we used trends in regional values from the Imaclim-R scenario inputs. The unit value of passenger car road occupancy, which is a unit that gives the vehicle equivalent in terms of cars, is assumed to be 2.5 for a truck and 2 for a bus, based on values from Adnan (2014).

a town (Bilbao-Ubillos, 2008). We chose to consider the two different levels of 600,000 and 900,000 vkm/paved lane.km as desirable utilization rates. A road occupancy target of 300,000 vkm/paved lane.km has also been tested. However, we assumed that the lowest utilization rates on international comparisons, such as those of India and China, would increase as a result of surges in mobility demand from private motorization. We therefore did not consider this value in our results. We also did not consider higher desirable utilization rates, such as current levels in Latin America. The region has experienced lack of investment in recent decades (Perrotti and Sánchez, 2011), so we do not see the current road utilization rate as a reasonable long-term target, but rather as an indicator of congestion or poor infrastructure quality.

The BRT trunk.km occupancy target was assumed to be 120,000 vkm per BRT km (Dulac, 2013) with roughly 100 people per bus. The BRT system also uses the road, but requires a separate lane, so there is no influence on road occupancy.

For rail transportation, passenger.kilometers and ton.kilometers were summed together in transport units following (UIC, 2016), assuming that 1 ton.kilometer is equivalent to 1 passenger.kilometer in terms of occupancy. Current rail occupancy levels range from less than 350,000 pkm and tkm per track.km for Eastern Europe to more than 30 million pkm and tkm in Mexico (Dulac, 2013). This big disparity in rail occupancy could arise from different factors: infrastructure stocks, operating strategies, etc. High and low values for rail utilization rates (30 and 5 million pkm-tkm/track.km) were tested in our model.

It is important to note that we use average infrastructure occupancy rates and that these values may mask some heterogeneity of use in the road network, particularly between urban and rural areas. For instance, an increase in the road occupancy rate induced by a growth in road traffic concentrating on part of the already saturated network could lead to new constructions and therefore additional costs not taken into account in our study. Similarly, an increase in traffic on lightly used road infrastructure would not lead to additional construction costs. We thus assumed, using the average rate, that these two effects offset each other at the regional level.

The speed at which the "desirable" utilization rates may be reached from current utilization rates was assumed to be either 35 (target values reached in 2050) or 65 years (target values reached in 2080). The changes towards the target utilization rates were assumed to be linear. At each time step, the combination of the desirable utilization rate, the speed assumptions, and the utilization rate from the previous time step, determine the objective infrastructure occupancy targeted.

Finally, the ideal infrastructure stock is calculated in the model, at each time step, as the ratio between transportation activity and the infrastructure occupancy objective. The actual infrastructure stock from the previous time step is compared with the ideal infrastructure stock. In the case of under-utilization (infrastructure stock greater than ideal infrastructure stock), new construction is not necessary and the occupancy rate can increase. In the case of over-utilization (infrastructure stock smaller than ideal infrastructure stock), new construction is needed. The calculated need for new construction is then compared with the maximum density of infrastructure in the region and reduced if the maximum would be exceeded. The rail and road density limits applied are based on values from Dulac (2013) (see Appendix B, Table 3.16).

For airports, the need for new construction is not calculated 'physically' because of lack of data on airports stock and the constraints on infrastructure capacity. It was assumed that passenger activity was the unique driving force for airports construction.

Costs associated with new construction, upgrade, reconstruction, and maintenance

The assumptions for the unit costs of infrastructure are taken mainly from Dulac (2013) and represent the yearly investments per unit of infrastructure capacity. Infrastructure costs in the different regions are summarized in Table 3.4.

Cost category	**Mode**	Unit	ASIA	CIS	MAF	LAM	OECD
New Build	road	thousand usd/lane.km	1100	1000	1100	1200	1200
	brt	thousand usd/trunk.km	7000	7000	7000	7000	15000
	hsr	thousand usd/track.km	24000	24000	24000	24000	24000
	rail	thousand usd/track.km	4500	4000	4500	5000	5000
	air	usd/pkm	0.25	0.25	0.25	0.25	0.25
Upgrade and Reconstruction	road	share of new build cost	0.008	0.0075	0.009	0.008	0.009
	brt	share of new build cost	0.025	0.025	0.025	0.025	0.025
Operation and Maintenance	road	share of new build cost	0.0075	0.0075	0.0075	0.0075	0.0075
	brt	share of new build cost	0.01	0.01	0.01	0.01	0.01
	hsr	share of new build cost	0.004	0.004	0.004	0.004	0.004
	airports	share of new build cost	0.01	0.01	0.01	0.01	0.01

Table 3.4 – Costs of infrastructures – Sources: Broin and Guivarch (2017), Dulac (2013)

For road investments, the costs are split into three categories: new build, upgrade & reconstruction, and operation & maintenance. Upgrade and reconstruction are less expensive than new construction because they involve work on existing infrastructure. It was assumed that road infrastructure requires reconstruction or upgrade every 20 years. For rail investment, only new construction costs and operation/maintenance were considered, following Dulac (2013) who suggested that rail is generally maintained through regular investment in operation and maintenance and is replaced in sections when track is no longer operable.

For BRT investments, reconstruction costs were assumed to account for half of BRT capital development costs. Infrastructure lifespan was also assumed to be 20years.

Airport costs are divided into two categories, one for new construction and one for stock maintenance. The price for new construction used is per additional passenger.kilometer and the price for maintaining the stock is per total passenger.kilometers. Because of lack of data, we used values from OECD countries for all regions.

Three different assumptions for cost changes over time were considered in this study: constancy over time, increase of 50% in 2080 relative to 2015 levels, and decrease of 50% in 2080.

Cost increases and decreases were assumed to be linear. An increase in infrastructure costs over time represents the case where, with infrastructure network development over time, construction costs (including materials and labor) increase, or the marginal infrastructure becomes more complex and thus more costly. A decrease in infrastructure costs over time represents the case where progress through learning-by-doing is a dominant effect.

To explore the uncertainty space, we combined all alternative options considered for the six uncertain factors, as summarized in Table 3.5. We therefore evaluated 144 quantifications of investment needs for each transportation activity scenario. Performing quantification for all 288 transportation activity scenarios arising from the previous step, we built a database of 144*288 (41,472) quantifications of investment needs. The limitations of this method of building a set of scenarios are the same as those already described in the previous section. Furthermore, it should be noted that we considered all combinations of the investment analysis parameters together with all the socioeconomic worlds included: the parameter sets are varied independently of each other. Doing so neglects possible cross-correlations between some of the sets and tends to produce a range of results that is too broad, because some combinations may not be internally consistent. However, removing combinations that appear less internally consistent may miss plausible surprising futures. We therefore considered the full set of scenarios produced in the analysis.

Uncertain factors	**Option 1**	**Option 2**	**Option 3**	**Parameter names**
Transport mode shares	Constant	Modal shift		Modal shift
Target road utilization rate (vkm/paved lane.km)	600,000	900,000		Road target
Target rail utilization rate (10^6 pkm+tkm	5	30		Rail target
Delays to reach target utilization rates (years)	35	65		Delay
Change in unit cost for roads	Increase by 50%	Constant	Decrease by 50%	Road costs
Change in unit cost for rail	Increase by 50%	Constant	Decrease by 50%	Rail costs

Table 3.5 – Summary of uncertain factors considered for investment analysis.

3.2.4 Global sensitivity analysis to identify the main determinants of investment needs

In order to identify the main determinants of investment needs, we conducted a global sensitivity analysis. Our chosen output metrics for this analysis are total infrastructure costs and annual investment needs relative to GDP (averaged over time). The inputs are the parameters or group of parameters described in Tables 3.2 and 3.5. We chose not to use the so-called "One At a Time" sensitivity analysis design, where each input is varied while the others are fixed. Although widely used by modelers, its shortcomings have been extensively described in the statistical literature (Saltelli and Annoni, 2010). An alternative is the Standard Regression Coefficients Approach (SRC), used for instance by Pye et al. (2015) to conduct a sensitivity analysis for an energy system model. According to the authors, the advantages of this metric are the lack of complexity in its calculation and its independence of the units or scale of the inputs and outputs being analyzed. However, the SRC approach is ill-suited to our model, because it is based on a linear relationship between the output and the inputs (Iooss and Lemaître, 2015), while the R2 coefficient of determination allows us to invalidate the linear hypothesis with values obtained that are lower than 0.8 in our case.

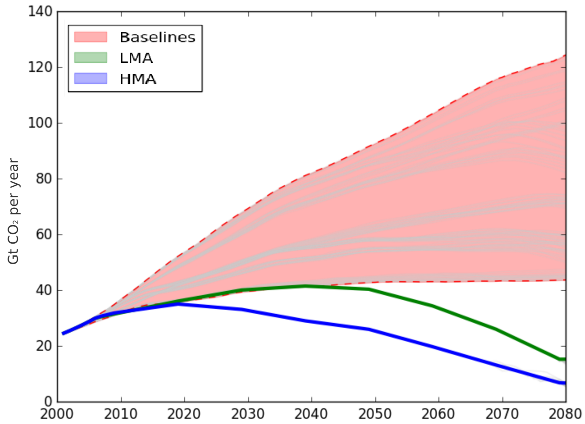
We therefore chose an approach that is more complex, but does not require a linear hypothesis: the variance-based decomposition method proposed by Sobol (2001) and described in Saltelli et al. (2008). The main advantage of this method is that it is robust to both non-linear and non-monotonic relationships between model inputs and outputs Iooss and Lemaître (2015). The proportion of total variance is attributed to individual input as well as to interactions between those factors. First-order effect indices represent the output variance attributable to each input without considering interactions with other inputs. Total effect indices represent the total contribution to output variance by each input, including interactions with all other inputs. Calculations were done using the SALib package in Python (available at github.com/SALib/SALib). We chose to display the results with radial convergence diagrams, which are drawn using R DataVisSpecialPlots (available at https://github.com/calvinwhealton/DataVisSpecialPlots).

3.3 Results

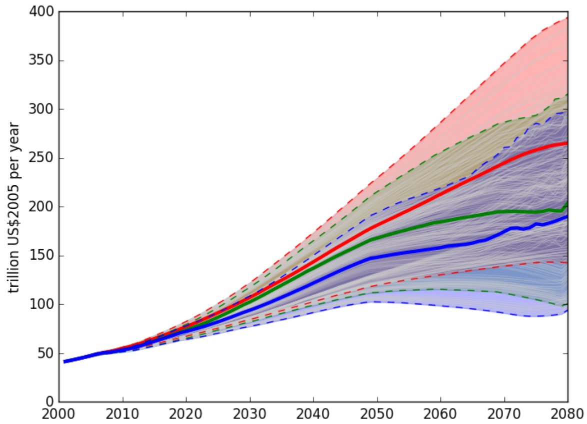
3.3.1 Socioeconomic scenarios and transportation pathways

The 96 baseline scenarios results range from about 3100 GtCO_2 to about 6300 GtCO_2 in terms of cumulative CO_2 emissions from fossil fuel combustion between 2001 and 2080 (Fig. 3.1a). Emission levels in 2050 range from 1.3 to 3 times 2010 levels. This range is comparable to the range covered by the baseline scenarios in the IPCC AR5 database, in which 2050 emissions range between 1.1 and 3.1 times 2010 levels. In the baseline scenarios, global GDP in 2080 ranges from 2 to 7.5 times its 2001 value (Fig. 3.1b). This range of results is also comparable with the range covered by baseline scenarios in the IPCC AR5 database, where global per capita GDP in 2080 ranges from approximately 2.5 to 8 times its 2001 value.

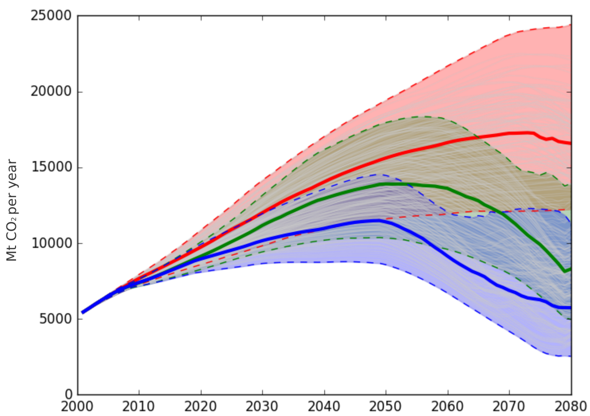
The fossil CO_2 emissions from the baseline transportation scenarios range from 11.6 to 19.4 Gt CO_2 per year in 2050 (Fig. 3.1c), which is comparable with the range of 11–18 Gt CO2 found by Yeh et al. (2017). In contrast with global CO_2 emissions trajectories that are fixed for all mitigation scenarios with the same ambition, emissions trajectories for the transportation sector differ between scenarios in the two groups of mitigation scenarios. Indeed, CO_2 emission mitigation efforts are not always the same from one economic sector to another, and depend



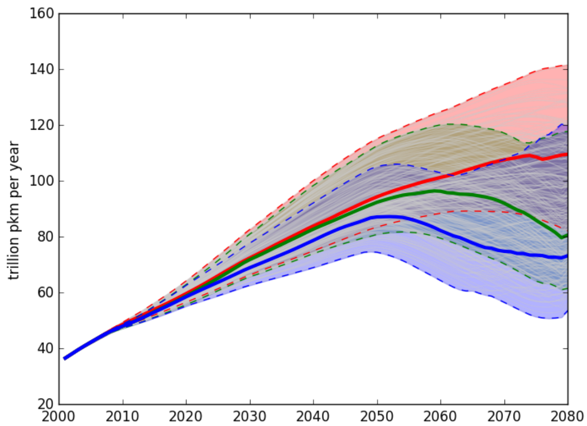
(a) CO_2 emissions from fossil fuel combustion



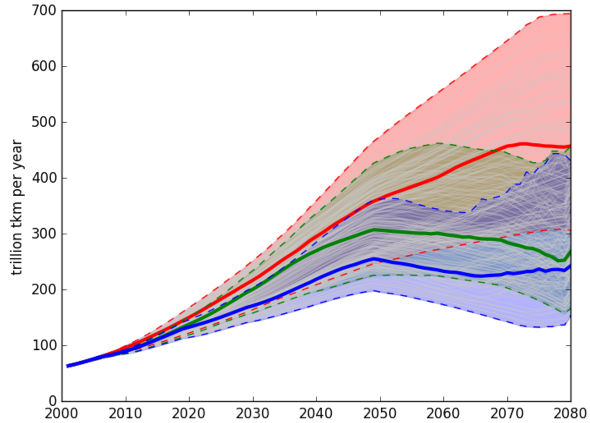
(b) GDP



(c) CO_2 emissions from the transport sector



(d) Passenger transportation activity



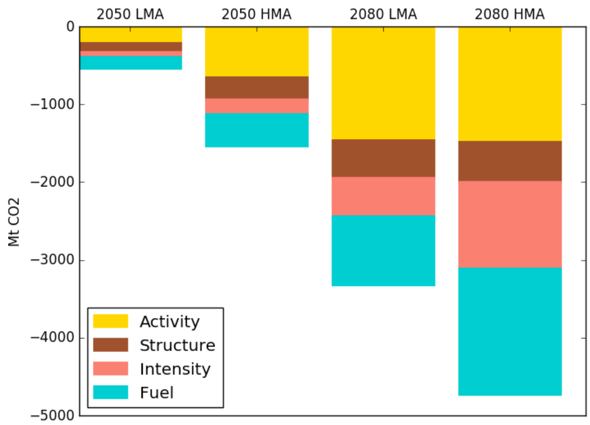
(e) Freight transportation activity;

Figure 3.1 – Evolution over time of global socio-economic outputs from Imaclim scenarios; median (solid line) and max/min (dashed lines).

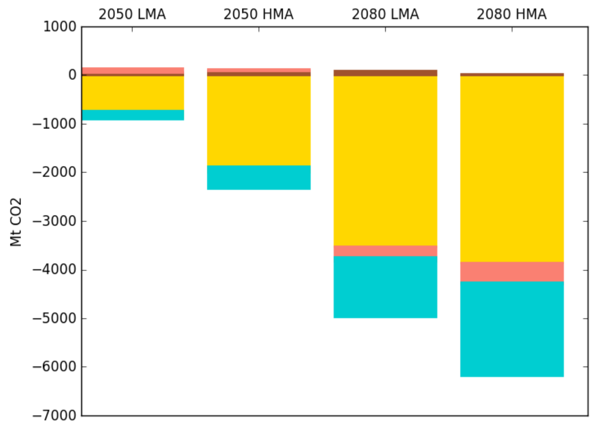
on the combination of assumptions made on the values of groups of parameters. For instance, in cases where the parameters are such that low-carbon technologies in the power sector have limited potentials and higher costs, less mitigation is done in the power generation sector, which requires more mitigation in other sectors in order to maintain the global constraint on total emissions.

Transportation activity for baseline scenarios reaches values in 2080 in a range from

2 to 4 times the 2001 value for passenger mobility and from 5 to 10 times the 2001 value for freight activity (Fig. 3.1d and 3.1e). Global passenger mobility is expected to increase by 1.75–2.33 times from 2010 to 2050, rising from approximately 48 trillion pkm in 2010 to 84–115 trillion pkm in 2050, which is slightly smaller than the range of 1.9–3.3 covered by the baseline scenarios from Yeh et al. (2017). Transportation activity is reduced in 2080 in low and high mitigation ambition scenarios compared with baseline scenarios with a median decrease value of respectively 26.4% and 33.2% for passengers and 41.2% and 46.9% for freight. In Fig. 3.2a and 3.2b, activity reduction and low-carbon alternative fuels appear to be the main factors for CO2 reduction. Their contributions are respectively greater than 25% in average for both passenger and freight in 2050 and 2080. The greater CO2 reduction in the HMA scenarios compared to the LMA scenarios is achieved mainly through a greater reduction in activity in the short term (2050) for freight and passenger and a higher contribution of energy efficiency in the long term (2080) for passenger transport. It should be noted that the contribution of modal shift may be underestimated given the high level of aggregation for public transportation and freight transport (that aggregate all terrestrial modes including road and rail) in Imaclim imposed by the data of energy accounting.



(a) Passenger



(b) Freight

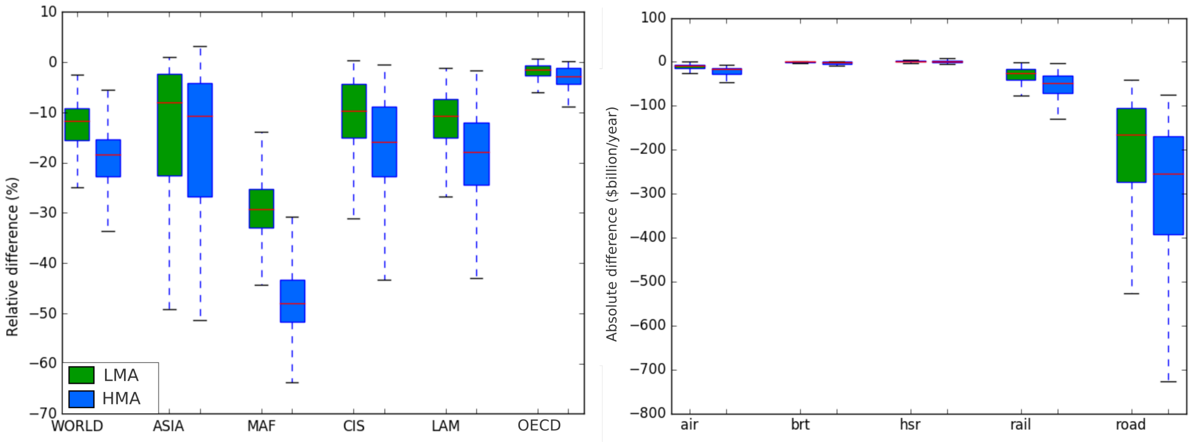
Figure 3.2 – LMDI decomposition analysis of ASIF factors underlying CO2 emissions reduction in the mitigation scenarios compared to baseline scenarios. The factors analysed are the activity (pkm/capita), the mode shares, the energy intensity (EJ/pkm) and the fuel mix (gCO2/EJ).

3.3.2 Effects of low-carbon policy on investments

In the case of the baseline scenarios, we found global investment needs between $1 trillion and $4 trillion per year on average, with a median value of $1.9 trillion per year. Those results are comparable with the $2.11 trillion value in Dulac (2013) (whose study also includes car parks, but not airports), and in Dobbs et al. (2013) of $1.35 trillion per year (including road, rail, and airports). Under low carbon policy, we obtained values (i) between $0.92 and $3.4 trillion per year with a median value of $1.7 trillion for LMA scenarios and (ii) between $0.87 and $3.4 trillion per year with a median value of $1.6 trillion for HMA scenarios. This range of results is comparable with the values of \$1.8 trillion from Dulac (2013) (2013) and of \$2.5 trillion from IEA (2016) obtained for rail and road infrastructures under a low-carbon scenario.

To have an order of magnitude for comparison, global Gross Fixed Capital Formation amounted to 18.7 trillion USD2016 in 2016, representing approximately 23% of world GDP. The main shares of investment are in road and rail infrastructures, with values between 42% and 95% and between 2% and 49% respectively. When considered relative to GDP, the annual investment needs averaged over time are similar for baseline, LMA and HMA scenarios with values between 0.7% and 2.5% of GDP.

For each combination of uncertain parameters, we computed the relative variation in investment needs between each mitigation scenario and the corresponding baseline (i.e. the baseline with the same combination of uncertain parameters), for each region and at the global scale (Fig. 3a). We find that climate policies lead to a reduction in cumulative spending needs on transportation infrastructures and confirm the results from past studies Dulac (2013); Broin and Guivarch (2017). In addition, we add that this effect is robust to the different assumptions on the uncertain parameters considered. The relative decrease in investment needs ranges from 2% to 25% for LMA scenarios, and from 5% to 33% for HMA scenarios.



(a) (b)

Figure 3.3 – Comparison of cumulative investment needs between mitigation scenarios and their corresponding baselines (a) Relative difference in cumulative investment needs (a negative value indicates that the investment is lower in the mitigation scenario); (b) Contribution of each infrastructure type to total annual investment difference.

The reduction in investment needs comes mainly from reduced need for investment in roads, followed by rail and airports: the contributions of each represent respectively between 40% and 99%, between 0.3% and 45%, and between 0.5% and 15% of the total decrease. In the case of HMA scenarios, it translates into an annual decrease in investment needs of between \$74 and \$976 billion/year for road, between \$4 and \$206 billion/year for rail, and between \$8 and \$66 billion/year for airports (Fig. 3.3b). Investments in high speed rail infrastructures increase in 67% of the scenarios with a maximum difference of \$39 billion/year which is below the values of roads investments decreases.

This result – a decrease in investment needs under mitigation scenarios – is also valid at the regional scale for most of the scenarios but with different magnitudes (Fig. 3.3a). Investments in MAF under ambitious mitigation policies are reduced by [35%-65%] whereas in OECD the variation is less than 10%. In a few cases for ASIA, investment needs are higher under climate policies with a maximum increase of 3%. Most (83%) of these cases are associated with the assumptions of an increase in rail costs over time, a high target of road utilization rate, and a low energy efficiency in the transportation sector.

The overall decrease in investment needs is brought about in particular by a reduction in transportation activity in a low carbon-world, according to Fig. 3.1d and 3.1e. The largest decreases in investment needs come from road infrastructures. This decrease is amplified for ASIA, CIS, and MAF by a modal shift from personal vehicles to low-carbon modes (public transit and non-motorized modes) triggered by climate policies (see Appendix C Table 3.17). However, the associated modal shift induced by climate policies can partly offset the effect of activity reduction and tends to increase overall investment (see Appendix C figure 3.10).

We did not correlate here the climate policy scenario and the evolution of mode shares including a modal shift from road to rail for public transportation and freight (see Section 3.2.2 for details). Indeed, modal shift can be sought for other reasons such as congestion. We analyzed as well investments difference for HMA scenarios assuming a correlation between this modal shift and climate policy. We obtained that the results of investments decrease remains valid for most of the scenarios at the global scale and for all regions except OECD (see Appendix B figure 3.7). Indeed, by triggering modal shift to rail, the implementation of climate policy tends to reduce investment needs at the global scale but to increase them in the OECD region which is a similar result to the one obtained in IEA. (2016) for the Nordic region.

It should be recalled that we did not take into account the additional investments associated with energy efficiency and the use of alternative fuels because they are already included in the existing studies about investments for energy infrastructures in low-carbon scenario. If included, those costs may nuanced the overall results of lower investments in mitigation scenarios in the transportation sector.

Though the investment needs are lower in mitigation scenarios compared with baselines, they are significant by comparison with other sectors, notably telecommunications and water infrastructures, where the needs quantified in the literature are lower than our lowest value (Table 3.6). The needs in the transportation sector even appear to be of the same order of magnitude as the investment needed in the energy sector. A notable difference with the energy sector is that investment needs decrease for transportation infrastructure in low-carbon pathways compared with baselines, whereas they increase in the energy sector. Nonetheless, financing these low-carbon investment needs may remain a challenge (Granoff et al., 2016). In the next section, therefore, we analyze regional investment needs in low-carbon pathways in order to identify cases of high and low investment needs and their main determinants.

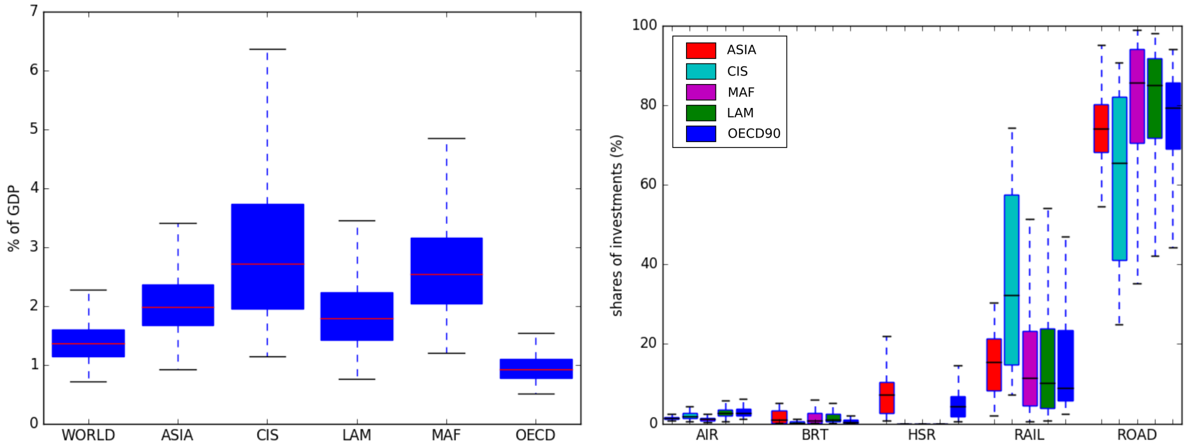
Sector	Annual investment needs ($trillion)	Source
Transportation	0.9-3.4	This study
	1.8	Dulac (2013)
	2.5	IEA (2016)
Water and sanitation	0.9	OECD (2017a)
Telecoms	0.6	OECD (2017a)
Energy demand/efficiency	0.4	OECD (2017a)
	1.9	IEA/IRENA (2017)
	0.6	McCollum et al. (2018)
Energy supply	1.7	OECD (2017a)
	1.6	IEA/IRENA (2017)
	2.4	McCollum et al. (2018)

Table 3.6 – Comparison of transportation infrastructure investment needs with those of other sectors under a low-carbon scenario

3.3.3 Regional investments under mitigation scenarios and their determinants

In this subsection, the analysis focuses on HMA scenarios, because we wanted to explore the investment needs in low-carbon pathways and understand their main determining factors. To be able to compare results between regions and with historical data, we quantified the investment needs relative to GDP, and averaged the results over the 2015-2080 period for each HMA scenario. Figure 3.4a shows that the distributions of results differ between regions. Median values are the lowest for OECD at 0.92%, and the highest for MAF and CIS, with values of 2.5% and 2.7% respectively. Values for ASIA and LAM lie in between, with median values of 2% and 1.8% respectively. The uncertainty ranges of the results are also specific to each region. While expenditure needs are less than 2% for OECD in all cases, the uncertainty ranges are the highest for MAF and CIS, where values range from 1.2% to 9% and 1.1% to 7.1% respectively. Over the period 1995-2015, most countries allocated a maximum of 3% of GDP to transportation infrastructures annually, with China being the exception with a maximum of 5% of GDP (see Appendix C Fig. 3.6). The investment needs we obtain therefore appear high in comparison with past values for CIS and MAF in the highest part of the results distribution, and for ASIA and LAM in a few cases.

These differences between regions in the level of investment needs can be partly explained by regional characteristics of the transportation sector, summarized in Table 3.7. Transportation intensity of GDP varies between regions and reflects their economic structure, with freight intensity depending mainly on both per capita income and the service sector's share of GDP (ITF, 2015). CIS has the specificity of combining a high initial rail utilization level and freight activity that mainly relies on rail infrastructures, with a mode share close to 90% (Appendix B table 3.15). Moreover, its freight intensity of GDP is more than twice the values of other



(a) (b)

Figure 3.4 – Comparison of investment needs between regions for HMA scenarios; (a) Distribution of annual investment needs relative to GDP (average on 2015–2080); (b) Allocation of investment between transportation modes.

regions. This combination leads to high investment needs, and a larger share allocated to rail infrastructures than in other regions (Fig. 3.4b). Investment needs are high in MAF as well, but the factors explaining its transportation structure are different. The region has a high passenger intensity of GDP. Moreover, MAF combines high initial road occupancy and a road-oriented transportation system with road shares of 88% for land freight and 94% for passenger land transportation (Appendix B table 3.15). This combination leads to higher and more road-oriented investment needs (Fig. 3.4b). High investment needs could have been expected in Latin America – the region with the highest initial road utilization rate – but low land freight intensity offsets this effect. Results for OECD can be explained by relatively low values for both freight and passenger intensity of GDP.

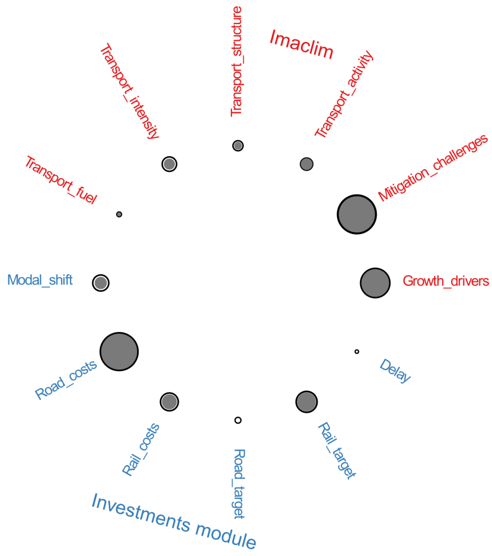
	ASIA	**CIS**	**MAF**	**LAM**	**OECD**
Road utilization rate in 2015 (thousand vkm/lane km)	200	300	900	1500	550
Rail utilization rate in 2015 (thousand pkm+tkm/track km)	20,000	25,000	10,000	6,000	6,000
Land freight intensity (mean) in 2030/2070 (tkm per US$2005)	0.71/0.65	1.68/1.72	0.71/0.64	0.47/0.38	0.18/0.16
Passenger intensity (mean) in 2030/2070 (pkm per US$2005)	1.36/1.09	0.88/0.7	1.47/0.95	1.08/0.68	0.45/0.27

Table 3.7 – Transportation sector characteristics obtained in the model for the five regions considered in this study.

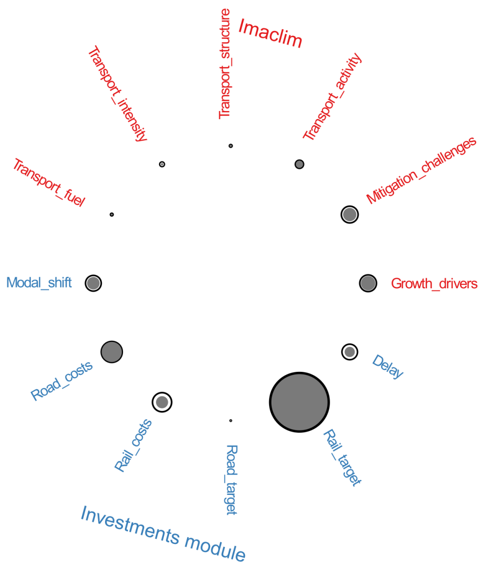
In order to analyze the uncertain factors determining the total variance (or total uncertainty) of results for each region, we conducted a global sensitivity analysis, following the Sobol method described in Section 3.2.3. First, second-order and total-order indices for investment needs relative to GDP are summarized in Fig. 3.5. Results for total cumulative investments as output are given in Appendix C figure 3.9. We find that the target rail utilization rate and the road costs are influential determinants for all regions. For ASIA, the three parameters that most influence the results are the changes in road costs, the mitigation challenges, and the growth drivers, with total index values of 29% [90% confidence interval of 2.5%], 30% [2%], and 17% [1%] respectively. The absence of black lines shows that the interactions between parameters are limited, the second-order indices being less than 5%. The target rail utilization rate is the main determinant in CIS with a total-order index of 73% [6%]. This result confirms the importance of rail investment in the total infrastructure expenditure needs for the region. Fig. 3.5c and 3.5d show that the determinants are similar for LAM and MAF. Changes in road costs and target infrastructure utilization rates (rail and road) do most to determine the results for these two regions with values of 17% [1%], 34% [3%], and 31% [2%] for MAF, and 18% [2%], 27% [2%], and 20% [2%] for LAM. For the modal shift parameter, we quantify first/total order indices as 4% [3%]/13% [1%] for LAM and 4% [3%]/18% [2%] for MAF. The interactions between this parameter and the target rail utilization rate make the modal shift assumption influence total uncertainty more than would be apparent in a one-at-a-time sensitivity analysis (Fig. 3.5c and 3.5d). For the OECD region, the main determinants of investment are the changes in road costs, the target infrastructure utilization rates, the growth drivers, and the transportation structure drivers (Fig. 3.5e).

The groups of parameters varied in the Imaclim-R model to construct transportation activity pathways have limited influence on the investment needs evaluated ex-post, mainly because general equilibrium effects and interactions with other sectors are at play (e.g. macroeconomic rebound effect in the case of improved fuel efficiency). Notable exceptions are the growth drivers (especially for ASIA, LAM and OECD regions), the mitigation challenge (for ASIA), and the transportation structure drivers (for LAM and OECD). The demography and productivity assumptions used are such that they lead to higher GDP growth associated with relatively lower transportation intensity when the growth drivers are as in SSP1, compared with SSP2, and in SSP2 compared with SSP3. Investment needs for transportation infrastructure relative to GDP are therefore lower in scenarios with SSP1-like growth drivers and higher in scenarios with SSP3-like growth drivers. Higher mitigation challenges lead to a higher macroeconomic cost for reaching a given mitigation objective, hence lower GDP, so investment needs relative to GDP are therefore higher. This effect is particularly visible for ASIA, for which mitigation costs increase in the 'high mitigation challenges' cases. The assumption regarding transportation structure parameters leads to a slower increase in passenger.kilometers traveled in the case of a structure oriented towards shared mobility, therefore reducing the need for investment in for roads. This reduction has a sizeable effect on overall investment needs for Latin America (a region where road utilization rates at the beginning of the period were very high) and for OECD, but only when combined with low target road utilization rates for the region.

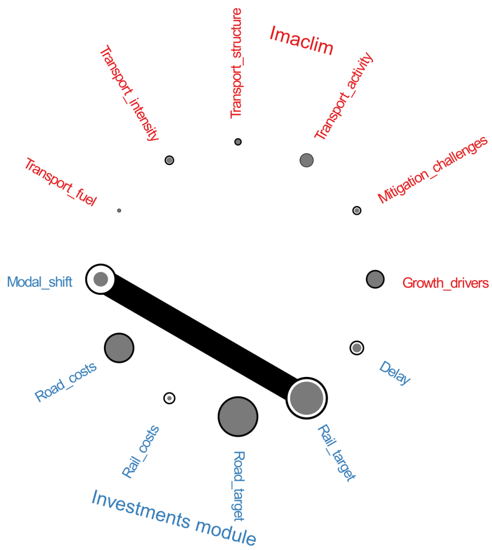
Road costs are an influential parameter in all regions. This result was to be expected



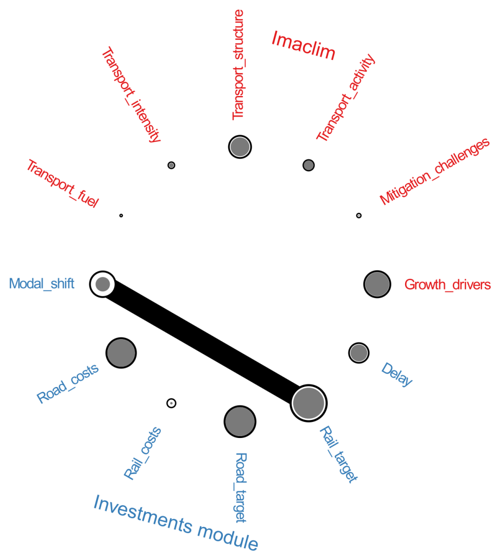
(a) ASIA



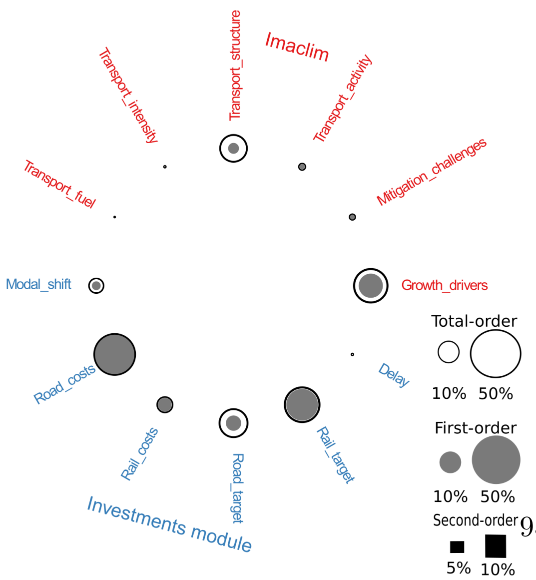
(b) CIS



(c) MAF



(d) LAM



(e) OECD

Figure 3.5 – Sobol method global sensitivity analysis results for each region, for investment needs relative to GDP. Filled nodes represent the first-order indices and rings the total-order indices. Lines represent second-order indices arising from interactions between inputs. Width of lines indicates the second-order indices. Only the second-order indices greater than 5% of total variance are represented. For a description of the parameters, see the last columns of Tables 3.2 and 3.5.

because road investments account for the main proportion of investment needs (Fig. 3.4b). A change in the price of road infrastructure therefore leads to significant variation in total investment costs. Research and development policy focused on less expensive road construction technologies could be relevant for reducing the cost of investment.

The influence of the target rail utilization rate on all regions needs to be qualified to the extent that it is a result of the two alternative values chosen here for this parameter. The result is indeed influenced by the difference between the two values, the high target being 6 times greater than the low target. Moreover, the target of 5 million pkm+tkm/track.km is below the initial rail utilization rates (Table 3.7) of all the regions and increases the importance of this parameter, because it implies the need for investment even in the absence of a rise in transportation activity. In a previous version of this study, we also analyzed scenarios with a lower target of 300 thousand vkm/lane.km for road occupancy. This value was low compared with 2015 road occupancy levels (Table 3.7), with the result that this parameter had a greater influence on the outcomes. The importance of target rail utilization rates for overall investment needs can be interpreted in two ways. A first possible interpretation is that aiming to decrease the rail infrastructure utilization rate may seem unrealistic in terms of investment needs. This is particularly the case for the CIS and MAF regions where investment needs are then higher than actual investments (as a share of GDP) observed in the past. A second interpretation is more policy-related and identifies an increase in rail utilization rates as a possible lever for reducing investment needs. For regions other than CIS and MAF, optimizing the rail network in order to achieve higher utilization could thus be an option to avoid high-cost pathways.

Similarly, for the target road utilization rate parameter, our results highlight the fact that, since LAM and MAF had the highest levels in 2015, reducing utilization rates inevitably leads to a sharp increase in investment needs.

The big influence of modal shift from road to rail for public transit and freight, associated with a strong interaction between this parameter and the rail occupancy target in the LAM and MAF regions, can be explained by the results summarized in Table 3.8. For both regions, this modal shift has an opposite effect depending on the rail utilization rate target: it decreases annual investment needs in the cases of high target rail occupancy and increases investment needs otherwise. The magnitude of the effect also differs depending on the rail utilization target: the decrease is relatively small whereas the increase is larger (Table 8). Mode shift may be sought for other reasons than CO_2 reduction (for instance, congestion relief, air quality improvement in cities, etc.). However, it can be a lever to reduce transportation infrastructure investment needs only if combined with actions to increase rail infrastructure utilization rates. Otherwise, there is a risk that modal shift could lead to higher investment needs.

3.4 Conclusion

In this study, we quantified the needs for investment in transportation infrastructures between 2015 and 2080 along high and low carbon pathways, considering road, rail track, BRT lanes, high-speed rail, and airports, at the global level and for five world regions. We first con-

Scenarios considered	MAF	LAM
Low rail occupancy target + no modal shift	2.6%	1.8%
Low rail occupancy target + modal shift	3.4%	2.4%
High rail occupancy target + no modal shift	2.3%	1.6%
High rail occupancy target + modal shift	2.2%	1.5%

Table 3.8 – Average annual investment needs for the scenarios considered.

structed transportation activity trends using a set of socioeconomic scenarios built with the Imaclim-R model, an integrated assessment model that explicitly represents the transportation sector, including its non-price determinants, and captures its principal interactions with the rest of the economy. We then performed an ex-post valuation of the annual investment needs consistent with these trends in transportation activity. We took uncertainty into account by combining alternative assumptions regarding influential parameters in both steps of our methodology.

We confirm the finding of the few analyses carried out on the subject of investments in low-carbon transportation infrastructure, that global cumulative investment needs are reduced in low-carbon scenarios compared with high-carbon pathways. We additionally show that this result is robust to the different assumptions regarding uncertain parameters that influence transportation patterns and infrastructure expenditure. This result is also valid at the regional level, for the five regions we analyzed. The overall diminution in investment needs is brought about in particular by a reduction in transportation activity in a low-carbon world. The biggest decreases in investment needs are in road infrastructures.

In low-carbon pathways, investment needs relative to GDP differ between regions, with lower needs for OECD, high needs for CIS and MAF, and intermediate values for ASIA and LAM. The uncertainty ranges and the factors of uncertainty also differ between regions. The uncertainty ranges are larger for CIS and MAF, and lower for OECD. For those regions, the results for investment needs are particularly high by comparison with the historical values for investment in transportation infrastructures in most of the countries.

We took the analysis further by using a global sensitivity analysis to identify the main determinants of investment needs in the different regions studied. Target rail utilization rate and road construction costs determine investment needs in all the regions, but differ in the magnitude of their contributions to uncertainty. Other determinants of investment needs are region-specific, such as mitigation challenges for ASIA, transportation structure for OECD, and modal shift from road to rail for LAM and MAF. For those regions, we found a strong interaction between modal shift and the long-term rail occupancy, the modal shift tending to lead to an increase or decrease in investment depending on the target rate of rail use.

We did not consider in this study additional investments related to energy efficiency or infrastructures for the use of alternative fuels. To obtain a comprehensive assessment of the costs related to the transport sector in a low-carbon world, these elements should be integrated. Inevitably, our results are conditional on the structures of the models we used, and on the alternative values we considered for the groups of uncertain parameters. They can therefore not be taken literally as definitive quantifications, and could be investigated further with alternative model structures or assumptions. In addition, the calibration for initial infrastructure occupancy levels is based on data collected from different sources, which potentially differ in their completeness and quality. If transportation activity is underestimated and/or infrastructure stocks overestimated in the data, we may underestimate the initial infrastructure utilization rates. This may be the case for ASIA, which in our data has very low initial road use. Conversely, utilization rates may be overestimated if transportation activity is overestimated and/or infrastructure stocks underestimated. For instance, this may be the case for LAM in our data. The lack of data for some regions or inconsistency between sources call for a serious effort to obtain open and comprehensive data on transportation infrastructures.

In our methodology, we do not account for the feedback effect of infrastructure development costs on economic activity, because the investments consistent with transportation activity scenarios are quantified ex-post. The literature has documented a positive feedback relationship with GDP, especially in developing countries (Straub, 2008). Accounting for this effect would be a future step towards improving the quantifications. Another caveat is that our methodology does not include other benefits (apart from reducing CO2 emissions) produced by investment in low-carbon transportation infrastructures, such as cutting air pollution and congestion. Moreover, the first benefit of low-carbon pathways is to reduce damage from climate change. Taking account of this damage reduction effect would have an impact on the evaluations of investment needs. In particular, we anticipate that high-carbon pathways would be associated with higher investment needs because of the costs of adaptation (Margulis and Narain, 2010), especially in developing countries (Chinowsky et al., 2011). This effect would reinforce our finding that investment needs for transportation infrastructure are lower in low-carbon pathways.

Notwithstanding these limitations, our results indicate a robust decrease in the levels of investment needed for transportation infrastructure in low-carbon pathways. This decrease could counterbalance higher investment needs for low-carbon pathways in other sectors, as has been estimated for the energy sector in particular (Gupta et al., 2014). This decrease has policy implications in terms of the reallocation of investment across sectors and of climate finance mechanisms. In addition, the main factors of uncertainty that affect the evaluation of investment needs can be interpreted as possible policy levers to avoid high investment needs and conversely to favor low investment needs. Research and development policy focused on low-cost road construction technologies and the optimization of rail utilization seems to be a potential strategy to consider in this context. Obviously the possibilities of increasing rail infrastructure utilization rates will depend greatly on local conditions with respect to geography, the structure of passenger travel patterns, or the types of goods transported, and the levers used to trigger this increase may differ in nature, sometimes institutional, sometimes technical.

Finally, we obtain high investment needs relative to GDP for some regions compared with historical values, and analyze the main determinant of these needs. This analysis shows, for example, that mobility trends in the CIS region do not seem to be compatible with a fall in the rail occupancy rates for investments of the same order of magnitude as past values. The module we developed to quantify the investment needs consistent with different transportation activity scenarios could be used to evaluate other transport activity pathways. In particular, it could be used as a sort of 'reality-check' for transportation activity pathways constructed with models that do not account for potential limitations on annual investment for transportation infrastructures.

Integrated assessment models (IAMs), such as the Imaclim-R model we used, are widely used to explore pathways for decarbonizing the transportation sector, in particular producing outputs on passenger and freight activity and economic growth over time. However, most of the models do not take transportation infrastructure investment into account in the global estimation of costs (Creutzig et al., 2015). Moreover, outputs for the transportation sector in projections on factors such as future volume of activity and modal share, differ between models (Yeh et al., 2017). Our methodology could therefore help to show what those differences means in terms of investment and to examine the realism of projections for the transportation sector from a financial perspective.

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3.A Appendix A - Details on scenario alternatives

Transport activity

The aim of this parameters set is to represent two alternatives contrasted: (i)continuation of urban sprawl and the lock-in phenomena associated with high freight use in the economy and (ii)a decrease of mobility needs and freight use in order to represent activities relocation, supply-chains organization and teleworking. In the model, freight content is represented by the input-output coefficient of freight sector intermediate consumption by productive sectors. To represent the decrease of transport use for passenger, we supposed a shift of budget allocation from transportation to other sectors.

Parameter	Assumption 1	Assumption 2
Household budget share allocated to transportation	Constant	0.5% decrease each year
Input-output coefficients for freight use	Constant in all sectors	1% decrease each year

Table 3.9 – Alternatives on transport activity determinants

Transport structure

For the baseline case, the car occupancy value was supposed to converge to the OECD countries values by 2100 in the 12 regions. In a second case, it was assumed that the car occupancy factor will converge to higher value in order to represent emerging new mobility phenomena as car sharing. In each region, the motorization rates increase with per capita income through variable income-elasticity: (a) low for poor households whose access to mobility relies on non-motorized and public modes; (b) high for households with a medium per capita income (c) low again, because of saturation effects, for per capita income level comparable to that of the OECD. For developing countries, high and low values of income growth multiplier for the motorization rate were studied. About infrastructures policies, we created two alternatives on the evolution of road capacity in the model. In one case the road capacity increases with automobile stock and in another case, this capacity converges to a value corresponding to a threshold per capita. The latter assumption can create congestion in the model causing lower profitability of road car mode.

Parameter	Assumption 1	Assumption 2
Car occupancy	Convergence to 1.53 by 2100	Convergence to 1.89 by 2100
Income growth multiplier for motorization rate in emerging countries	1 (OECD value)	0.6
Road capacity for car	Increase with automobile stock	Convergence to a value corresponding to 7000 pkm per capita

Table 3.10 – Alternatives on transport structure determinants

Transport intensity

High and low values for the learning rate value of the different car technologies (liquid fuel, hybrid, electric) were studied. This parameter has an impact on the investments costs and hence influences the evolution of the vehicle fleet. About the other terrestrial transports (trucks, train and public transports), two values of price elasticity of the sector energy intensity were studied.

Parameter	Assumption 1	Assumption 2
Learning rate for car technologies	0.1	0.2
Price elasticity of the energy sector intensity for other transports	-0.2	-0.4

Table 3.11 – Alternatives on determinants of transport energy intensity

Transport fuels

In our numerical exercises with the Imaclim-r modelling framework, biofuels (first and second generation) and Coal-to Liquid fuels represent the main alternatives to refined oil over the 21st century. In our first assumption, we represented a relatively high availability of coal-to-liquids and a relatively low availability of biofuels, whereas it was the contrary in our second assumption, such that we considered one alternative (assumption 1) where alternative fuels were carbon intensive and one alternative (assumption 2) where alternative fuels had a lower carbon content.

Parameters subset	Parameter	Assumption 1	Assumption 2
Biofuels	Inertia factor on production	0.75	0.65
	Supply multiplying factor	1	1.2
Coal to liquids	Time scale of reactive anticipation for production	6	20

Table 3.12 – Alternatives on transport fuel determinants

Natural growth drivers

The natural growth rate of the economy defines the growth rate that the economy would follow if it produced a composite good at full employment, like in standard neoclassical models developed after (Solow, 1956). In the IMACLIM-R model, it is given by exogenous assumptions on active population and labor productivity growth. We considered three alternatives corresponding to the Shared Socioeconomic Pathways (SSP)1, SSP2 and SSP3 values (Marangoni et al., 2017)

Parameters subset	Parameter	Assumption 1	Assumption 2	Assumption 3
Productivity	Growth of the leader from 2001 to 2100	from 2.5% to 1.5%	from 2% to 1%	from 1.4% to 0.4%
	Convergence speed of the "laggards' in years	Low income : 400 Medium income : 200 High income : 150	Li: 500 Mi : 300 Hi : 200	Li : 800 Mi : 300 Hi : 200
Population	Growth rate of population	SSP1 projection	SSP2 projection	SSP3 projection

Table 3.13 – Alternatives on growth factors

Mitigation challenges determinants

Parameters subset		Parameter	Assumption 1	Assumption 2
End-use energy efficiency		Exogenous energy efficiency rate of the leader at fixed energy prices	0.5%	1%
		Other countries' speed of convergence (% of the initial gap after 100 years)	95 %	70%
		Asymptotic level of catch-up targeted by the laggards (% of the leader's energy efficiency	30 %	85%
		Maximum rate of annual induced energy efficiency	3% for OECD countries 4% for others	3% for OECD countries 5.85% for others
		Maximum rate of autonomous energy efficiency	1% for OECD countries 1.13% for other countries	1% for OECD countries 2% for other countries
Availability of fossil fuels	Oil	Amount of ultimately recoverable	3.6 Tb	3.6 Tb
	Gas	Indexation of gas price on oil price	Until 80$/bl	Always indexed
		Price growth elasticity to production decrease	1	1
		Price growth elasticity to production decrease	3.5	2.5
	Coal	Price growth elasticity to production decrease	1	1
		Price growth elasticity to production increase	0.8	3
Development patterns		Asymptote to surface per capita	80-100	60-80
		Households industrial goods consumption saturation level	1.5-3	1.2-2

Availability of LC technologies for electricity	Nuclear	Maximum market shares	20%	No new nuclear
	Renew.	Maximum market shares	50%	80%
		Learning rates	5%	15%

Table 3.14 – Alternatives on mitigation challenges determinants

3.B Appendix B - Description of the data used in the module investments evaluation

Region	Passenger bus	Passenger rail	Passenger BRT/bus	Passenger high speed rail	Freight road	Freight rail
ASIA	73.4	23.2	0.1	3.5	71.4	28.6
CIS	57.5	42.5	0	0	12	88
MAF	94.4	5.6	0.13	0	88.2	11.8
LAM	98	2	0.9	0	78	22
OECD	55.7	35.5	0.7	8.8	64.7	35.3

Table 3.15 – Mode split (%) of land transport activity (public transport and freight transport) for the past trend scenario, calibrated from different databases [6]

Mode	Unit	ASIA	CIS	MAF	LAM	OECD90
Road	lane.km/km2	3	1	1	1	4
Rail and HSR	track.km/km2	0.05	0.05	0.05	0.05	0.1

Table 3.16 – Applied infrastructures density limits for the different regions in the model

6. World Bank (2017), Schafer (1998), Singh (2006), OECD (2017b), UIC (2017) for ASIA; OECD (2017b), ESCAP (2017) for CIS; World Bank (2017), Schafer (1998), UIC (2015), ITF (2017) for MAF; ITF (2017), Schipper et al. (2010) for LAM; UIC (2017), UIC (2015), OECD (2017b), European Commission (2016) for OCDE. The overall volume of BRT activity taken from Dulac (2013) has been distributed among the different regions based on the shares of BRT infrastructure in each region (data from EMBARQ (2017)

3.C Appendix C - Supplementary results

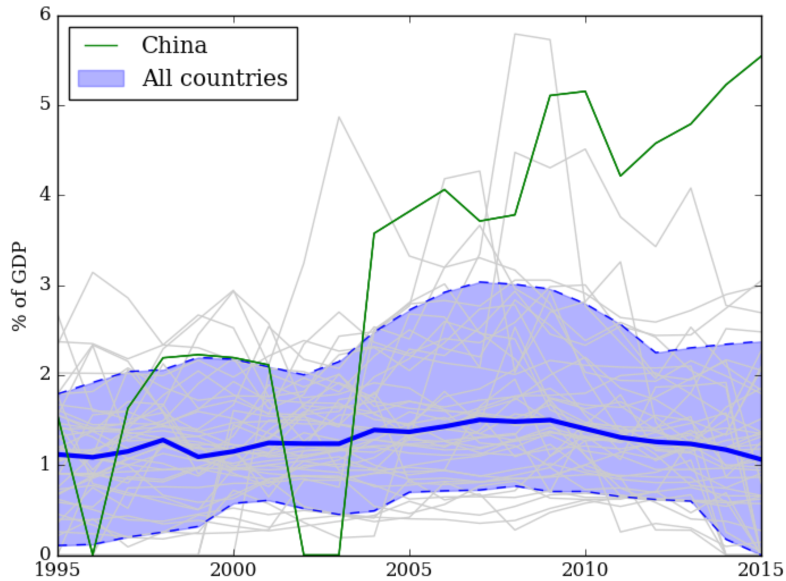


Figure 3.6 – Historical annual investments on transport infrastructures (rail, road and airports) - median(solid line) and 10th and 90th percentile (dashed lines) - Data aggregated by the authors from OECD (2017b) and World Bank (2017)

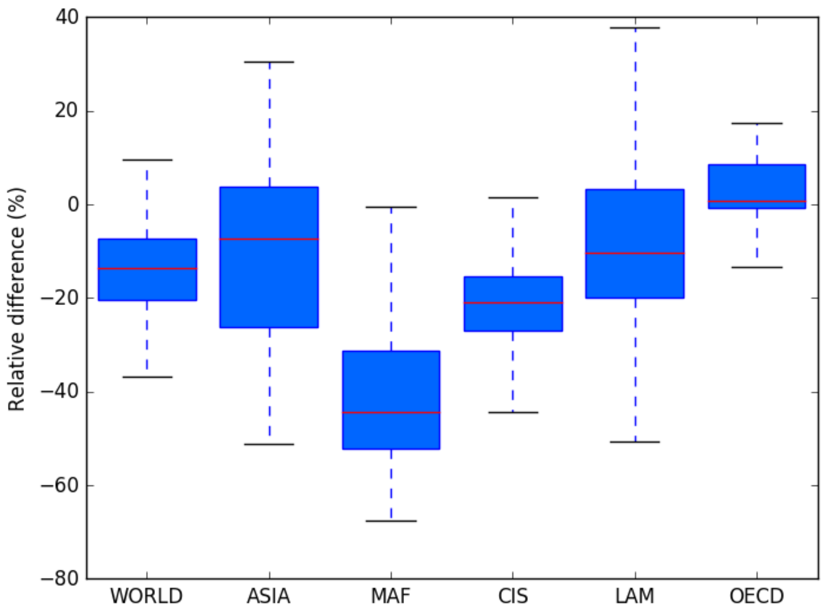


Figure 3.7 – Relative difference in cumulative investment needs between mitigation scenarios with modal shift (from road to rail for public transportation and freight) and baselines scenarios without modal shift

		2015	2050			2080		
			Baseline	LMA	HMA	Baseline	LMA	HMA
ASIA	Personal Vehicle	24%	37%	34%	30%	41%	35%	30%
	Air	1%	3%	3%	3%	5%	4%	3%
	Public transport	40%	49%	50%	51%	44%	45%	41%
	Non Motorized	35%	11%	13%	17%	10%	16%	26%
CIS	Personal Vehicle	64%	68%	66%	61%	67%	47%	44%
	Air	2%	8%	8%	8%	14%	12%	9%
	Public transport	23%	20%	22%	24%	16%	26%	27%
	Non Motorized	11%	4%	4%	7%	3%	15%	20%
MAF	Personal Vehicle	31%	43%	41%	38%	50%	32%	27%
	Air	2%	5%	3%	3%	7%	2%	1%
	Public transport	42%	40%	42%	40%	30%	25%	21%
	Non Motorized	25%	12%	13%	19%	14%	41%	50%
LAM	Personal Vehicle	49%	52%	51%	52%	55%	57%	58%
	Air	5%	10%	10%	9%	12%	8%	6%
	Public transport	38%	36%	36%	37%	30%	31%	30%
	Non Motorized	8%	2%	3%	2%	3%	4%	6%
OCDE	Personal Vehicle	81%	69%	69%	70%	62%	66%	67%
	Air	6%	14%	14%	13%	19%	15%	13%
	Public transport	12%	16%	16%	16%	19%	19%	19%
	Non Motorized	1%	1%	1%	1%	0%	0%	1%

Table 3.17 – Transportation mode shares in the different regions in Baselines, low mitigation ambitions (LMA) scenarios and high mitigation ambitions (HMA) scenarios (average values across scenarios sets)

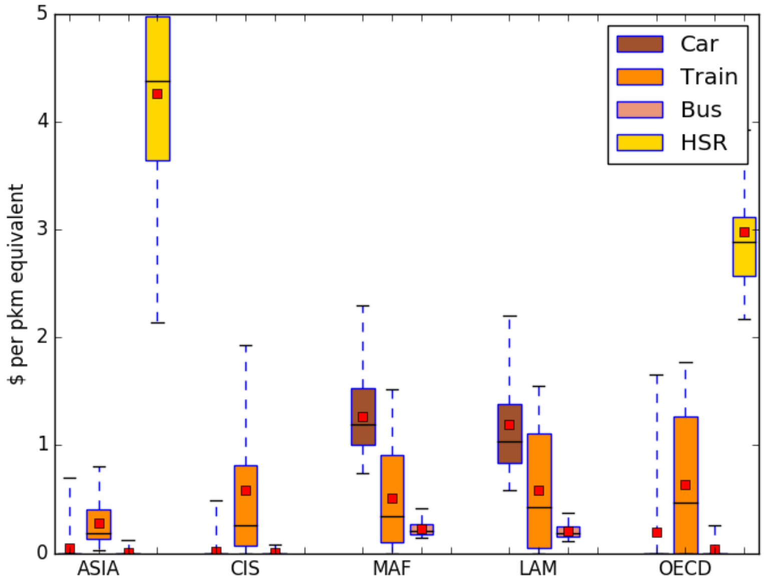
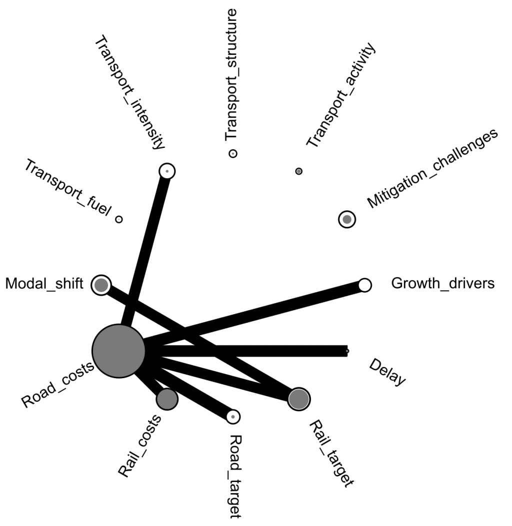


Figure 3.8 – Distribution of marginal investment cost of one passenger-kilometer from 2015 to 2050 for the different regions and modes for passenger activity. Red squares represent the average of the distribution for all scenarios.

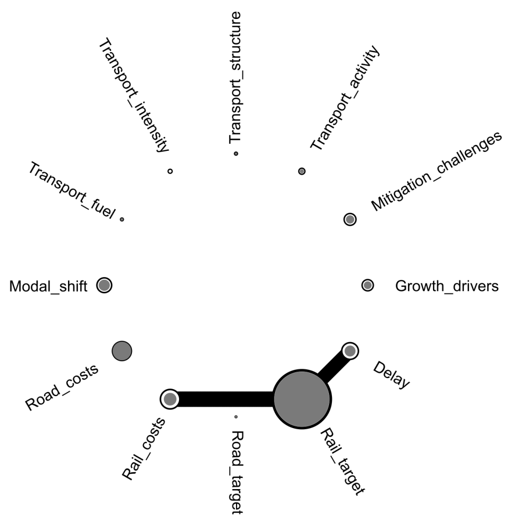
We calculated the marginal investment cost of passenger-kilometer for the mode i in average for the period 2015-2050 using the next formula:

$$Marginal\_inv_i = \frac{Cum\_inv_{i,2015-2050} - Constant\_maint\_inv}{pkm_{i,t=2050} - pkm_{i,t=2015}}$$

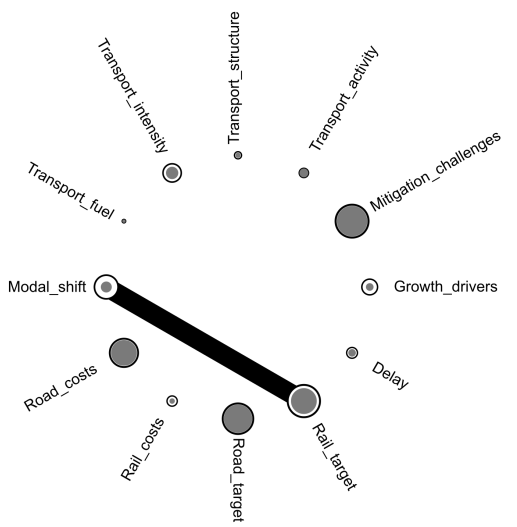
with $Cum\_inv_{i,2015-2050}$ the cumulative investments (new built and maintenance) from 2015 to 2050; $Constant\_maint\_invvestments$ the cumulative investments of maintenance if no new builds is added from 2015 to 2050 (constant activity);$pkm_{i,t}$ the passenger activity for the mode i at the year t. Data of activity for the different infrastructures types (road and rail) have been converted in passenger-kilometers equivalent for the three modes using vehicle occupancy factors applied in the model.



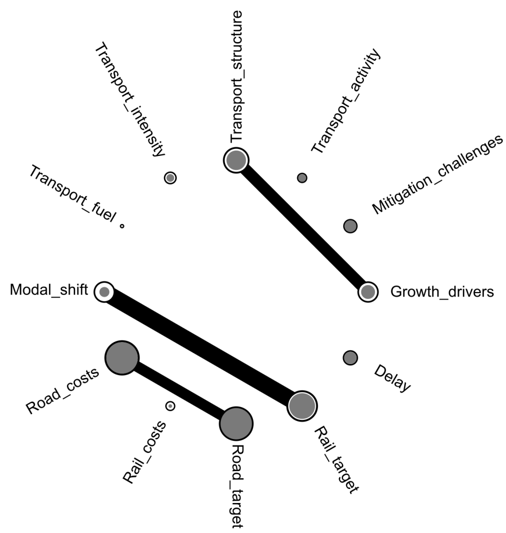
(a) ASIA



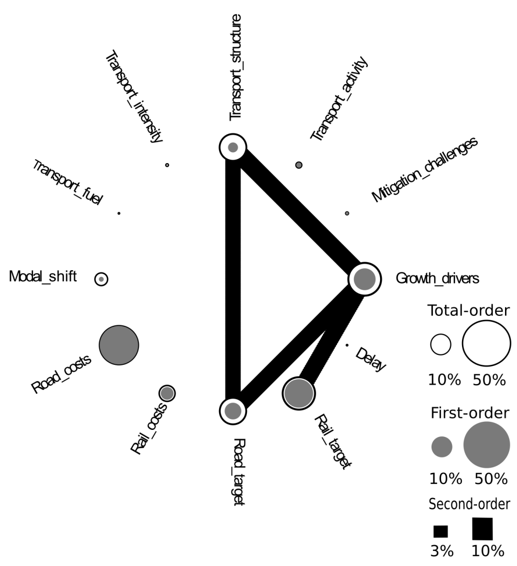
(b) CIS



(c) MAF



(d) LAM



(e) OECD90

Figure 3.9 – Sobol method global sensitivity analysis results for each region, for the cumulative investments needs. Filled nodes represent the first-order indices and rings the total-order indices. Lines represent second-order indices arising from interactions between inputs. Width of lines indicates the second-order indices. Only the second-order indices greater than 2% of total variance are represented (because of many interactions between parameters for OECD, we choose a threshold of 4% for a better readability).

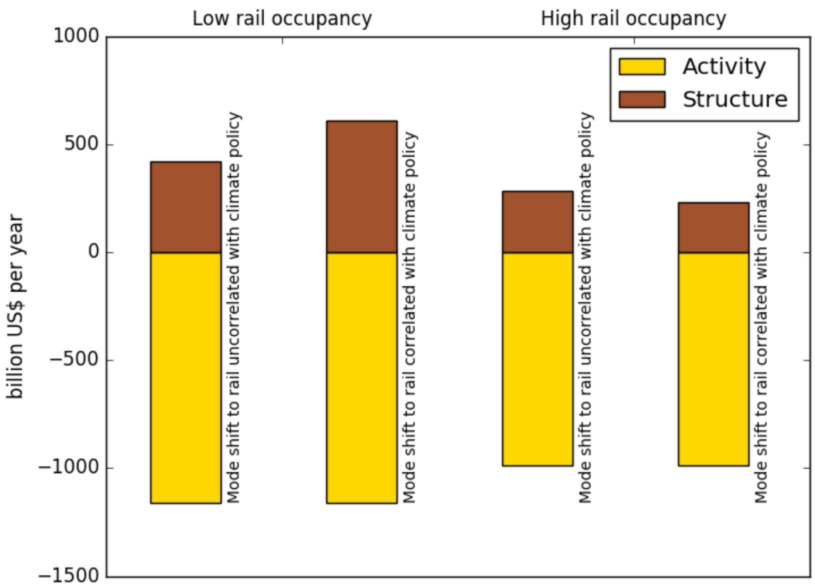


Figure 3.10 – Decomposition of transport activity and structures effects on global investments needs per year for one scenario. Two rail occupancy rates have been tested. Red edges represent the cases where modal shift to rail is correlated to low carbon policy implementation. Fuel and Intensity factors are not on this figures because we did not consider in this study additional investments related to energy efficiency or infrastructures for the use of alternative fuels

Chapter 4

Embodied carbon dioxide emissions to provide universal high levels of access to basic infrastructures

4.1 Introduction

Human societies face the challenge of increasing well-being while limiting impact on the climate. Assessing the relationship between human well-being and carbon emissions or energy consumption is crucial to highlight the (un)consistencies between mitigating climate change and providing a high quality of life for all. Since human well-being differ from economic affluence (Roberts et al., 2020) and GDP is a limited indicator to represent social progress (Stiglitz et al., 2009), indicators beyond GDP or incomes should be used to measure well-being.

Different metrics have been applied to investigate empirically the link between human development and energy or carbon footprint. Some authors have used life expectancy whereas others used composite indicators such as the Human Development Index (HDI) to integrate the multidimensional aspect of human well-being (Kahneman and Krueger, 2006). All these studies have found non linear-relationship with a high correlation between energy consumption or carbon emissions and well-being at low levels of well-being but not at high levels (Steinberger and Roberts, 2010; Costa et al., 2011; Lamb et al., 2014; Jorgenson, 2014; Ribas et al., 2019).

Using composite indicators is however problematic because it implies a substitutability between the dimensions and requires to assign weights to them (Decancq and Lugo, 2013). Doyal and Gough (1991) and Max-Neef et al. (1992) have proposed a set of universal human needs to fulfill. In the human needs theories, needs are plural, non-substitutable, satiable, cross-generational and universal but the way to satisfy those needs (need satisfiers) can differ between regions such as the type of food or dwelling. Doyal and Gough (1991) distinguished two basic needs-personal autonomy and health- that depend on other intermediate needs such as security in childhood or clean water. Gough (2015) updated this analytical framework and highlighted the need to define 'sufficient' levels for human needs regarding the environmental constraint.

The human needs approach has permeated the climate mitigation literature trough different concepts that aim at quantying the energy or carbon emissions associated with basic needs satisfaction : the Subsistence Emissions (Shue, 1993), the Decent Living Emissions (Rao and Baer, 2012) or the 'Safe and Just Operating Space '(so-called 'Doughnut') (Raworth, 2012). It is also reflected in the Sustainable Development Goals agenda containing 17 goals and 169 targets

(United Nations, 2015).

Infrastructures such as buildings and civil engineering networks influence the achievement of many development goals either directly or indirectly (Thacker et al., 2019). This pivotal role is evident for the SDG 9-*Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.* Infrastructures stock is one of the factors explaining economic growth (Calderón and Servén, 2004; Straub, 2011) and hence contributes to the achievement of the SGD 8 - *Promote inclusive and sustainable economic growth, employment and decent work for all.* It is also a determinant of poverty reduction (Akanbi, 2015; Ogun, 2010) which is essential for the SGD1-*End poverty in all it forms everywhere.* Infrastructures are instrumental in providing essential services to meet human needs (Steckel et al., 2017; Clark et al., 2018) such as water, sanitation or transport. However, access to basic infrastructures varies widely among countries even when incomes are similar (Steckel et al., 2017).

Yet, manufacturing the construction materials required for infrastructures is an important source of greenhouse gas emissions. The emissions embodied in materials account for over 90% of lifecycle emissions in infrastructures (Huang et al., 2018) and emissions from the construction of new urban infrastructure could represent 27.5% of total urban emissions between 2016 and 2030 (Creutzig et al., 2016). Mitigating these embodied emissions are crucial to reach carbon neutrality.

Most of embodied emissions come from cement and steel productions, which are CO_2 intensive industries. These two core materials are used in all countries at any development stage for construction, the other construction materials such as aluminium and cooper being specific to more advanced applications (Bleischwitz et al., 2018). In 2014, the steel and cement industries accounted for 5.8% and 5.6% of global CO_2 emissions respectively (IEA, 2017b).

Their contribution to global CO_2 emissions is expected to continue in the short-term for two reasons. First of all, process emissions resulting from chemical reactions involved to manufacture materials are difficult to eliminate without carbon capture and storage technologies (Davis et al., 2018). Secondly, the technical lifetimes of the capital used in the heavy industries are between 30 and 40 years, creating inertia in the renewal of technologies and slowing possibilities to reduce emissions (Erickson et al., 2015). A rapid increase of the global infrastructure stock in the short term could consume a significant part of the carbon budgets available to meet the Paris Agreement targets (Müller et al., 2013; Krausmann et al., 2020).

In this paper, I ask if high level of access to basic infrastructure services can be provided at the global scale in 2030 without compromising climate mitigation targets. I analyse how the access rates evolve with the increase of infrastructure stock and construction materials consumption and how much building materials and CO_2 emissions are associated with providing high infrastructure access.

A first literature strand has assessed the carbon impact of providing high access levels to different infrastructure services but without considering the embodied CO_2 emissions in construction materials. Some studies have estimated the CO_2 emissions from final energy use of expanding energy access and have found a small contribution to global warming (Chakravarty and Tavoni, 2013; Pachauri et al., 2013, 2014). Other studies have analysed empirically the relationship between GHG emissions or energy consumption - all sectors aggregated - and access levels to basic infrastructures such as water, sanitation or electricity (Rao et al., 2014; Lamb and Rao, 2015; O'Neill et al., 2018). They have highlighted the best fit curves are either linear-logarithmic or saturation curves. This suggests that after a certain threshold of access, a low increase of access level is associated with a high level of carbon impact. Lamb and Rao (2015) and O'Neill et al. (2018) have also projected the aggregated carbon emissions associated with the achievement of high access rates to sanitation, electricity or water but only in pathways unconstrained by mitigation actions.

Another literature strand has projected the CO_2 emissions from cement and steel sectors but without considering whether or not infrastructure access needs were met. Several studies have used econometrics relationship between cement or steel production and GDP (Zhang et al., 2018; van Ruijven et al., 2016; Steckel et al., 2013). Among them, Steckel et al. (2013) suggested a potential tension between energy consumption decrease in existing scenarios and the energy necessary for infrastructures build-up. Other studies from industrial ecology field have used the concept of in-use material stock to link the increase of infrastructures and the material flows required (and the associated embodied emissions) to build it up (Pauliuk et al., 2017; Chen and Haynes, 2015). Müller et al. (2013) showed an extension at the global scale of wealthiest countries' in-use stock levels for cement, steel and aluminium would consume a significant part of the carbon budget available to stay below 2°C. The convergence of developing countries to infrastructure level of wealthiest countries will be associated with higher access level to basic infrastructures. However, this objective is questionable because of potential negative outcomes such as land take (Colsaet et al., 2018) and it could not induces significant progress for countries with already high access rates (Rao et al., 2014; O'Neill et al., 2018). Krausmann et al. (2020) has recently estimated the embodied CO_2 emissions - all materials considered - for a global convergence at the per-capita level of in-use stocks that the developed countries had achieved in 1970, considering it as 'sufficient' in terms of life quality. Authors have shown large reductions in global resource demand and emissions compared to the scenario where countries converge to the current infrastructure level of industrialized countries.

In this paper, I first use historical data to describe the global trends of access to 5 basic infrastructures services - electricity, water, sanitation, shelter or transport - in relation to the steel and cement embodied in infrastructures stocks. Then, following historical patterns, I quantify the amounts of cement and steel needed in each country associated with reaching high access levels in 2030 and maintaining it until 2050 for each of the infrastructure services. Finally, I estimate the cumulative $C0_2$ emissions from manufacturing cement and steel requirements. I discuss my findings with respect to the available carbon budgets and the existing material production and greenhouse gas emission scenarios in the cement and steel industries.

This study goes beyond the existing literature in different aspects. First, I assess the material and carbon impact of achieving 5 sustainable development goals related to infrastructures access. Then, I took into account country-specific determinants of cement and steel consumption such as trade structure and carbon intensity of material production to calculate production-based CO_2 emissions. Finally, I built 3 decarbonization scenarios of the cement and steel industries to see how the projected low-carbon transition in these industries limits the carbon impact of providing infrastructure access.

The rest of this article is structured as follows: Section 4.2 describes the methodology, Section 4.3 presents the results and discussion and Section 4.4 provides a summary and a conclusion.

4.2 Methodology

In a first step, I used historical data to quantify the cement and steel consumption for each country to provide high access levels to different infrastructures services in 2030 and maintain them until 2050. Subsection 2.1 describes the data and the global historical patterns of infrastructure access along the material stocks increase. Subsection 2.2 details the modelling approach used in this step. In a second step, I quantified the CO_2 emissions corresponding to the materials consumption obtained in the previous step. Subsection 2.3 describes how I represented in the modelling framework country-specific determinants of CO_2 emissions related to cement and steel consumption.

4.2.1 Analysing trends in infrastructure access levels along the in-use materials stocks build-up

Data and definitions

I chose to focus on 5 basic infrastructure services - water, electricity, shelter, sanitation and transportation. In the human needs theory, they are essential needs satisfiers contributing through different channels to personal autonomy and physical health (Gough, 2015). Access definition is more straightforward than other infrastructure services such as health or education (Steckel et al., 2017) and data are available over several years and countries (Table 4.1). The infrastructures associated are capital-intensive and require cement and steel (see Du Fei et al. (2013) for water and sanitation systems, Anastasiou et al. (2015) for road network or Bumby et al. (2010) for power distribution).

Different indicators of access are available in the literature for each infrastructure service. For instance, for transportation access, researchers used in the literature the Rural Access Index (Iimi et al., 2016) defined as the proportion of population living within 2 km of an all-season road, the travel time required to reach the nearest urban centre (Weiss et al., 2018) or the existing stock of paved roads (Jakob et al., 2016). I privileged the official indicators used to assess sustainable development goals progress or those closest to, depending on data availability (Table 4.1). The complete list of indicators used in the SDGs is available at https://unstats.un.org/sdgs/indicators/indicators-list/.

Electricity access contributes to physical health by reducing indoor air pollution through replacing biomass fuels and coals (Duflo et al., 2008). It is related to the SDG 7.1 "*Universal access to affordable, reliable and modern energy services*". I used the official SDG indicator being defined as the percentage of population having access to household electricity.

Services	SDG target	Official indicator	Chosen indicator	Coverage	Source
Electricity	7.1 Universal access to affordable, reliable and modern energy services	Percentage of population with access to household electricity	Percentage of population with access to household electricity	214 countries, 1990-2014	World Bank (2018)
Water	6.1 Universal and equitable access to safe and affordable drinking water for all	Proportion of population using safely managed drinking water services	Percentage of population having access to an improved water source	203 countries; 1990-2015	World Bank (2018)
Sanitation	6.2 Access to adequate and equitable sanitation and hygiene for all and end open defecation	Proportion of population using safely managed sanitation services	Percentage of population having access to improved sanitation facilities	202 countries, 1990-2015	World Bank (2018)
Shelter	11.1 Adequate, safe and affordable housing and basic services and upgrade slums	Proportion of urban population which is living in slum household	Proportion of urban population which is not living in slum household	96 countries; 2000, 2005, 2007, 2009 and 2014	World Bank (2018)
Transport	9.1 Develop quality, reliable, sustainable and resilient infrastructure, including regional and trans-border infrastructure	Proportion of the rural population who live within 2 km of an all-season road	Proportion of population living within 2 km of an all-season road	151 countries, 2014	Mikou et al. (2019)

Table 4.1 – Description of infrastructure access data

At least 50 litres per person per day is needed to ensure hygiene including laundry and domestic cleaning and inadequate access to safe drinking water is associated with diarrhoea disease and exposure to chemical pollutants (Hunter et al., 2010). This is related to the SDG 6.1 "*Universal and equitable access to safe and affordable drinking water for all*". The official indicator is the percentage of people using safely managed drinking water services. I used the percentage of population having access to an improved water source such as piped household water, public tap, tube well/borehole, protected dug wells, protected springs or rainwater collection. This indicator is close in definition to the official one and has better geographical and temporal coverages.

Sanitation access contributes to physical health, lack of access being a risk factor child health facilitating fecal-oral transmissions of pathogens and causing various diarrheal disease (Larsen et al., 2017). It corresponds to the SDG 6.2 "*Access to adequate and equitable sanitation and hygiene for all and end open defecation*". The official indicator is the proportion of population using safely managed sanitation services. I used the percentage of population having access to improved sanitation facilities included flush/pour flush (to piped sewer system, septic tank, pit

In-use material stock	Coverage	Source
Cement	184 countries. 1990-2014. All sectors aggregated	Cao et al. (2017)
Steel	139 countries. 1990-2008. Sector "buildings-construction-infrastructure"	Pauliuk et al. (2013)

Table 4.2 – Description of in-use material stock data. In-use steel stock is assumed to be equal to in-use iron stock following Morfeldt et al. (2015).

latrine), ventilated improved pit (VIP) latrine, pit latrine with slab, and composting toilet. This indicator is close in definition and has better temporal and geographical coverages.

Shelter access indicator is defined as the proportion of urban population that does not live in slum household. A slum household is considered here as a group of individuals living under the same roof lacking one or more of the following conditions: access to improved water, access to improved sanitation, sufficient living area, and durability of housing. It is the official indicator of the SDG 11.1 "*Ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums*".

Transportation accessibility contributes to personal autonomy, and has an impact on employment (Johnson et al., 2017) and leisures participation (Kessides, 1993). It can be linked to the SDG 9.1 "*Develop quality, reliable, sustainable and resilient infrastructure, including regional and trans-border infrastructure*". The official indicator associated is the Rural Access Index (RAI) defined as the proportion of the rural population living within 2 km of an all-season road. Although mobility can also take place by rail, this indicator can be considered as a proxy for transportation accessibility by assuming that railway lines are mostly doubled with roads. I modified this indicator to get the share of the overall population who live within 2 km of an all season road using urbanization rate data, assuming all urban inhabitants live within 2km of an all-season road.

I aim to relate the cement and steel materials consumption to the access to infrastructures services. However, linear meters of infrastructures and construction materials used are not available at the country scale for each infrastructures services. I therefore used the overall in-use stocks of cement and steel, i.e the amounts of steel and cement contained in the aggregated infrastructures and building stocks (Chen and Haynes, 2015). Researchers have characterized historical patterns of cement and steel stocks using dynamic material flow analysis. This approach tracks the different flows and stocks evolution including international trade and taking into account the products lifetime containing the material studied. Data and sources for in-use material stocks used in this study are synthesized in Table 4.2.

Patterns of infrastructure access

Literature mentioned non-linear functional forms such as the semi-logarithmic or the hyperbolic curves (Rao et al., 2014; Lamb and Rao, 2015; O'Neill et al., 2018) as relevant to characterize relationships between infrastructure access and environmental impact. In the same manner, the scatter plots of each infrastructures access-material stock pair (figure 4.1) suggests a correlation between those variables following a non-linear trend. It indicates that, from a certain access threshold and before reaching full access, a small increase of access rate is associated with a high increase of infrastructure stocks and construction material needs.

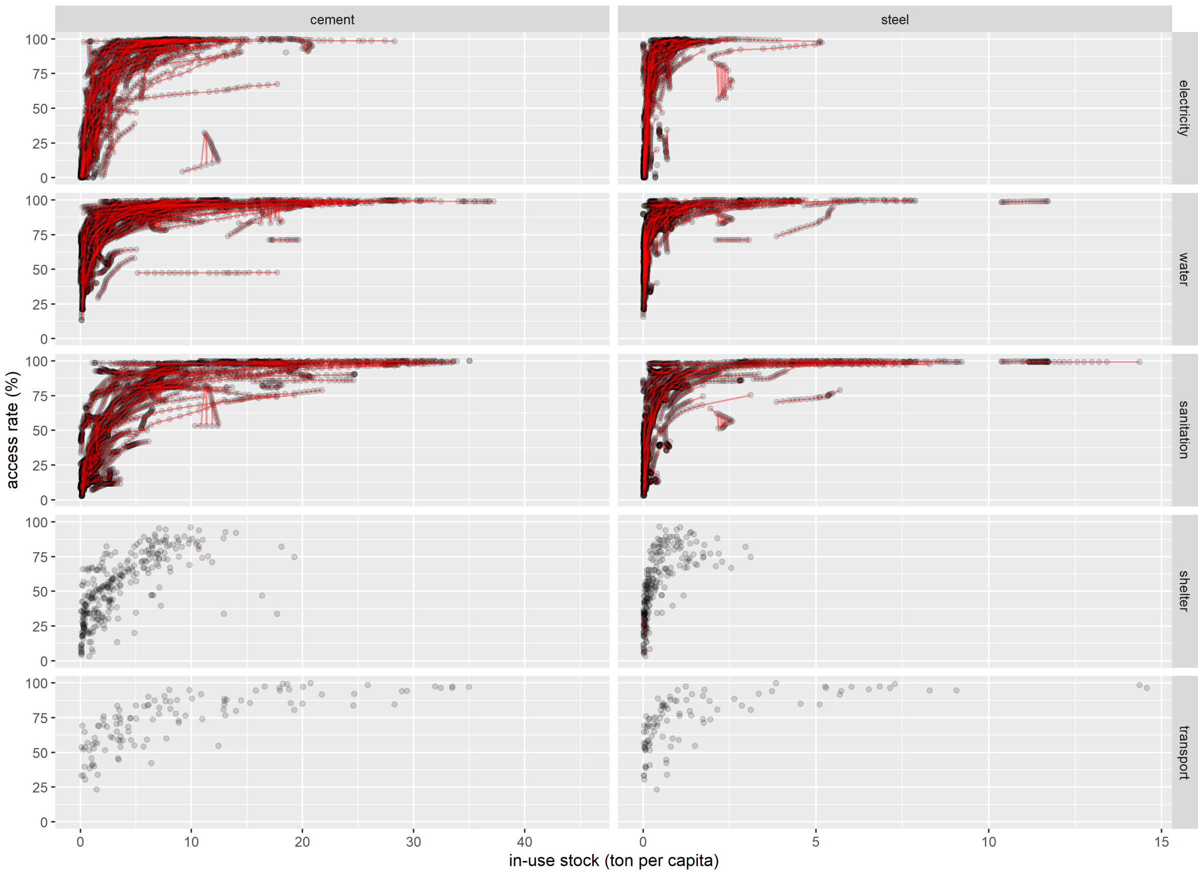


Figure 4.1 – Scatter plots of infrastructures access rates against in-use material stocks. The samples have been filtered out by removing values of 0% and 100% access rates for readability purpose. Steel stock have been projected from 2008 to 2014, assuming the cement stock elasticity of steel stock was the same as the 2005-2008 period for each country. Each line refers to the evolution of the data for a country. Lines are not drawn for shelter and transport scatter plots since access data are not available for two consecutive years.

I estimated the in-use material stock levels per capita that are consistent with high access rates for each infrastructures services. I first defined as high level of infrastructure access a percentage of the population in each country having access to each infrastructures services. I recognize this process is normative. Even though in the SDG framework universal access to infrastructures services is targeted, some indicators are today below 100% even in the wealthiest countries for transportation or sanitation access. I hence considered the level of 90% as target as used in Lamb (2016) and Rao et al. (2014). I also tested the 95% value for illustrative purpose and to show the sensitivity of the results to a higher coverage level.

Following O'Neill et al. (2018), I then selected, for each infrastructure services and among all years and countries of our sample, the 20 values of cement and steel stocks per capita associated with the access rates closest to the target value. The 20 value sample allows to get a representative subset of the points closest to the access threshold without deviating too far from it. For each country, I only kept the data associated with the access rate closest to the target value so that a country's own performance does not unduly influence the overall result. Since transportation access data were available only for the year 2014, I projected steel stock values from 2008 to 2014, assuming the cement stock elasticity of steel stock was the same as the 2005-2008 period for each country. I then identified the distribution and the median value of material stocks per capita on this sub sample and compared them according to infrastructures or materials considered.

Figure 4.2 presents the distribution of in-use cement and steel stocks per capita for the 20 countries closest to the access threshold of 90%. These values represent the materials embodied in the whole infrastructure stock. They should not be considered as materials used specifically for one infrastructure type but rather as the construction material intensity of the economic system to provide access to an infrastructure type. This approach allows to take into account the interdependencies between infrastructures, such as having a certain level of transportation access for the delivery of materials necessary for the construction of a drinking water network.

The median values differ between infrastructure type and materials to achieve high access rates. Values are higher for cement than steel for all infrastructures considered, with a factor ranging from 6 for water to 12 for shelter. While the lowest values obtained are for electricity with 4.53 tons of cement per capita and 0.46 ton of steel per capita, these values are the highest for transportation reaching respectively 13.08 and 1.75. Infrastructures access tend to follow a sequencing process along material stocks increase with electricity and water coming first, and transport access last, which is in line with previous results (Steckel et al., 2017). For the year 2014, only 10 countries reach an access rate to sanitation services without having done the same for either electricity or water. 8 countries reach an access rate to transportation higher than 90% without having done the same on one of the other infrastructures.

4.2.2 Estimating the cement and steel needs in each country to reach high infrastructure access

The global median values of in-use material stocks per capita associated with high infrastructure access, obtained in the last section, may seem plausible as targets for developing countries. However, some countries have already reached the access level of 90% on some infrastructures for lower values of in-use material stocks per capita. Conversely, other countries have not yet reached the access level of 90% on some infrastructures for higher values of in-use material stocks per capita. Country specific determinants such as the urbanization level or spatial organization can affect the cement and steel consumption in each country even when the economic development levels are similar. Higher urban density decreases the materials stocked in networked infrastructures but increases the structural material stock contained in buildings because of greater height (Norman et al., 2006; Schiller, 2007). Construction techniques and

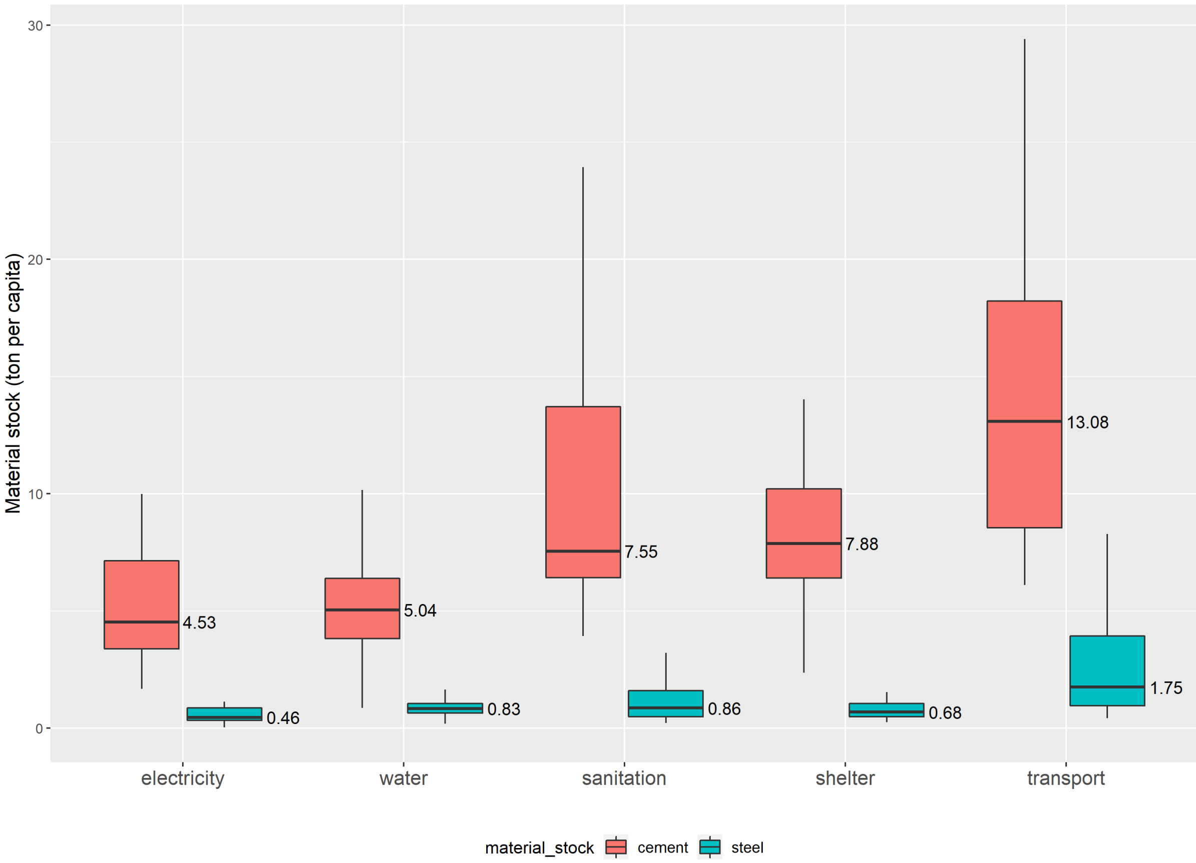


Figure 4.2 – Distribution of in-use cement and steel stocks per capita for the 20 countries with the access rate closest to 90%. These values represent the materials embodied in the whole infrastructure stock and should not be considered as materials used specifically for a infrastructure type.

materials used can also differ between countries. Explicitly integrating the influence of these parameters goes beyond the scope of this study and could be done in further research.

I hence refined the median estimation approach to represent partially country specific patterns of cement and steel consumption and to represent two stylized facts observed in the literature about cement and steel in-use stocks : (i) cement and steel stocks per capita increase during the development process before saturating or decreasing for wealthiest countries and (ii) material stocks are immobile for many decades and will not decrease in the short term (Cao et al., 2017; Bleischwitz et al., 2018). I considered different conditional cases summarized in the table 4.3 to allocate to each country and for each infrastructure service a level of in-use materials stocks per capita to reach for providing high access. The way in which the different cases are constructed gives rather lower bound of in-use stocks to target. I also performed the same analysis replacing the global median value by the first and the third quartiles of the distributions obtained in the last subsection to integrate uncertainties. This approach is also relevant to limit the discontinuities effects induced by the different conditional case for countries with access rates close to 90% or in-use stock per capita close to the global median value.

I then estimated the cement and steel needs to reach the in-use stocks per capita targeted

Access rate in 2014	In-use stock per capita in 2014	In-use stock per capita targeted	Underlying assumptions
<90%	<Global median value associated with a 90% access rate	Global median value associated with a 90% access rate	Countries are still in the development process so the in-use stocks per capita will increase.
<90%	>Global median value associated with a 90% access rate	2014 value	Countries with access rates below 90% are still in the development process so the in-use stocks per capita will not decrease
>90 %	<Global median value associated with a 90% access rate	2014 value	Country specific conditions allows lower in-use stocks levels per capita than global median value to provide high access to infrastructures. In-use stocks levels per capita will saturate in developed countries.
>90%	>Global median value associated with a 90% access rate	Global median value associated with a 90% access rate	Country specific conditions lead to higher in-use stocks levels per capita than global median value to provide high access to infrastructures. In-use stocks levels per capita can decrease in the highly developed countries.

Table 4.3 – Description of the different conditional cases to allocate a target of in-use material stock per capita to each country. The way in which the different cases are constructed gives rather lower bound to target. Same methodology have also been applied replacing the global median values by the first and third quartiles.

in 2030 and to keep it at this value until 2050 in case of population increase. I did not integrate capital depreciation here so the material needs obtained should be considered as lower bounds. I used national population projection from the Shared Socioeconomic Pathway 2 (SSP2) scenario (O'Neill et al., 2017). It is a medium scenario with global population increasing from 6.9 billion people in 2005 to more than 9 billion people in 2050 (Kc and Lutz, 2017). Using this population scenario also allows to compare my quantifications of material needs and carbon emissions with the literature. I assumed linear evolution of national in-use material stock towards targeted stock.

4.2.3 Quantifying the production-based CO_2 emissions related to manufacturing cement and steel

In this section, I detail the modelling choices for calculating the production-based CO_2 emissions induced by cement and steel requirements in each country, obtained in the previous step.

Steel production

The steel production is today mainly divided into two production routes, the blast furnace-basic oxygen furnace (BF-BOF) and the electric arc furnace (EAF). In the conventional BF-BOF route, iron ore and coke are melted in a blast furnace in order to reduce iron ore and obtain pig iron. The latter is then converted to steel in the basic oxygen furnace. Instead of using BOF, iron can also be refined into steel in an open hearth furnace (OHF) but this technology is energy intensive and is used to a smaller extent (World Steel Association, 2016). Electric arc furnace steelmaking uses scrap steel as the main feed material. Direct reduced iron (DRI) can also be used in electric arc furnace, the iron ore being reduced by a gas produced from natural gas or coal.

The four steel production routes (BF-BOF, BF-OHF, scrap-EAF and DRI-EAF) differ in terms of energy consumption and CO_2 emissions (Morfeldt et al., 2015). I synthesised in Table 4.4 the related direct CO_2 emissions and the electricity consumption. I considered here emissions from raw material preparation processes (sintering and coking) to rolling processes using mill to be consistent with the decarbonisation scenarios of the steel sector I used (see subsection "Scenarii used for the dynamics of the production-based emissions determinants").

Process routes	**Direct emissions (CO_2/ton steel)**	**Electricity consumption (kWh/ton steel)**
BF-BOF	2.19	226
Scrap-EAF	0.17	625
DRI gas-EAF	1.55	754
DRI coal-EAF	2.95	759
OHF	2.91	300

Table 4.4 – Carbon and electricity intensities of the different steel production routes. Values have been calculated using data from Morfeldt et al. (2015) and Milford et al. (2013)

For each steel producing country, I calculated the technology weighted average emissions for one ton of steel produced. Doing so, I assumed possible substitution between scrap-based steel and steel produced from virgin materials, following (Morfeldt et al., 2015) and (Milford et al., 2013). National production routes shares for the year 2015 were obtained from World Steel Association (2016) and grid carbon intensity for the year 2015 from IEA (2017a). When value were unavailable for a country, I applied the global average technology mix or the global average value of grid carbon intensity. Data and sources are synthesized in table 4.5.

The calibration is consistent with previous estimations. Hasanbeigi et al. (2016) obtained for the year 2010 CO_2 emissions intensity of production equal to 2.15 t CO_2/ton steel for China, 1.71 t CO_2/t steel for Germany, 1.08 t CO_2/t steel for Mexico, and 1.74 t CO_2/t steel for U.S.A. My corresponding calibrated values are respectively 2.19, 1.73, 1.40 and 1.12 tCO_2/t steel. This indicates a change in the technology used to produce steel in Mexico and U.S.A. from 2010.

Cement production

Cement manufacturing can be separated into two distinct stages. The first stage is producing clinker by limestone calcination reaction in a rotating kiln. This chemical reaction releases

CO_2 in itself, which is referred to here as process emissions. Process emissions represent the major part of cement emissions and depend on the amount of clinker contained in one ton of cement, which varies between regions and over time (Andrew, 2018; Kermeli et al., 2019).

The direct CO_2 emissions come from the combustion of fossil fuels to heat the kiln and depend on the energy intensity of the kiln system and the carbon intensity of the fuel used. Clinker can be produced in wet, dry, semi-dry or semi-wet kilns depending on the moisture content of raw materials. The dry process is the most energy efficient kiln technology and is the most used one. The reduction of emissions in the cement sector is more related to a change in technological level than to a choice of production route as in the steel sector (van Ruijven et al., 2016).

The second production stage is the blending and grinding of clinker with other materials to produce cement (Branger and Sato, 2017). The conversion of primary energy into electricity used during this process also generates CO_2 emissions, which I refer to as indirect emissions.

I estimated process, direct and indirect emissions to produce one ton of cement in each cement producing country. The World Business Council for Sustainable Development (WBCSD) developed the Getting the Numbers Right (GNR) database synthesizing from 2005 to 2018 technical informations for more than 900 individual cement plants in different world regions. I extracted for the year 2015 the regional average values of clinker ratio, carbon intensity of the fuel mix, thermal energy consumption and cement plant power consumption (WBCSD, 2016). I applied these values to each countries included in the related world regions. Process emissions factor for clinker production was taken from Eggleston et al. (2006) and national CO_2 intensity of grid from IEA (2017a). Data and sources are synthesized in table 4.5.

Trade structure

I aim to calculate producing-based CO_2 emissions to be able to compare the results with national or regional carbon budget. This calls for representing in the modelling framework the trade structure to allocate CO_2 emissions to the producing countries for each ton of cement and steel used in a given country. The trade ratio - the ratio of traded products weight and global production weight - highlights which materials are particularly concerned by trade flow and imported or exported emissions. For pig iron, an intermediate product of steel manufacturing, the trade ratio was 8% in 2015 (World Steel Association, 2016) and for cement products 5% (Van Oss, 2016; UNSD, 2018). Cement is a commodity consumed mostly locally because of high transportation costs (Cao et al., 2017). I assumed the related trade effects associated on emissions for these products are negligible. I considered here one ton of cement produced in a country is consumed in the same one following Hache et al. (2020) and Denis-Ryan et al. (2016).

Conversely, the 2015 value of trade ratio for crude steel is 30% highlighting potential imported or exported emissions. To represent the steel trade structure, I first extracted from BACI database (Gaulier and Zignago, 2010) the imports and exports flows in weight of steel primary products for the year 2015 and for 207 countries. The commodity HS codes considered are from 7206 to 7306 following the World Steel Association guidelines (World Steel Association, 2011). I summed all the steel flows from one country to another and built a bilateral trade matrix where each element (i,j) represent the aggregated weight of steel primary products imported by the country i from the country j. I then incorporated in the matrix diagonal the domestic consumption assuming it as equal to the steel production minus the steel exports (in case of negative values, it was considered as null). I finally divided each line i by the apparent consumption - domestic production minus exports plus imports - of the country i. Steel production data was obtained from World Steel Association (2016). In each cell (i,j), the obtained value represent the share of country i consumption of steel primary products coming from the country j.

Sector	Quantity	Source	Comments
Electricity	Grid carbon intensity	IEA (2017a)	142 countries for the year 2015
Steel	Production route shares (%)	World Steel Association (2016)	89 countries for the year 2015
	Carbon intensity of the production routes (t CO_2/t steel)	Milford et al. (2013); Morfeldt et al. (2015)	see Table 3 for calculated values
	Electricity intensity of the production routes (kWh/t steel)	Milford et al. (2013); Morfeldt et al. (2015)	
	Bilateral traded flows (t steel)	BACI databse (Gaulier and Zignago, 2010)- HS codes from 7206 to 7306	207 countries for the year 2015
	Domestic production (t steel)	World Steel Association (2016)	91 countries for the year 2015
Cement	Clinker/cement ratio (%)	WBCSD (2016) - variable 92AGW	11 world regions for the year 2015
	Carbon intensity of the fuel mix (g CO_2/MJ)	WBCSD (2016) - variable 593AG	
	Thermal energy consumption (MJ/t clinker)	WBCSD (2016) - variable 93AG	
	Electricity intensity of cement production (MWh/t cement)	WBCSD (2016) - variable 33AGW	
	Clinker CO_2 emissions factor (t CO_2/t clinker)	Eggleston et al. (2006)	

Table 4.5 – Description of the data used to represent the steel and cement sectors.

Scenarii used for the dynamics of the production-based emissions determinants

I considered 3 alternative scenarios - *baseline*, *mitigation1*, *mitigation2* - to project the evolution of carbon intensity for cement and steel production, and grid (table 4.6). In the baseline scenario, all the parameters are assumed constant. In both low-carbon scenarios, the grid emissions reach 0 in 2050. I assumed the steel trade structure as constant for all scenarios but alternatives can be done which will change the allocation of producing-based CO_2 emissions. Carbon intensities of production values in 2030 and 2050 are based on the 2°C (2DS) and the

Beyond 2°C (B2DS) scenarios trajectory (IEA, 2017b, 2018) for respectively the *mitigation1* and the *mitigation2* alternatives. [1] The emissions reduction relies on using best available technologies to improve overall energy efficiency and deploying CO_2 capture technologies. It also implies for steel production to increase the global share of steel production for EAF route -both from scrap-based and DRI-based- to more than 50% and for cement production to decrease the clinker ratio. I assumed for all countries a linear evolution of carbon intensity from 2015 to 2030 and from 2030 to 2050 and also for grid emissions from 2015 to 2050.

	baseline	**mitigation1**	**mitigation2**
Grid emissions	Constant	0 in 2050	0 in 2050
Trade structure	Constant	Constant	Constant
Direct cement emissions	Constant	2030 : 0.52 t CO_2/t cement 2050 : 0.37 t CO_2/t cement	2030 : 0.41 t CO_2/t cement 2050 : 0.2 t CO_2/t cement
Direct steel emissions	Constant	2030 : 1 t CO_2/t cement 2050 : 0.7 t CO_2/t cement	2030 : 0.7 t CO_2/t cement 2050 : 0.33 t CO_2/t cement

Table 4.6 – Evolution of parameters in the different scenarios of cement and steel sectors decarbonisation

4.3 Results and discussion

Some results are presented in this section following the format *median value (lower value-upper value)* based on the different target values of in-use stock per capita tested to integrate uncertainties (see section 4.2.2 for description).

4.3.1 Cement and steel requirement to reach high infrastructure access

I estimate the steel and cement in-use stocks levels in line with providing globally high access rates for each infrastructure service. To do so, I used for each country as targets of stocks per capita either the value derived from global trends or the national stock per capita for the year 2014 (see methodology section for the different cases and underlying assumptions).

This translates into different material requirements depending on the infrastructure considered. On one hand, the global in-use material stock-both cement and steel aggregated-increases by a median value close to 10% on the period 2015-2030 to reach high access levels to water or electricity. Cumulative material demands equal to 7.17 (5.2-9.4) Gt of cement and 1.32 (1-1.7) Gt of steel for water and 8.8 (5.3-17.2) Gt of cement and 0.7 (0.5-1.7) Gt of steel for electricity. On the other hand, for transportation access, the aggregated in-use stock increase by a median value of 50% with material demands reaching 46.8 (26.2-73.3) Gt of cement and 5.9 (2.6-16.9) Gt of steel. Sanitation and shelter infrastructures give intermediary results with

1. The 2DS scenarios refers to a CO_2 emissions trajectory consistent with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100, with cumulative emissions of 1 170 Gt Co_2 between 2015 and 2100. The B2DS cumulative emissions from the energy sector of around 750 Gt CO_2 between 2015 and 2100, which is consistent with a 50% chance of limiting average future temperature increases to 1.75°C.

global in-use material stock increasing by a median value of 26%. In the modelling framework, global population increases by 15% from 2014 to 2030 which highlights the high contribution of access provision for sanitation, shelter and transport infrastructures.

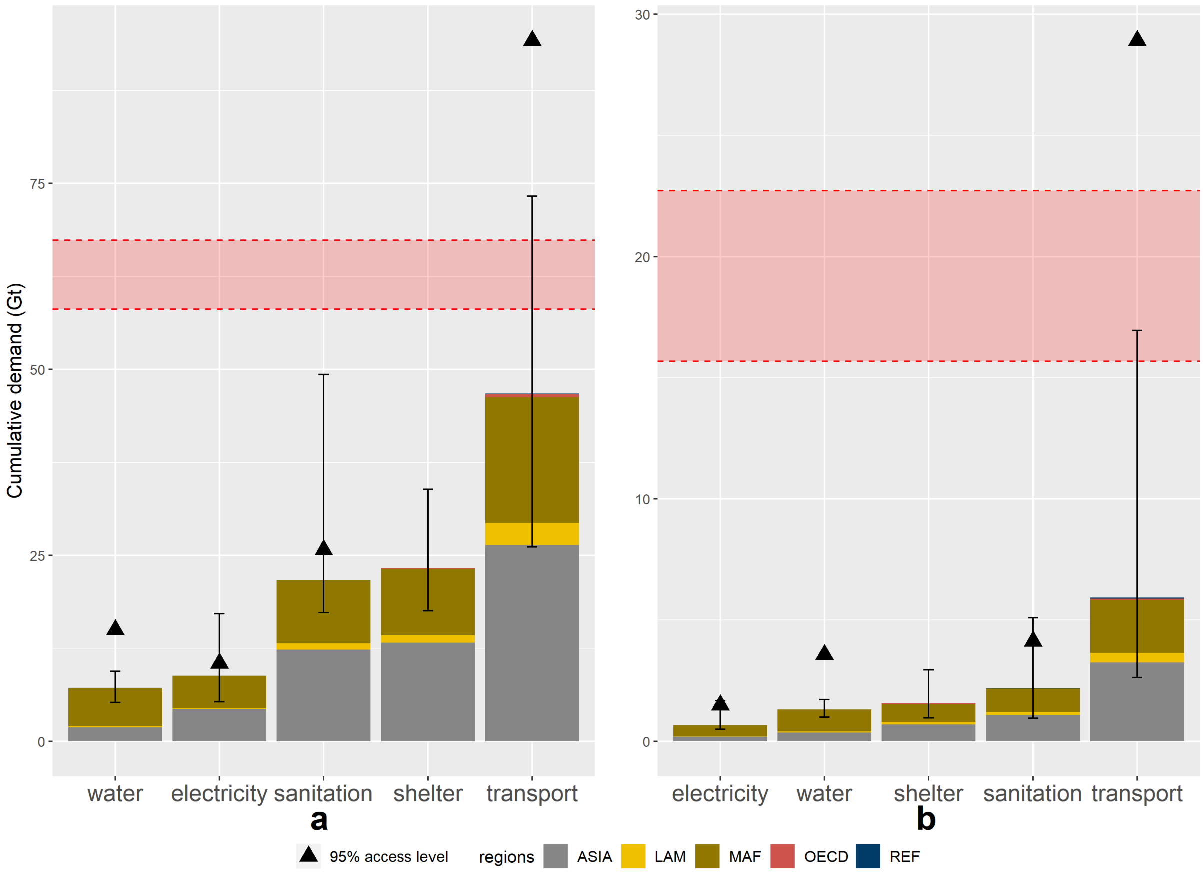


Figure 4.3 – Global cumulative material demand of cement (a) and steel (b) from 2015 to 2030 associated with meeting high access rate (90%) to different infrastructures. Material consumption levels are presented here in a sequential manner to be consistent with high access levels to the different infrastructure services. Red area represents the range of values from existing cement and steel production scenarios (van Ruijven et al., 2016; Edelenbosch et al., 2017; Winning et al., 2017; IEA, 2018). They are considered as 'baseline' trajectories meaning a continuation of past trends regarding the implementation of climate policies and energy material efficiencies. Error bars are constructed by deriving from past trends low or high target values of in use material stock per capita. Triangles represent the cumulative demand (median value) for a 95% access rate except for shelter where data is not available.

Some results below are presented at regional aggregations of the world to be consistent with the scenarios used for emissions comparison in the next section. The different world regions are Asia, Middle East & Africa (MAF), Latin America and the Carribean (LAM), Countries from the Reforming Economies of the Former Soviet Union (REF) and the OECD 1990 countries as well as EU members and candidates (OECD90). Composition of the regions can be found in the description of the Advance Scenarios Database (https://db1.ene.iiasa.ac.at/ADVANCEDB/dsd?Action=htm page=about).

Most of the material demand is concentrated in the developing regions ASIA and MAF which represent more than 90% of global demand regardless of the infrastructure considered (figure 4.3). Within these regions, material demand is unevenly distributed across countries (figure 4.4). Some countries contributes particularly to the global demand such as India, Nigeria, Indonesia, Pakistan, Ethiopia, Congo Dem.Rep, the Philippines and Tanzania where material needs are greater than 1 Gt to reach high access levels to transportation infrastructures. One factor is the high population growth over the period 2015-2030, ranging from 21 million inhabitants for Tanzania to 235 million inhabitants for India. Achieving high levels of access in 2030 appears as a challenge in MAF if looking at the relative growth of the in-use material stocks. Water and electricity access, which are the less material intensive objectives, induce a stock multiplication by a factor greater than 15 in Madagascar, Ethiopia, Niger, Tchad, Central African Republic, Congo Dem. Rep. and Guinea (figure 4.4).

I compare the cumulative material consumptions I estimated with existing scenarios of global steel and cement production on the same period (van Ruijven et al., 2016; Edelenbosch et al., 2017; Winning et al., 2017; IEA, 2018). I filtered out only baseline scenarios - continuation of past trends regarding the implementation of climate policies or energy/material efficiencies - to be consistent with my estimations. In these scenarios, demand for materials is related to economic activity and population without consideration of infrastructure needs.

The material demand for providing high access to water, electricity and shelter is consistent with these scenarios. The associated global cement and steel demands represent in the median cases respectively at most 35-40% and 10-15% of literature values. If I consider the case of reaching a quasi universal access with a 95% access rate, material needs are as expected higher but still consistent with the existing scenarios in the median cases (figure 4.3).

For sanitation and transportation, the consistency of the obtained cumulative material demands with existing steel and cement production scenarios is less clear, to a smaller extent for sanitation and to a larger extent for transport. This consistency is all the less obvious as we are not considering here the materials needed to maintain the capital already installed in 2014, which would lead to additional material needs, particularly in developed countries. For sanitation, it depends on the assumption about the target value of the in-service cement stock per capita. Considering the upper bound leads to a cumulative demand representing 73-84% of literature values. For transportation, median material needs reach the shares of 70-80% for cement and 22-32% for steel compared to values of scenarios from literature. The upper values estimated are even at a similar level for steel and above for cement. In the case of an access rate targeted of 95%, median cumulative demands for both materials are more than doubled increasing to levels higher than any existing values from literature. It calls into question the realism of achieving a high access level to transportation at the global scale in 2030.

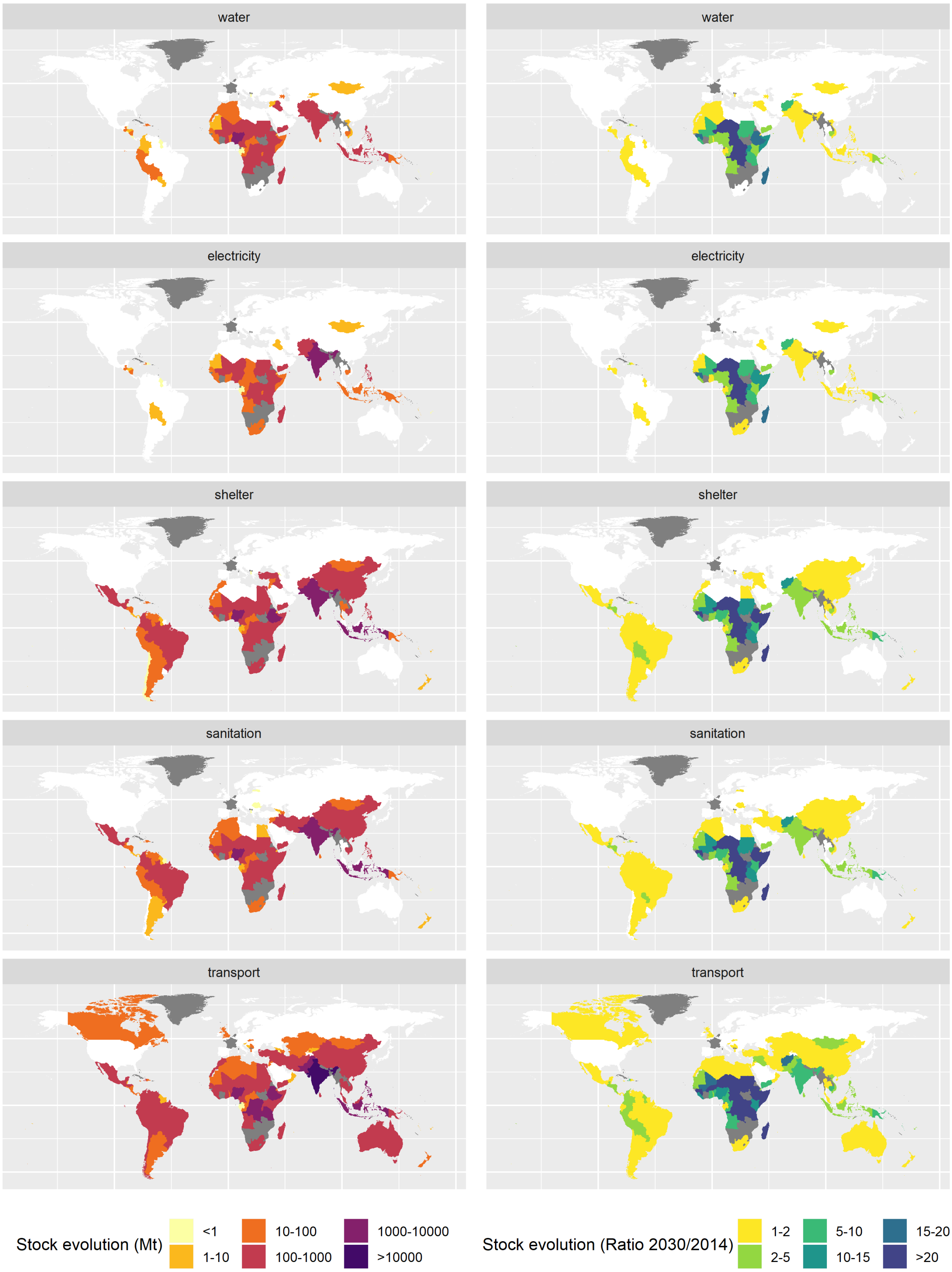


Figure 4.4 – Evolution of material stocks (median case) at national scale from 2015 to 2030 associated with reaching high infrastructures access

4.3.2 Embodied CO2 emissions

I quantified the CO_2 emissions from the production of materials needed to reach high access level to the different infrastructures in 2030 and also to maintain this access level until 2050. To do so, I applied three scenarios of emissions mitigations ambition in the cement and steel industries, described in the methodology section : *baseline*, *mitigation1* and *mitigation2* scenarios.

For baseline scenarios, I obtain cumulative emissions - including indirect emissions from primary energy conversion into electricity used during the manufacturing process - on the period 2015-2030 from 6.7 (4.2-13.8) Gt CO_2 for electricity to 39.8 (21.1-76.2) Gt CO_2 for transportation. Assuming that the access rate is maintained at a high level until 2050, cumulative emissions for the 2015-2050 period range from 9.7 (6.5-18.7) Gt CO_2 for electricity to 60.3 (27.7-94.1) Gt CO_2 for transportation. The major part of emissions come from cement production which represents in baseline scenarios between 67% and 85% of global cumulative emissions depending on the infrastructure considered. For *mitigation1* and *mitigation2* scenarios, the values obtained for transportation - the most material-intensive access objective-decrease to respectively 42.8 (23.3-78.4) and 37.3 (20.3-68.6) Gt CO_2.

These results are low compared to the recent literature on emissions induced by global infrastructure development (Table 4.7) for different reasons. Contrary to Krausmann et al. (2020) and Lamb and Rao (2015), I only focus on emissions from the steel and cement sector. Also, projections of steel and cement consumption are not driven by GDP or by a convergence of stocks towards richest countries levels but by a convergence of stock per capita to *sufficient* levels to assure high infrastructure access.

The cumulative emissions I obtained have been compared to the carbon budgets available related to Paris Agreement targets. Considering the highest emitting case- reaching a 90% transport access level in 2030 in baseline scenarios and assuming the upper target of in-use material stock per capita - would consume from 2015 to 2050 about 7% and 18% of the budgets available from 2015 to respectively achieve the 2°C and the 1.5°C targets. [2]

I also analyse the consistency at finer geographical and sectoral scale between the emissions I quantified and the existing CO_2 emissions pathways (figure 4.5). I use as reference low-carbon scenarios from the ADVANCE database (Luderer et al., 2018; Vrontisi et al., 2018). In this database, nine integrated assessments models have produced a set of global climate policy pathways consistent with limiting temperature increase in the 1.5-2°C range with different levels of short-term ambition. This database has also the advantage of giving quantification of CO_2 emissions in the industrial sector - both process and direct emissions from energy consumption - at the global scale and at a 5 world regions disaggregation level.

To be able to compare our results with the ADVANCE scenarios database, I first exclude in this part the indirect emissions - emissions induced by the conversion of primary energy into electricity used- which are aggregated to the electricity sector emissions in the ADVANCE

2. Carbon budgets available to achieve the 2°C or the 1.5 °C targets (66% chance) are respectively 1170 and 420 Gt CO_2 from 2018 (Rogelj et al., 2018). Adding the 106 Gt CO_2 that have been emitted from 2015 to 2017 (Project, 2019), I obtained $C0_2$ budgets of 1276 and 526 Gt CO_2 from 2015.

Study	**Infrastructure**	**Emissions (Gt CO_2)**	**Modelling framework**
This study	Electricity	9.7 (6.5-18.7)	2015-2050; CO_2 emissions from steel and cement sectors
	Water	10.3 (7.9-13.1)	
	Sanitation	28.2 (17.1-50.8)	
	Shelter	23.1 (17.4-34.1)	
	Transportation	60.3 (27.7-94.1)	
Krausmann et al. (2020)	Unspecified	500-880	GDP driven material consumption or convergence to in-use stock levels per capita of wealthiest countries ; 2018-2050 ; CO_2 emissions from manufacturing sectors
van Ruijven et al. (2016)	Unspecified	245	GDP driven material consumption ; 2015-2050 ; CO_2 emissions from manufacturing sectors
Lamb and Rao (2015)	Composite access indicator including sanitation, water and electricity	1003	2015 -2050 ; Energy consumption related to the access indicator value; GHG emissions from all sectors
Müller et al. (2013)	Unspecified	350	Convergence to in-use stock levels per capita of wealthiest countries ; 2008-2050 CO_2 emissions from cement, steel and aluminium sectors

Table 4.7 – Comparison of global cumulative emissions with the literature under a scenario without mitigation policies

database. Secondly, in order to have an order of magnitude of cement and steel sectors emissions in the database scenarios, I assumed that their share in the total industry sector emissions were similar over time and between the five world regions. The cumulative emissions of the industry sector extracted from the ADVANCE database scenarios were therefore multiplied by 0.55 following IEA (2017b). Finally, to be consistent with the decarbonisation scenarios I applied for the cement and steel sectors in the modelling framework, I selected in the ADVANCE database (i) the *2020 Med2C* and *2030 Med2C* scenarios as comparison references for the *mitigation1* estimations and (ii) on the *2020 WB2C* and *2030 WB2C* scenarios as comparison references for the *mitigation2* estimations.[3]

According to figure 4.5, providing globally a high level of access to the five infrastructures considered in this study leads to emissions related to cement and steel requirements lower than

3\.

2020 Med2C : Mitigation efforts strengthened after 2020 to limit cumulative 2011-2100 CO_2 emissions to 1600 Gt CO_2 ; more likely than not (>50%) to stay below 2°C.

2020 WB2C : Mitigation efforts strengthened after 2020 to limit cumulative 2011-2100 CO_2 emissions to 1000 Gt CO_2; >67% chance of staying below 2°C.

2030 Med2C : After implementing the NDCs without strengthening until 2030, carbon budget from the *2020 Med2C* scenario is adopted. Meets cumulative CO_2 emissions budget of *2020 Med2C* scenario.

2030 WB2C : After implementing the NDCs without strengthening until 2030, carbon budget from the *2020 WB2C* scenario is adopted. Meets cumulative CO_2 emissions budget of *2020 WB2C* scenario.

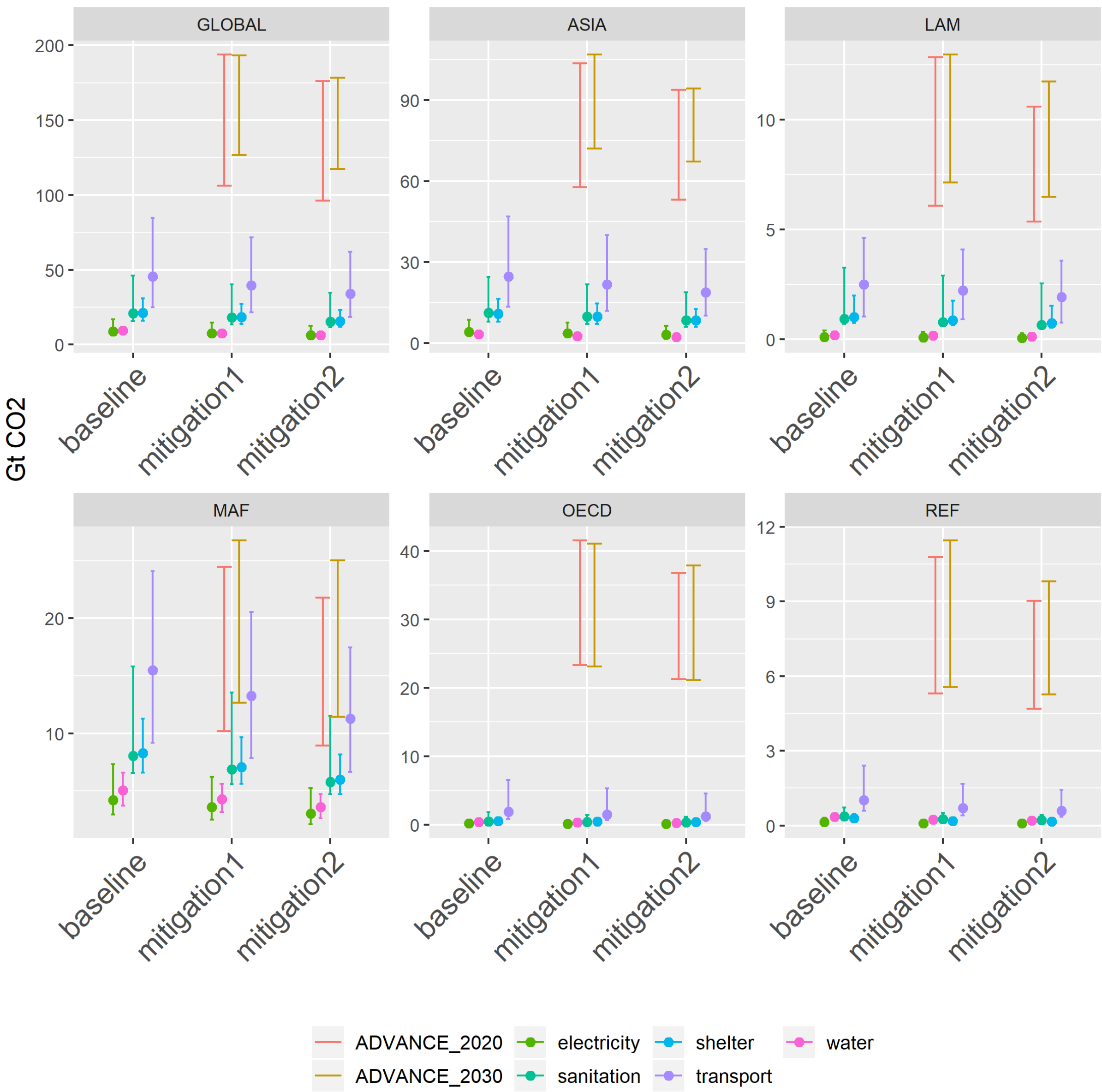


Figure 4.5 – Cumulative emissions (direct and process-related) from 2015 to 2050 associated with the cement and steel requirements to reach a 90% access level. Points represent the central value of the estimations for each combination of infrastructure and mitigation ambition in the cement and steel sector. Vertical line represent the range of cumulative emissions between the lower and upper target values of in-use stocks per capita. Bars shows the range of estimations from the ADVANCE scenarios database.

the cumulative emissions of these sectors from the Advance low-carbon scenarios on the same period. This result is also valid for the world regions ASIA, LAM, OECD and REF where the cumulative emissions resulting from this modelling represent a maximum of 67% of cumulative emissions from the corresponding reference scenarios (figure 4.5). However, for the MAF region, providing a high level of access to sanitation and transportation induces emission levels that are of the same magnitude order than some estimations of the Advance corresponding scenarios.

For transportation, our median estimates are even above the lower bounds of the ADVANCE scenarios estimations regardless of the climate ambition level.

4.4 Conclusion

Manufacturing the cement and steel materials required for infrastructures is an important source of greenhouse gas emissions. In this paper, I assess if high level of access to 5 basic infrastructure services - electricity, water, shelter, sanitation and transportation - can be provided at the global scale in 2030 and maintained until 2050 without compromising climate mitigation targets.

I first analysed the historical patterns of access rates in relation to the in-use cement and steel stocks per capita evolution. To do so, I used data samples on the period 1990-2014 covering between 96 and 184 countries depending on the infrastructure service examined. I highlight for each infrastructures access-material stock pair a correlation between these variables following a non-linear trend. It indicates from a certain access threshold and before reaching full access a small increase of access rate is associated with a high increase of infrastructure stocks and construction material needs. I show infrastructures access tends to follow a sequencing process along material stocks increase with electricity and water coming first, and transportation access last.

I then estimated the cement and steel needs to provide high access level to infrastructure services and the induced producing-based CO_2 emissions. To do so, I integrated in the modelling framework country-specific determinants of cement and steel consumption emissions such as trade and production technologies mix. I show cement and steel needs associated with reaching at global scale high access level (90%) in 2030 is concentrated in Asia and Middle-East & Africa regions. For this latter region, it induces notably for some countries a relative increase of stocks from 2015 to 2030 by a factor greater than 15. For water, electricity and shelter, I find global cement and steel needs for reaching in 2030 high access level that are consistent with existing global projections of cement and steel production. I obtain on the contrary less consistent results to a smaller extent for sanitation and to a larger extent for transportation. This calls into question the realism of achieving high levels of access to these infrastructures in the short term.

I highlight global cumulative embodied emissions from 2015 to 2050 from cement and steel requirements would represent small shares of the carbon budgets associated with the Paris agreement objectives. Assuming relative decoupling of cement and steel production from CO_2 emissions following existing industry roadmaps, I find on the same period lower cumulative emissions than those from existing low-carbon pathways, at the global scale and for four world regions over five. However this result doesn't stand for sanitation and transportation access in the Middle-east & Africa region.

This work has some limitations related to the chosen methodology. First, I estimated the construction material intensity of the economic system to provide access to an infrastructure type but not the materials specifically dedicated to each infrastructure service. A spatialized estimation of infrastructure and construction material needs would be an interesting approach, as recently carried out by Wenz et al. (2020) on road access, to quantify the emissions induced by the achievement of different access objectives at finer scales. Second, the trade structure evolution is assumed as constant and could be refined in order to assess the effects of heavy industries relocation or taxes on imported materials, as the United States recently did on Chinese steel. Finally, potential influencing factors of technology production choice such as capacity installed, production price or steel scrap availability should be integrated in future research.

Despite these limitations, I can provide a twofold interpretation based on this study. A first possible interpretation is that the 'carbon space' left in the existing global low-carbon scenarios is too limited to allow the basic infrastructures development in emerging countries in the short to medium term. While this ensures global efficiency, cost-optimal approaches used in these scenarios do not lead to equitable results as it disproportionately burdens less affluent countries (Leimbach and Giannousakis, 2019; van den Berg et al., 2019). A second possible interpretation is that relying solely on the decarbonisation of the steel and cement sectors is not enough to achieve the goals of access to basic infrastructure services by 2030 without compromising the climate mitigation targets. Other levers must therefore be used in the short term. Material efficiency is a first significant opportunity decreasing the cement and steel consumption for the same infrastructure services. This material efficiency could take different forms as a more intensive use of existing capital (lifetime extension, reducing per capita floor area...) or the reuse of steel and cement components (Pongiglione and Calderini, 2014; Hertwich et al., 2019). Substitution to less intensive construction materials is another potential lever such as using timber over steel and concrete in buildings construction (Heeren et al., 2015). More research is needed to understand the underlying drivers of cement and steel accumulation along the development process to implement relevant policy instruments for lower usage of cement and steel.

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Chapter 5

Conclusions and perspectives

Infrastructures are at the interplay of human development and climate change mitigation. These two objectives are interrelated so the infrastructures dynamics should close the existing infrastructure gap but also support the transition to carbon neutral economy. However, the infrastructure dynamics are subject to various constraints that can be bottlenecks to this conciliation. In this thesis, I have investigated how the global infrastructure stocks dynamics can contribute to the conciliation between human development and emissions reductions. I have focused on three bottlenecks to unite these issues: the carbon lock-in induced by the short term infrastructure development, the limited financing available for infrastructures investment and the carbon emissions space available for a sufficient infrastructures development in the short term.

In this conclusive chapter, I summarise the contributions of my research. I then interpret the results to highlight the conditions under which infrastructures can enable the conciliation between human development and emissions reduction. I also discuss the limits of this thesis. Finally, I conclude by outlining some avenues for future research.

5.1 Contributions of the thesis

Infrastructures are subject to technical, economical and institutional constraints inducing inertia in their evolution. They can prevent or delay transitions towards low-carbon systems and will influence the paths of future emissions for several decades. Developing infrastructure in the short term to meet human needs can thus induce carbon lock-in in the long term. It is therefore essential to assess to what extent the existing stock and its expected evolution is compatible, or not, with long-term climate objectives, and to identify levers available to make this stock "climate compatible". No study to date has comprehensively synthesized case studies and associated results on carbon lock-in. The rapid expansion of the scientific literature on the topic calls for scalable methods to deal with large numbers of articles.

In the chapter 2, I review the literature on case studies on carbon lock-in induced by infrastructures. I applied systematic mapping approach to provide a comprehensive, rigorous and transparent overview of the available evidence. To do so, I first extracted articles from bibliographic databases using a search query built with keywords related to carbon lock-in and infrastructures. I then screened this sample based on the abstracts using a machine-learning algorithm trained with an articles sample screened manually. I also applied a thematic analysis of policy implications to break out carbon lock-in by analysing 136 qualitative statements extracted from abstracts, discussions or conclusion sections.

I show that the literature has focused on the power generation sector and on global or national case studies. I identify 11 indicators used to quantify carbon lock-in which have been applied for different time frames of analysis : backward-looking, static for a given year, or forward-looking using scenarios. Committed emissions - cumulative emissions that would occur over the remaining entire operation lifetime of an asset - or stranded assets - premature retirement/retrofitting or under-utilization of existing assets along a given pathway - are the most used metrics, whereas institutional indicators are scarcely represented. Global committed emissions have slightly increased over time and coal power plants are a major contributor. They are highly exposed to risk of becoming stranded and delayed mitigation action increases this risk. Stranded assets may be even more important in the buildings sector in developed countries due to its high market value and low turnover rate. I identify through the thematic analysis three governance dimensions often mentioned to escape carbon lock-in, regardless of the instruments used : the stability of climate policy orientations, the coordination between actors and sectors and the legitimacy of targets and instruments used. Carbon price introduction is a policy instrument frequently mentioned but literature has consistently pointed out that it cannot prevent carbon lock-in if used alone. It should be complemented with technology mandates and financial support to low-carbon infrastructures deployment.

However, this presupposes that governments are able to finance these infrastructures at least partially. Many investments in the next decades will be needed for the construction of new infrastructures but also for the renovation and maintenance of the existing stock. Yet, both developed and developing countries have known in the last years chronic and substantial investments shortcomings, resulting in inadequate infrastructures notably in the transport sector. The impact of climate policies on transportation infrastructure investment is ambiguous. If the divergence between available financing and spending needs is prolonged, it might require a trade-offs between investments scaling-up for human development or investing in low-carbon capital to escape carbon lock-in. There were to date no estimates in the peer-reviewed literature of transportation infrastructures investment needs induced by the evolution of freight and passenger activity under climate constraints.

In the chapter 3, I quantified the investment needs in transportation infrastructures between 2015 and 2080 along high and low carbon pathways, considering roads, rail tracks, bus rapid transit lanes, high-speed rail tracks, and airports, at the global level and for five world regions. I first constructed transportation activity trends using a set of socioeconomic scenarios built with an integrated assessment model that explicitly represents the transportation sector and its determinants. I then performed an ex-post evaluation of the annual investment needs consistent with these trends of transportation activity. I took uncertainty into account by combining alternative assumptions regarding influential parameters in both steps of the methodology. I finally used a global sensitivity analysis to identify the main determinants of investment needs in low carbon-scenarios.

I show that contrary to the energy sector, global cumulative investment needs in transportation infrastructures are reduced in low-carbon scenarios compared with high-carbon pathways, all things being equal. This result is (i) robust to the uncertainties that influence transportation patterns and infrastructure expenditure, and (ii) is also valid at the regional level for the five world regions I analyzed. The overall diminution in investment needs is brought about in particular by a reduction in transportation activity. However, investment needs are still significant in comparison with other sectors and are of the same order of magnitude as those required in the energy sector. Investment needs relative to GDP are also high for some regions in comparison with the historical values. Rail utilization rate and road construction costs appear to be determining factors of future investment needs.

Even if the infrastructure investment burden is reducible in low-carbon pathways, the distribution of emissions reduction efforts between countries must be fair to engage them in the process of global climate action. National determined contributions are currently inconsistent with the Paris Agreement objective of limiting global average temperature increase to well below 2°C and should be enhanced. This 'ratcheting-up' process will most likely include some evaluation of fairness where the question of carbon emissions spaces to allow 'sufficient' development in developing countries should be of concern. However, emissions associated with infrastructure development are hardly reducible in the short term. I hence question the coherence between the SDGs of universal access to basic infrastructure services by 2030 and the emission reduction trajectories envisaged.

I address this question in the chapter 4 where I assess if high level of access to 5 basic infrastructure services - electricity, water, shelter, sanitation and transportation - can be provided at the global scale in 2030 and maintained until 2050 without compromising climate mitigation targets. Following historical patterns, I first quantified the cement and steel requirements in each country associated with providing high access levels. I then estimated the production-based carbon dioxide emissions related to manufacturing the cement and steel needs. To do so, I modeled influencing factors such as national production technologies mix, trade structure and mitigation actions in the cement and steel industries.

I show infrastructures access tends to follow a sequencing process along material stocks increase with electricity and water coming first, and transportation access last. Most of the cement and steel demand are concentrated in Asia, Middle-East and Africa. For all infrastructures services, achieving high access level in 2030 and keeping it until 2050 induces cumulative carbon dioxide emissions well below the overall carbon budgets related to Paris Agreement targets. However, I find providing high sanitation and transportation access in Middle-east and Africa conflicts with existing low-carbon pathways.

To sum-up, I interpret the results of the three chapters to highlight the conditions under which infrastructures can enable the conciliation between human development and emissions reduction.

Making the short-term infrastructure evolution compatible with long-term climate objectives

It is necessary to act as quickly as possible in order to avoid sinking further into carbon lock-in. Because of the interdependence between infrastructures, a public intervention is necessary to induce coordination between sectors. Climate policy needs to be stable over the long term so that stakeholders are confident and invest early in low-carbon infrastructures and stop investing in high carbon infrastructures. Climate targets and instruments must appear to be legitimate by for instance highlighting co-benefits and avoided costs or creating of participatory processes. Although carbon pricing has dominated climate policy debates for decades, it does not stand up to the examination of the three conditions mentioned above (e.g. the Yellow Vests protest in France against the planned doubling in the carbon tax (Douenne and Fabre, 2020)) and does not appear to be sufficient by itself to stop carbon lock-in or solve the problem of stranded assets.

Releasing the financial burden to be able to ensure both investments scaling-up for human development and investment in low-carbon capital
Acting early limits the financial risk induced by stranded assets. It is also crucial to limit the investment needs in infrastructures in construction, operation and maintenance. While investments are going to be substantial in the energy sector, this can be counterbalanced by a reduction in the transportation sector through actions on two levers : the reduction of road construction costs and the optimization of rail network utilization. The latter is crucial to limit investment needs for countries aiming at a modal shift from road to rail.

Ensuring sufficient carbon space for critical infrastructure development.
Cement and steel decarbonisation will be too slow to limit in the short term the emissions due to the installation of new capital to fulfill basic human needs. It is then crucial to limit the usage of these materials by implementing policies favouring construction material efficiency. Also, substitution to less carbon intensive construction materials can be sought.

The feasibility of the conciliation between human development and emissions reductions depends on technical, political and economic conditions which evolve over time creating a 'dynamic feasibility space' (Jewell and Cherp, 2020). This thesis highlights some conditions related to the infrastructures dynamics to keep this space as large as possible over time. The current exceptional conditions with the announced government stimulus in different countries could be an opportunity to integrate these elements (Andrijevic et al., 2020; Hepburn et al., 2020).

5.2 Limitations of the thesis

There are limits to this thesis, which I outline here. First of all, the thesis has specific limitations to the methodology used in each chapter. In the chapter 2, I realized a systematic map of the literature on carbon lock-in induced by infrastructures. Some articles have been omitted because the terminology used can vary between research strands as carbon lock-in is a transdisplinary topic. In addition, although the authors defined commonly criteria for publications inclusion/exclusion, the manual filtering of articles can be subject to a certain amount of subjectivity . Although time consuming, one way of limiting this potential bias would have been to jointly check all the excluded articles. A second point is that, because of the literature focus on the electricity sector, some of the cited policy implications can apply more to the latter than to other sectors. This calls for more studies outside the electricity sector.

In the chapter 3, I estimated transport infrastructure needs in line with the transport sector activity scenarios derived from the IAM Imaclim-R. I used an ex-post approach which implies that I integrated the effect of economic growth on mobility and infrastructure demands but not the feedback of infrastructure investment on GDP. Including this effect requires answering other questions. Its order of magnitude is heterogeneous across the periods and countries studied (Holmgren and Merkel, 2017). Representing this effect would imply to disentangle the different channels through which infrastructures investment impact economic growth. Moreover, there is still a lack of consensus between economists of whether supplementary infrastructures investments induce crowding-out of financial resources or not, which would lead to very different short term growth (Mercure et al., 2019). Another caveat is that I did not integrate in the different scenarios the impact of climate change on transportation infrastructures which would induce supplementary supplementary costs of adaptation or maintenance (Chinowsky et al., 2019).

In the chapter 4, I estimated the cement and steel needs to provide high access level to infrastructure services and the induced producing-based CO_2 emissions. The trade structure evolution is assumed as constant and could be refined in order to assess the effects of heavy industries relocation or taxes on imported materials. I also assumed for some scenarios emissions reduction in the steel and cement sector without addressing their affordability or feasibility. Finally, global cement and steel requirements have been compared to global material demand scenarios, but the induced productions in each country have not been compared to existing production capacity which could be a limiting factor.

Secondly, this thesis as a whole partially answers the question of how the dynamics of infrastructures can enable the reconciliation of human development and emission reduction issues. The first reason is that I study in this thesis three bottlenecks to this conciliation but in isolation. Thus, I show that the implementation of climate policies reduces the need for investment in transport infrastructures, notably by reducing transport activity. However, I do not know whether this trajectory of activity in the transport sector is 'sufficient' to allow the satisfaction of basic human needs in the short or medium term. Conversely, I estimated the cement and steel needs necessary to achieve high levels of access to infrastructure services. However, I do not know whether the associated infrastructure investments are bearable by the countries. Moreover, the countries concerned by the issue of stranded assets may be in financial difficulty and may not be able to invest in basic infrastructure.

The second reason is that, using my results, I identify several determinants on which it is relevant to act, such as limiting the use of cement and steel in infrastructures or increasing the capacity of the rail network. However, the room for manoeuvre on these determinants depends on local conditions that need to be analysed in more depth in further research.

5.3 Future researches

I plan to do further research in order to overcome some of the limitations of this thesis and to go further on the subject of the evolution of infrastructures as an element of feasibility of the development-climate conciliation.

First of all, it is crucial to further research carbon lock-in in the energy demand sector and in particular on the risks of stranded assets. There is a scarce literature on this topic while the amounts at stake could be very high notably in the buildings sector (Saygin et al., 2019; Muldoon-Smith and Greenhalgh, 2019; Oshiro and Fujimori, 2020). Research could be based on real estate transaction data available in many countries.

Secondly, carbon lock-in is a phenomenon based on multiple constraints, be they technical, institutional or economic. Erickson et al. (2015) has quantified carbon lock-in in a multidimensional way by integrating four dimensions of carbon lock-in and highlighting that certain types of capital, despite relatively short lifetimes, contribute significantly to carbon lock-in. It might be interesting to develop a multidimensional carbon lock-in indicator integrating its different dimensions, in the way that has been done for some development indicators (Anand and Sen, 1994; Alkire and Santos, 2010). This would make it easier to communicate the room for manoeuvre of each country and each sector at a given moment.

Finally, it would be relevant to explicitly represent within an integrated assessment model the evolution of access to infrastructure and to integrate into the mitigation costs the investment needs in infrastructures and the stranded assets in order to analyse the trade-offs and synergies on these issues. This would provide new insights into the desirability and feasibility of low-carbon scenarios (Jewell and Cherp, 2020). If a policy to reduce emissions must actually be put in place as quickly as possible, economists can no longer economize on an analysis of its feasibility.

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