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# Methodological Approach to Account for Disaster Risks in Life Cycle Assessment: Application to the Energy Production Sector

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**THÈSE DE DOCTORAT**  
**DE L'UNIVERSITÉ PSL**

Préparée à Mines Paris-PSL

**Methodological Approach to Account for Disaster Risks  
in Life Cycle Assessment. Application to the Energy  
Production Sector**

*Approche Méthodologique pour Prendre en Compte les Risques de  
Catastrophes dans l'Analyse de Cycle de Vie. Application au  
Secteur de la Production d'Énergie*

Soutenue par

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Le 10 octobre 2024

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*“¡Momento!”*

In loving memory of  
Matilde Buendía Gómez, M.D.  
who despite the risks,  
always chose to be good  
and compassionate to all.  
*Te extraño, Abu.*



## Messages of Gratitude

*Remerciements* in French and *Agradecimientos* in Spanish, these words convey the meaning of performing acts of gratitude. These are the names that I would have given this section if my thesis were written in either of these languages. The conventional English translation for these terms is 'Acknowledgements', which means "recognition or favorable notice of an act or achievement" (Merriam Webster dictionary). It didn't sound right to me, because I could not find where the sense of showing gratitude was. Therefore, this section has a more appropriate name to frame what I wish to convey.

**On the academic side**, I want to wholeheartedly thank my three supervisors, Philippe, Paula, and Eric. This PhD would've definitely been something entirely different if it weren't for the time and effort you all dedicated to guiding and supporting me both in the theoretical and the technical aspects. Your guidance and passion for the project kept me motivated even in the most difficult periods, and I continue to carry the same passion for the projects that are to come. I hope we keep working together in the near future. Thank you for giving me all the space and opportunities I have needed to develop my academic and personal skills.

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## Résumé étendu

Dans le contexte actuel de la transition énergétique, de nouveaux systèmes de production d'énergie sont développés pour répondre à la demande croissante d'énergie et d'électricité. Ces projets doivent être développés en tenant compte d'objectifs ambitieux établis par la communauté mondiale, qui visent à minimiser les effets négatifs que ces projets d'infrastructures critiques pourraient avoir sur la santé humaine et environnementale. Parmi les outils disponibles pour évaluer ces impacts potentiels, le plus utilisé est l'Analyse du Cycle de Vie (ACV). L'ACV est un outil d'aide à la décision multicritère normalisé (ISO 14040, 2006) qui prend en compte chaque étape du cycle de vie d'un système de produit pour estimer ses impacts environnementaux.

Dans le contexte du changement climatique, les questions environnementales ne sont pas les seules préoccupations des décideurs potentiels. Ils doivent également tenir compte de l'intensité et de la fréquence accrues des phénomènes dangereux, tels que les catastrophes naturelles. Les systèmes de production d'énergie et les infrastructures critiques en général sont plus exposés et potentiellement vulnérables à ces aléas. Ces situations pourraient entraîner des conséquences dévastatrices pour les communautés et l'environnement. Par exemple, dans une centrale photovoltaïque (PV), les conséquences des catastrophes telles que les tempêtes décennales seraient liées aux dommages physiques causés aux structures de soutien, aux panneaux PV et à d'autres composants électriques. Ces dommages provoquent des interruptions dans le service de production d'électricité. Pour rétablir le service et remettre le système en état de fonctionnement normal, les composants endommagés doivent être réparés ou remplacés. Cela nécessite la mobilisation de l'ensemble de la chaîne d'approvisionnement, en particulier dans le cas du remplacement des composants, ce qui implique des processus ayant des potentiels impacts supplémentaires et non négligeables sur l'environnement.

L'estimation de ces impacts potentiels en utilisant l'approche ACV standardisée est limitante car cette évaluation s'adresse conventionnellement aux systèmes de produits fonctionnant dans des situations moyennes ou stationnaires. Ainsi, les déviations potentielles à ces situations moyennes causées par les risques de catastrophe ne sont pas prises en compte. Cela a été identifié comme un défi pertinent pour la recherche en ACV qui, si abordé au niveau de l'inventaire, pourrait permettre d'obtenir des résultats d'impact environnemental plus complets pouvant mieux soutenir les décideurs dès la phase de planification d'un projet d'infrastructure critique.

L'objectif de cette thèse de doctorat est de permettre de prendre en compte les conséquences de l'évolution des risques de catastrophes sur la performance opérationnelle et environnementale des infrastructures critiques à moyen et long terme en se concentrant sur les centrales de production d'énergie.

Pour atteindre cet objectif et relever le défi scientifique, une approche basée sur le développement d'un module d'inventaire novateur pour l'ACV est proposée. Ce module présente une démarche méthodologique pour (i) guider la définition d'un groupe de scénarios représentatifs de l'évolution potentielle des risques de catastrophe et de leurs effets sur un territoire et les infrastructures étudiées, et pour chaque scénario, (ii) la définition des trajectoires spécifiques décrivant les conséquences de différentes alternatives décisionnelles sur la performance opérationnelle et environnementale des infrastructures critiques.

Trois questions scientifiques ont été posées pour aborder le développement méthodologique :



1. Comment pourrait-on guider de manière cohérente la formulation d'un problème spécifique intégrant des concepts issus de différents domaines de connaissances ?
2. Comment pourrait-on élaborer des scénarios représentatifs d'évolutions possibles des risques de catastrophes ? Dans le contexte de ces scénarios, comment pourrait-on aborder les conséquences des événements de catastrophe dans l'analyse de la performance de l'infrastructure critique tout au long de sa durée de vie ?
3. Comment pourrait-on intégrer les résultats issus des scénarios guidés par les risques de catastrophes au niveau de l'Inventaire du Cycle de Vie (ICV) afin qu'ils représentent des éléments pertinents pour la prise de décision ? Comment peut-on présenter les résultats de l'ACV produits en utilisant ces scénarios de manière qu'ils soient utiles et pertinents pour les décideurs ?

Chaque question est liée à un défi spécifique, et chacune d'elles a été abordée de manière distincte. Le premier défi était d'organiser un cadre conceptuel pour résoudre un problème multidisciplinaire, incluant les domaines de l'ACV, des risques de catastrophe et des infrastructures critiques. Cela a été abordé à travers l'élaboration d'une ontologie spécifique à une application, appelée *OntoDRUID*. Cette ontologie aide à établir les concepts fondamentaux et les relations qui soutiennent la conception d'une méthode prospective multidisciplinaire. Le deuxième défi concernait la conception de la méthode elle-même, et comment représenter les conséquences des événements catastrophiques sur l'infrastructure par l'analyse de scénarios. Cela a abouti à l'élaboration d'une méthode de développement de scénarios guidée par les risques de catastrophes en évolution, qui est compatible avec l'ACV. Le troisième défi concernait l'application de la méthode à un étude de cas illustrative en ACV pour tester ses apports, ses limites et ses domaines d'opportunité en tant qu'outil de soutien à la décision.

Le résultat de ces efforts est le module d'inventaire novateur pour l'ACV, appelé la méthode de Définition de Scénarios guidée par les Risques de Catastrophe (DRUID) - Module ICV (Figure i). Il s'agit d'un cadre méthodologique avec des lignes directrices et des recommandations qui vise à étudier les conséquences potentielles des risques de catastrophe évoluant sur la performance environnementale des infrastructures critiques. La méthode DRUID se compose de quatre étapes générales : 1) Définition du problème, 2) Construction de scénarios, 3) Étude de la résilience de l'infrastructure et 4) Transfert de scénarios à l'ICV. La méthode a été appliquée sur une étude de cas illustrative en ACV liée au secteur PV en France.

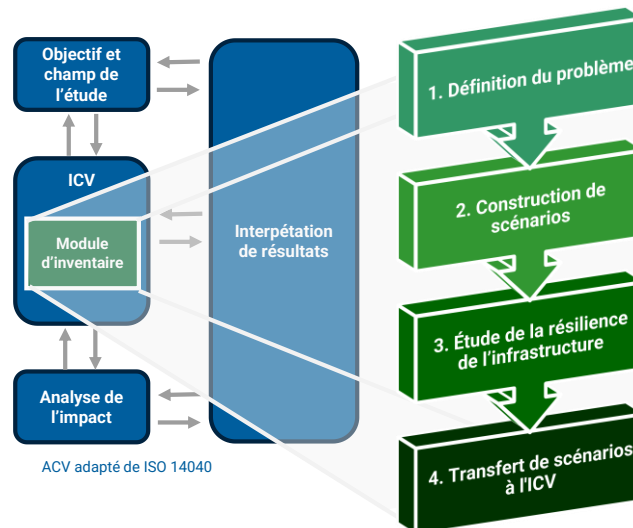


Figure i. Définition de Scénarios guidée par les Risques de Catastrophe (DRUID) - Module ICV

Plus précisément, l'application présente une étude de cas comparative en ACV pour une seule infrastructure PV dans le contexte du développement du secteur énergétique PV dans un territoire montagneux avec un climat méditerranéen dans le sud de la France, à l'horizon 2050. Les données climatiques de la région Provence-Alpes-Côte d'Azur (PACA) ont été utilisées comme références. L'étude compare les résultats en ACV obtenus à partir d'un scénario de référence par rapport aux résultats obtenus en utilisant des scénarios DRUID qui prennent en compte le risque de vents violents. Il est important de noter que les résultats présentés dans cette thèse sont exploratoires et non exploitables en raison de la portée limitée de l'étude de cas, qui ne considère que l'influence d'une seule source de danger sans prendre en compte l'influence de risques complexes.

## La Méthode DRUID

### Étape 1 : Définition du problème

La première étape de la méthode DRUID est la définition du problème (Figure i), qui établit les bases nécessaires pour aborder le problème. L'objectif est de poser le problème avec précision et de recueillir les informations nécessaires pour construire les scénarios. Le défi de conception de cette étape est lié à la grande variété de concepts et de données à recueillir ainsi qu'à la manière de les organiser. L'approche adoptée consiste en des lignes directrices orientées vers des questions qui aident le praticien à identifier les éléments essentiels du problème et à recueillir les données nécessaires. Trois tâches principales sont réalisées.

L'objectif de la **première tâche** est de définir le problème en utilisant la structure canonique du problème DRUID, qui guide le praticien pour identifier les six éléments essentiels du problème :

L'évolution des risques <type> induite par <tendances> affectera-t-elle significativement la performance <type de performance> de <infrastructure critique> située <location> dans <horizon temporel> ?

Dans le cadre de l'étude de cas, le problème DRUID est défini comme : L'évolution des risques de vents violents induite par le changement climatique et changement territorial affectera-t-elle significativement la performance environnementale du cycle de vie d'une centrale PV située dans une

région montagneuse à climat méditerranéen dans le sud de la France au cours des 30 prochaines années ?

L'objectif de la **deuxième tâche** est de recueillir des informations liées aux éléments essentiels de l'étude et d'identifier les changements futurs -tendances- de ces éléments. Les informations sont collectées sur quatre groupes thématiques : (1) Le groupe infrastructure concerne l'objet de l'étude, lié aux spécificités techniques de l'infrastructure ; (2) Le groupe territoire concerne les caractéristiques régionales et géographiques du lieu où l'infrastructure est installée ; (3) Le groupe risque et aléa concerne la nature, l'intensité et la fréquence des risques auxquels l'infrastructure étudiée est exposée ; (4) Le groupe capacité d'absorption concerne les mesures que l'infrastructure a en place pour faire face aux effets de différents types d'aléas. Ces informations peuvent être collectées à partir de sources publiques ou privées, de la littérature scientifique et grâce à des entretiens avec des acteurs spécifiques au domaine.

L'objectif de la troisième tâche est d'organiser les informations collectées pour chaque groupe thématique. Pour l'étude de cas, cela inclut : des détails techniques sur la centrale PV, la couverture du sol dans la région montagneuse, la ressource solaire (irradiance globale annuelle horizontale en kWh/m<sup>2</sup>) pour estimer la production d'électricité, les rafales de vent (données historiques et prévisions) pour les risques de vents violents, et la résistance mécanique des panneaux PV pour la capacité d'absorption. Enfin, trois tendances ont été identifiées : (i) les scénarios de consommation d'énergie en France à 2050 proposés par RTE (Réseau de transport d'électricité), (ii) les changements d'utilisation de sols et de couverture végétale, et (iii) les trajectoires socio-économiques (SSP) et climatiques (RCP). Ces tendances représentent la manière dont les éléments dans chaque groupe thématique pourraient évoluer.

## **Étape 2 : Construction de scénarios**

La deuxième étape de la méthode DRUID est la construction de scénarios (Figure i). L'objectif est de développer des scénarios représentatifs des évolutions potentielles de l'infrastructure et de son environnement. Le défi de conception de cette étape était la création de scénarios cohérents tout en tenant compte de la diversité d'éléments quantitatifs et qualitatifs contenus dans l'espace problème DRUID. Pour répondre à cela, la littérature liée aux méthodes orientées vers le futur a été consultée, notamment les méthodes de développement de scénarios, à partir desquelles l'Analyse Morphologique Générale (AMG) a été identifiée comme un outil utile.

L'AMG est une approche de modélisation conceptuelle qui facilite l'évaluation des relations possibles entre les éléments contenus dans un problème multi-dimensionnel. Dans le développement de scénarios, l'AMG a été utilisée pour explorer des ensembles de scénarios plausibles, cohérents et pertinents et établir des développements futurs possibles avec l'objectif d'utiliser les informations pour prendre des décisions pertinentes. Grâce à son approche visuelle, l'AMG facilite les interactions et les discussions entre les acteurs concernés. De plus, avec l'aide des outils logiciels et de la documentation générée tout au long du processus, il est possible de retracer l'origine des résultats obtenus avec l'AMG, ce qui permet une certaine reproductibilité et transparence.

Par conséquent, cette phase est basée sur l'AMG afin de décrire des scénarios représentatifs et leurs narratives. Elle se compose de cinq tâches.

L'objectif de la **première tâche** est de fournir une vue d'ensemble de tous les scénarios possibles qui pourraient être évalués. Pour commencer à construire les scénarios, l'espace problème DRUID est

transformé en boîte morphologique DRUID. Cette boîte décrit l'univers des scénarios possibles sur la base de la manière dont les tendances liées au problème DRUID pourraient affecter le futur. Ainsi, les conditions qui décrivent les évolutions de ces tendances doivent être clairement définies. Dans l'étude de cas, il existe trois tendances :

- 1) Les trajectoires SSP-RCP, avec trois conditions :
  - a. La durabilité, impliquant un développement inclusif et où les limites environnementales sont respectées,
  - b. Le « chemin du milieu », où les tendances sociales, économiques et technologiques suivent des modèles historiques.
  - c. Le développement alimenté par les fossiles, où il y a une progression technologique rapide et le développement du capital humain et où les marchés mondiaux sont de plus en plus intégrés.
- 2) Les scénarios de consommation RTE, avec trois conditions :
  - a. La trajectoire de référence, où il y a une électrification progressive visant à remplacer les combustibles fossiles et une forte ambition d'augmenter l'efficacité énergétique.
  - b. La trajectoire de sobriété, où les habitudes de vie évoluent vers une plus grande sobriété en termes d'utilisation et de consommation, entraînant une réduction générale des besoins énergétiques.
  - c. La réindustrialisation profonde, où des investissements sont réalisés dans des secteurs technologiques avancés et stratégiques et les processus à fortes émissions sont délocalisés à l'étranger pour réduire l'empreinte carbone de la consommation française.
- 3) Le changement d'utilisation des sols et de couverture végétale (LUC, « land use change » en anglais), avec trois conditions : aucun changement de LUC, désertification, et reforestation.

En combinant chaque valeur possible de chaque tendance, 27 scénarios potentiels existent dans l'univers des scénarios. Cependant, toutes ces possibilités ne sont peut-être pas réalistes.

L'objectif de la **deuxième tâche** est de réduire le nombre de scénarios pour ne laisser que des alternatives possibles et plausibles à travers une évaluation de cohérence transversale (CCA en anglais). Cela implique une analyse comparative entre les valeurs des tendances en termes de cohérence logique, empirique et normative. Dans l'étude de cas, des évaluations de cohérence normative ont été utilisées lors de la comparaison des 27 paires de conditions - SSP-RCPs vs RTE, SSP-RCPs vs LUC et RTE vs LUC -, réduisant ainsi le nombre de scénarios à 12.

L'objectif de la **troisième tâche** est de regrouper les scénarios qui partagent des caractéristiques prédominantes. L'approche recommandée est d'établir des classes de scénarios basées sur une tendance prédominante, ce qui implique de choisir une tendance prédominante à partir de la boîte morphologique DRUID en fonction de certains critères. Le critère de sélection recommandé est basé sur l'ampleur d'influence de la tendance, ce qui signifie que la tendance la plus importante est probablement celle qui a l'influence la plus large. Pour chaque classe de scénarios, les caractéristiques représentatives doivent être décrites. Dans l'étude de cas, la tendance prédominante choisie est le parcours SSP-RCP en raison de son ampleur mondiale, ce qui aide à établir trois classes de scénarios pour les 12 scénarios.

L'objectif de la **quatrième tâche** est de choisir les scénarios représentatifs qui seront évalués dans les étapes suivantes. La manière d'aborder cette sélection dépend entièrement du praticien et des objectifs de l'étude. Cependant, il est recommandé de sélectionner un scénario par classe de

scénarios qui représente des situations extrêmement différentes pour une étude comparative ultérieure. Pour l'étude de cas illustrative, les résultats ne sont présentés que pour un seul scénario : le « chemin du milieu » avec la trajectoire de référence RTE et aucun changement de LULC.

L'objectif de la **cinquième tâche** est de décrire les caractéristiques essentielles de chaque scénario représentatif choisi compte tenu des tendances liées. Cette description est la « narrative du scénario », et elle se compose de quatre contextes qui décrivent les évolutions potentielles tout au long de la période d'évaluation, qui dans l'étude de cas est de 30 ans :

- 1) Le contexte du scénario, basé sur la description générale des tendances. Dans l'étude de cas, les modèles historiques sont suivis, des changements économiques et sociaux entravent la progression vers les objectifs de développement durable, le couvert végétal ne change pas dans la région, et en France, l'objectif est d'améliorer l'efficacité de l'utilisation de l'énergie, car on s'attend à une demande énergétique accrue.
- 2) Le contexte des infrastructures, qui décrit l'état du secteur des infrastructures, du marché et des changements technologiques attendus. Dans l'étude de cas, cela concerne le marché des technologies PV, les investissements sont orientés vers des technologies au silicium cristallin (Si) plus fiables et efficaces, et les technologies produites proviennent principalement de Chine.
- 3) Le contexte territorial, qui décrit les caractéristiques régionales pertinentes. Dans l'étude de cas, la variation annuelle de la population saisonnière constitue un défi pour les autorités régionales pour atteindre les objectifs de développement durable, influencée par la demande énergétique variable.
- 4) Le contexte du risque de catastrophe, qui décrit le profil des dangers et des capacités d'absorption. Dans l'étude de cas, les vents forts sont des événements rares qui sont décrits grâce au profil régional des rafales de vent, représenté par une distribution de Weibull avec une valeur moyenne de 18 m/s et quelques valeurs supérieures à 50 m/s. La capacité d'absorption est basée sur la résistance aux charges mécaniques des modules PV, en considérant que les mesures de résilience ne changent pas tout au long de la période.

### **Étape 3 : Étude de la résilience de l'infrastructure**

La troisième étape de la méthode DRUID est l'étude de la résilience de l'infrastructure (Figure i). L'objectif est d'étudier l'évolution de la résilience des infrastructures sous certaines conditions de scénarios. Le défi de conception de cette étape était de relier les effets des risques de catastrophe à la performance des infrastructures. L'approche adoptée consiste à étudier la résilience en termes de mesures prises pour faire face aux catastrophes, la capacité d'absorption, comme abordé dans le modèle « Disaster Resilience of Place » (DROP).

Le modèle DROP prend en compte les mesures de prévention et de préparation avant un événement dangereux, les conséquences sur l'environnement, et le degré de rétablissement dépendant de la capacité à absorber l'impact et des mesures de résilience prises à long terme. Le concept de résilience par rapport à la performance est également clé pour cette étude, car lorsqu'un événement de risque de catastrophe se produit, la performance de l'infrastructure se dégrade. À ce stade, les décideurs doivent intervenir pour déterminer comment remettre le système en fonctionnement normal, ou si cette situation est une opportunité d'améliorer la performance globale du système.

En intégrant ces concepts, les scénarios représentatifs (résultats de l'étape 2) peuvent être utilisés pour évaluer les effets des risques de catastrophe sur la performance des infrastructures. Cela produit un inventaire des dommages et du type de décisions prises.

L'évaluation est effectuée en utilisant le modèle de résilience proposé avec les caractéristiques suivantes :

- *Les aléas*, qui sont décrits par leur intensité et leur probabilité d'occurrence sur une période donnée. Dans l'étude de cas, cela concerne les rafales de vent tout au long de la période de 30 ans.
- *La capacité d'absorption*, qui peut être divisée en classes ou niveaux représentant différents seuils de défaillance probable ou de conditions de dommage des infrastructures par rapport à différentes intensités d'aléa. Cette capacité d'absorption est décrite par des courbes de fragilité, dans l'étude de cas liées à la résistance mécanique des panneaux PV aux rafales de vent.
- *Les niveaux de choc*, qui décrivent l'intensité des dommages que les infrastructures ont subis après comparaison de la probabilité d'occurrence de l'aléa avec la capacité d'absorption associée. Dans l'étude de cas, le choc correspond au pourcentage de capacité de production perdue en kWc.
- *Le type d'événement*, qui établit le type d'événement qui s'est produit : aucun événement, des événements de réparation et des événements de remplacement. Réparer signifie que la capacité de production de l'infrastructure critique est rétablie à son niveau initial pour l'itération suivante, dans ce cas une année. Dans l'étude de cas, cela représente le remplacement des composants endommagés par de nouveaux composants ayant les mêmes caractéristiques. Remplacer signifie que la capacité de production de l'infrastructure critique est améliorée pour l'année suivante. Dans l'étude de cas, cela concerne la remise en puissance (« repowering » en anglais), c'est-à-dire que tous les composants de la centrale PV sont remplacés par des technologies performantes, augmentant la capacité installée tout en utilisant la même superficie préparée pour la centrale d'origine.
- *Les seuils de performance*, qui sont utilisés pour déterminer si l'infrastructure doit être réparée ou remplacée après un choc. Une limite supérieure et une limite inférieure sont établies. Si la performance est au-dessus de la limite supérieure, alors un événement de réparation se produit. Si la performance est en dessous de la limite inférieure, un événement de remplacement se produit. Si la performance se situe entre les deux seuils, le type d'événement est déterminé par le décideur. Dans l'étude de cas, la valeur de la limite supérieure correspond à la production annuelle d'électricité attendue en kWh à la 30<sup>ème</sup> année d'exploitation de la centrale PV sans dommage (1 134 MWh), et les deux limites inférieures ont été testées avec des valeurs correspondant à 50 % et 75 % de la valeur de la limite supérieure.
- *Le profil du décideur*, qui décrit la probabilité qu'un acteur décide soit de réparer uniquement les dommages causés ou de remplacer l'ensemble de l'infrastructure, lorsqu'il est confronté à une situation située entre les seuils de réparation et de remplacement. Dans l'étude de cas, quatre profils ont été testés avec des probabilités différentes de choisir le remplacement (remise en puissance) lorsqu'ils peuvent : minimum de remise en puissance (0 %), peu de remise en puissance probable (10 %), remise en puissance moyen (50 %) et maximum de remise en puissance (100 %).

Le modèle de résilience proposé est un processus itératif avec 30 itérations dans la période d'évaluation pour l'étude de cas, qui correspond à la durée de vie opérationnelle de 30 ans des infrastructures PV. Cette évaluation commence par comparer l'intensité maximale de l'aléa de rafale de vent par an avec la capacité d'absorption. Si l'intensité de la rafale de vent est égale au niveau de capacité d'absorption dans la courbe de fragilité, alors la probabilité d'avoir des dommages au système à ce niveau est évaluée, et le résultat est le niveau de choc lié à cet événement annuel. Le niveau de choc détermine combien de capacité de production d'électricité a été perdue. Ainsi, la capacité de production perturbée de l'année en cours est comparée aux seuils de performance et le type d'événement est établi avec ses effets correspondants sur la capacité de production. L'hypothèse est qu'un seul événement de remplacement peut se produire pendant la période d'évaluation. Ensuite, une nouvelle itération commence à moins que ce ne soit la dernière itération. À la fin du processus itératif, le modèle stocke des données sur le nombre et le niveau de chocs, la quantité et le type d'événements qui se sont produits, ainsi que la date à laquelle l'événement de remplacement a eu lieu. Ceux-ci représentent les scénarios de décision pour un contexte de scénario représentatif donné.

Pour obtenir des résultats représentatifs dans l'étude de cas, 100 000 simulations de Monte Carlo du modèle de résilience ont été exécutées par profil de décideur et par seuil inférieur de performance, ce qui représente un total de 800 000 simulations de Monte Carlo. Les résultats liés aux niveaux de chocs sont présentés sous forme d'histogramme montrant la distribution des dommages cumulés à la centrale PV pendant la période de 30 ans (Figure ii. a). Dans la plupart des cas, il n'y a pas de dommages à la centrale PV, ce qui est cohérent avec la faible incidence de rafales de vent intenses (>40 m/s). Le nombre moyen d'événements est de 1,13 avec un dommage cumulé moyen de 1,75 % de la capacité installée. De plus, en analysant la fonction de distribution cumulative liée aux dommages cumulés (Figure ii. b), on observe une probabilité de 90 % que la centrale PV subisse des dommages inférieurs ou égaux à 3,4 % de sa capacité installée pendant la période de 30 ans.

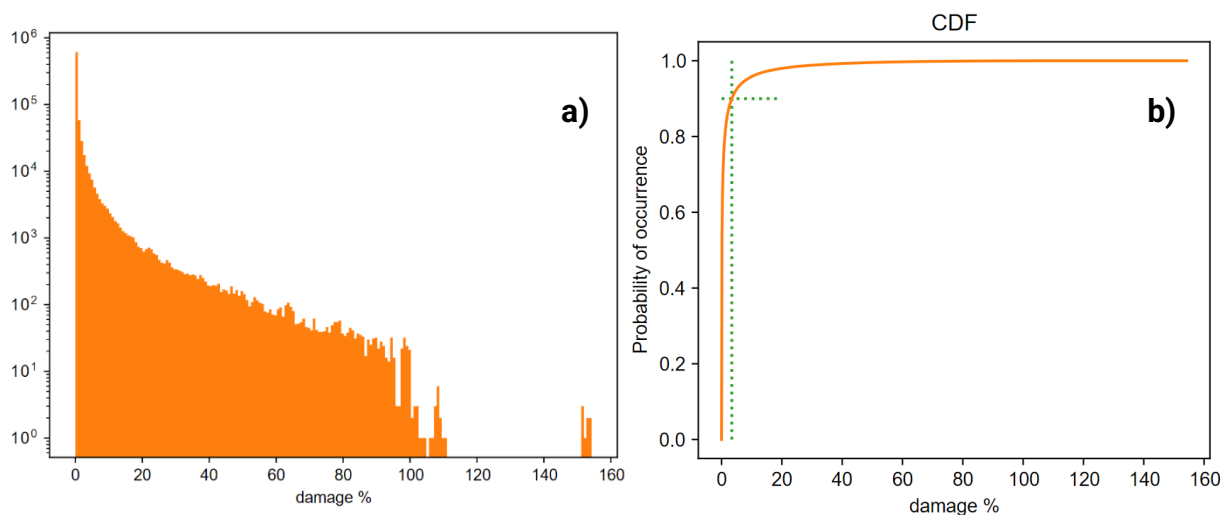


Figure ii. Dommages cumulés à l'usine PV, 30 ans a) Répartition, et b) Fonction de distribution cumulative

Lorsque l'on compare les différents profils de décideur, on constate que les événements de remise en puissance sont peu fréquents dans l'étude de cas. Par exemple, pour le profil de remise en puissance maximum avec un seuil de remise en puissance élevé, sur environ 133 400 événements, seuls 4 967 étaient des événements de remise en puissance, ce qui représente 4,38 % du total des événements.

Les résultats obtenus pour les huit scénarios de décision sont des inventaires contenant le profil d'intensité des dommages, les événements qui se sont produits, la production d'électricité tout au long des 30 ans et l'année où s'est produit l'événement de réaménagement.

#### Étape 4 : Transfert de scénarios à l'ICV

La quatrième étape de la méthode DRUID est le transfert de scénarios à l'ICV (Figure i). L'objectif est de définir un modèle d'ICV pour étudier les conséquences des risques de catastrophe sur la performance environnementale de l'infrastructure étudiée. Le défi du design de cette étape était de traduire les sorties du modèle de résilience en ICV. Ainsi, le modèle d'ICV doit gérer efficacement les informations variables dans chaque inventaire de scénario de décision (résultats de l'étape 3) pour chaque scénario représentatif évalué (résultats de l'étape 2). L'approche retenue consiste à utiliser un modèle d'ACV paramétrisé comme base.

Les modèles paramétrisés ont la capacité de prendre en compte la variabilité temporelle, spatiale et technologique des systèmes, en utilisant des paramètres d'entrée pour décrire les flux sélectionnés. Ces paramètres peuvent décrire les flux de matière et d'énergie dans l'ICV soit sous forme de valeurs uniques, soit sous forme d'un intervalle de valeurs décrites par une fonction de distribution de probabilité. Ainsi, l'étape de transfert de scénario DRUID consiste à définir des paramètres et des processus qui représentent les résultats de l'étude de résilience. Ces paramètres et processus sont ensuite intégrés de manière cohérente avec le modèle d'ACV paramétrisé de référence pour développer le modèle ICV paramétrisé DRUID de l'infrastructure critique qui sera utilisé dans l'étude ACV.

Dans l'étude de cas, l'étude ACV de référence qui utilisera la méthode DRUID pour étudier les impacts environnementaux potentiels des vents violents présente les caractéristiques suivantes :

- Unité fonctionnelle : 1 kWh d'électricité produite par une centrale PV dans le sud-est de la France.
- Catégories d'impact : à partir de la méthode d'impact Ecological Footprint (EF) version 3.0, catégories d'impact « midpoint » basées sur des indicateurs sans la prise en compte des émissions long terme (no LT).
- Limites du système : approche du « berceau à la tombe », prenant en compte l'extraction des matières premières ; la fabrication des panneaux PV, du système de montage, de l'onduleur et de l'installation électrique ; le transport sur le site d'installation ; l'installation du système ; le fonctionnement du système ; et le recyclage de certains matériaux à la fin de vie.
- Durée de vie du système : 30 ans.
- Inventaire : les activités d'arrière-plan (« background ») sont basées sur la base de données Ecoinvent v.3.9.0, version « cut-off », et les processus de premier plan (« foreground ») sont basés sur le modèle paramétrisé pour les modules en silicium multicristallin PARASOL\_LCA développé par Besseau et al. (2023) L'efficacité du module est de 17,5 %.
- Modèle d'impact : prend en compte l'impact environnemental des processus mentionnés ci-dessus et les évalue par rapport à la production totale d'électricité tout au long de la durée de vie opérationnelle de 30 ans,  $\frac{\text{Impacts Environnementaux}_{base}}{\text{Production d'Électricité sur la Durée de Vie [kWh]}}$ , présentant ainsi les résultats d'impact par unité fonctionnelle,  $\text{Impact}_i/\text{kWh}$ .

Le transfert de scénario vers l'ICV consiste en trois tâches générales. Premièrement, les flux et processus du cycle de vie qui sont affectés par des événements de réparation et de remplacement sont identifiés. Pour chaque type d'événement, des processus supplémentaires qui modifieront les



limites du système originales sont inclus. Les événements de type remplacement introduisent une seconde version du système produit, tandis que les événements de type réparation introduisent des activités de maintenance supplémentaires. Deuxièmement, les flux qui sont spécifiquement affectés par les événements sont réévalués pour déterminer lesquels peuvent être paramétrisés. Troisièmement, l'équation algébrique représentant le modèle d'impact qui relie les impacts de tous les processus à l'unité fonctionnelle est établie en tenant compte des modifications apportées en raison des nouveaux processus, flux et paramètres.

Dans l'étude de cas, les hypothèses suivantes sont faites pour les événements de type réparation et de remplacement :

- Les événements de type réparation impliquent un remplacement partiel de la capacité installée de la centrale PV. Ainsi, des paramètres liés au pourcentage de composants réparés dans la centrale PV sont établis, c'est-à-dire pour les panneaux PV, le système de montage et les onduleurs. De plus, un paramètre lié au temps nécessaire pour effectuer les opérations de réparation est introduit car cela représente une interruption du service de production d'électricité.
- Les événements de type remplacement sont plutôt appelés événements de remise en puissance (« repowering » en anglais). Ces événements impliquent le remplacement de l'ensemble de la centrale PV par une nouvelle et plus performante, ainsi tous les processus du cycle de vie sont pris en compte une seconde fois. Les nouveaux panneaux PV ont une efficacité supérieure, 22 % s'ils étaient remis en puissance après la 10<sup>ème</sup> année, et 24 % s'ils étaient remis en puissance après la 20<sup>ème</sup> année. Des paramètres supplémentaires incluent l'année de remise en puissance et le temps nécessaire pour démonter l'ancienne centrale PV et construire la nouvelle.

Le modèle d'impact prend en compte les impacts environnementaux des conséquences des événements de réparation et de remise en puissance (flux de matériels et énergie additionnels dans la phase d'inventaire), en plus des impacts pour la centrale PV de base. Dans le cas des impacts liés à la remise en puissance, il est considéré que la centrale PV remise en puissance peut continuer à fonctionner au-delà de la portée originale de 30 ans de l'étude en raison de la durée de vie prévue des composants. Toutes les activités liées à la maintenance sont prises en compte dans leur intégralité car elles sont liées aux conséquences des chocs qui se sont produits dans la portée de 30 ans,

$$\frac{Impacts_{base} + Impacts_{base,maintenance} + Impacts_{repower} \left(1 - \frac{tr_y}{30}\right) + Impacts_{repower,maintenance}}{Production\ d'Électricité\ sur\ la\ Durée\ de\ Vie\ [kWh]}$$
, présentant ainsi les résultats d'impact par unité fonctionnelle.

Des tests préliminaires pour étudier les différences dans les résultats de l'ACV entre le scénario de base utilisant une approche de modélisation ACV conventionnelle et cinq scénarios déterministes DRUID ont été effectués dans le but de vérifier que le modèle fonctionnait comme prévu (Figure iii). Pour le scénario de base sans chocs, les résultats obtenus pour la catégorie d'impact changement climatique sont de 30,71 g CO<sub>2</sub>-eq/kWh, et pour l'utilisation des sols, il est d'environ 3,31 unités par kWh pour l'Indice de Qualité des Sols. Ces résultats sont dans la plage des résultats attendus et disponibles dans la littérature pour une étude ACV de ce type avec les hypothèses établies.

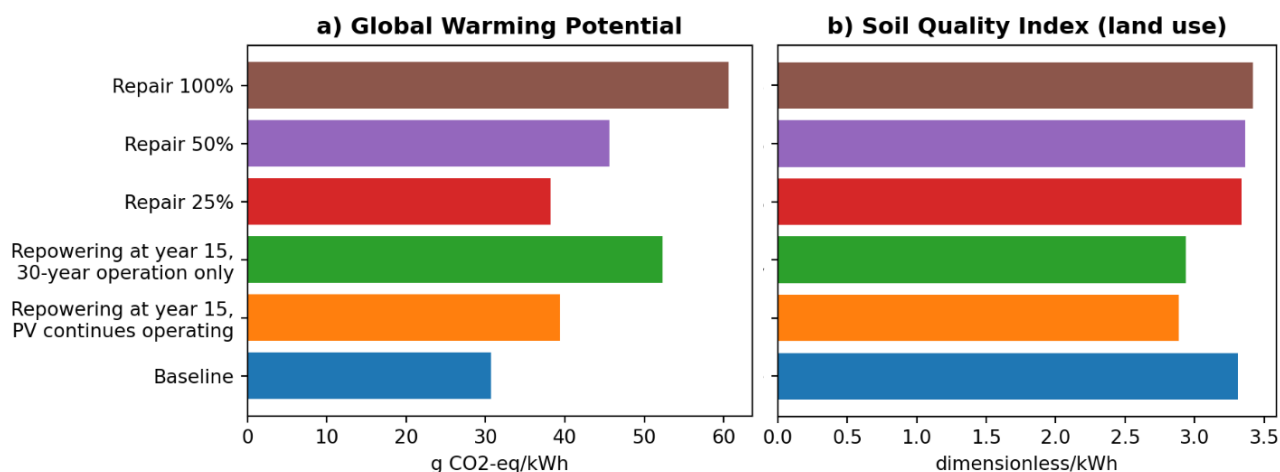


Figure iii. Résultats préliminaires de l'ACV pour les scénarios déterministes DRUID sur a) Changement climatique et b) Utilisation des sols

Les cinq scénarios déterministes considèrent que 25 %, 50 % et 100 % de la centrale PV nécessitent des réparations et qu'un scénario prend en compte un événement de remise en puissance qui s'est produit à la 15<sup>ème</sup> année. De plus, un modèle d'impact alternatif a été testé sur ce dernier scénario, où les impacts du système PV remis en puissance étaient entièrement attribués à sa période d'exploitation car le système fonctionnerait jusqu'à la durée originale de 30 ans.

Pour ces tests, les résultats du changement climatique pour les scénarios de réparation et de remise en puissance présentent des impacts plus élevés que ceux du scénario de base : l'impact du scénario de réparation à 100 % est le double de celui du scénario de base. Cela est dû au remplacement des composants défectueux par des composants ayant les mêmes caractéristiques et donc les mêmes impacts environnementaux associés. Dans le cas de la remise en puissance, les impacts sont inférieurs à ceux du scénario de réparation à 100 %. En effet, bien que l'ensemble de la centrale PV soit également remplacée, les panneaux PV ont une efficacité plus élevée, ce qui augmente la capacité installée en kWp de la centrale et donc la production d'électricité (kWh). Enfin, les différentes considérations d'attribution pour les scénarios de remise en puissance montrent qu'arrêter l'exploitation de la centrale PV à la 30<sup>ème</sup> année serait nuisible pour l'environnement. Des comportements similaires sont observés pour d'autres catégories d'impact, sauf pour l'utilisation des sols.

Pour les résultats d'impact de l'utilisation des sols, il n'y a pas de différence significative entre les scénarios, excepté pour la remise en puissance. C'est parce que ces impacts sont liés aux processus de transformation et d'occupation des sols, qui ne sont comptabilisés qu'une seule fois lorsque la centrale PV de base est installée. La production d'électricité plus élevée de la centrale PV située dans la même superficie abaisse la valeur des résultats d'impact.

Ayant confirmé que le modèle fonctionne comme prévu, les résultats de l'étude de résilience sont évalués et analysés pour répondre à la question posée par le problème DRUID. Les huit scénarios décisionnels sont testés. La Figure iv et la Figure v montrent des résultats à l'échelle logarithmique correspondant au seuil de remise en puissance faible pour les catégories d'impact changement climatique et de l'utilisation des sols. Les différents profils de décideurs montrent que plus la probabilité de choisir la remise en puissance est élevée, plus la contribution des impacts liés à la remise en puissance sur les résultats est importante. Un effet similaire se présente avec les deux

seuils de remise en puissance : le plus le seuil est élevé, plus la contribution de ces événements est importante.

Dans toutes les catégories d'impact, la plupart des impacts sont liés aux scénarios où aucun dommage n'est survenu à la centrale PV au cours de sa durée de vie opérationnelle. Cela signifie que ces résultats d'impact environnemental sont identiques à ceux de la centrale PV de base. Ceci est prévisible étant donné la faible incidence de vents violents et le profil de capacité d'absorption des panneaux PV. Les impacts liés aux scénarios de réparation sont les seconds plus fréquents car dans la plupart des cas où la centrale PV subit des dommages, ceux-ci sont d'intensité moyenne voire faible, comme le montre l'étude de résilience. De plus, les résultats d'impact pour les scénarios de réparation peuvent être plus intenses mais il est rare que leurs valeurs soient 50% supérieures à la valeur de base, c'est-à-dire plus de 45 g CO<sub>2</sub>-eq/kWh pour la catégorie d'impact changement climatique.

Dans la catégorie d'impact changement climatique (Figure iv), les événements liés à la remise en puissance ne sont pas aussi fréquents que les événements liés à la réparation. En effet, l'incidence de vents très violents dont les dommages sur la centrale PV pourraient déclencher la décision de remplacer l'ensemble de l'infrastructure est rare. Les impacts liés à la remise en puissance peuvent atteindre des valeurs qui doublent l'impact de base. Mais cela dépend fortement du moment où survient l'événement de remise en puissance en raison des différentes efficacités des panneaux PV et de façon que les impacts sont attribués dans le modèle d'impact. L'efficacité des panneaux PV est de 22% lorsque la remise en puissance se fait entre la 10<sup>ème</sup> et la 20<sup>ème</sup> année d'exploitation et de 24% lorsque la remise en puissance a lieu après la 20<sup>ème</sup> année. Une remise en puissance plus tardive entraîne des impacts relativement plus faibles en raison de la production d'électricité plus élevée et de l'attribution moindre des impacts sur la durée de vie opérationnelle de la centrale PV.

Toutes les catégories d'impact sauf l'utilisation des sols ont des résultats similaires à ceux de la catégorie d'impact changement climatique.

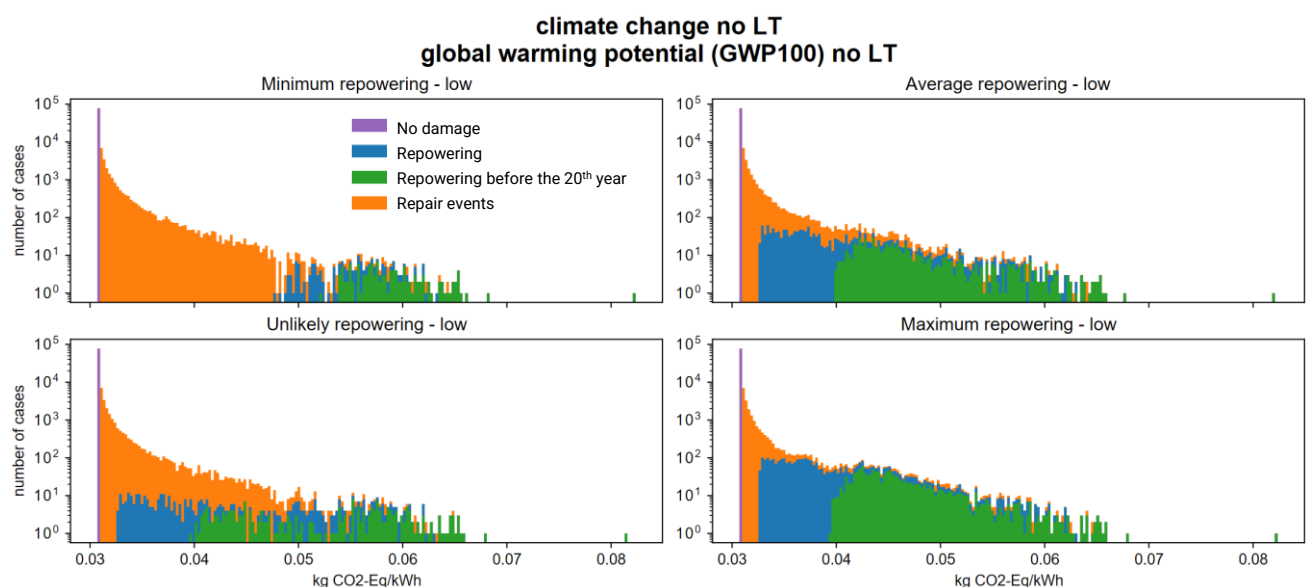


Figure iv. Résultats de l'ACIV pour les scénarios décisionnels avec seuil de remise en puissance faible, catégorie d'impact du Changement climatique

Dans la catégorie d'impact de l'utilisation des sols (Figure v), les impacts liés au scénario « aucun dommage » et à la gamme de scénarios « réparations » suivent un comportement similaire aux autres catégories d'impact, bien que les valeurs relatives ne changent pas significativement par rapport au scénario de base. Comme le montrent les tests préliminaires, les impacts liés à la remise en puissance ont la valeur la plus faible, et plus tôt la remise en puissance est effectuée, moins les impacts sont importants car l'électricité est produite avec un système plus efficace pendant des périodes plus longues.

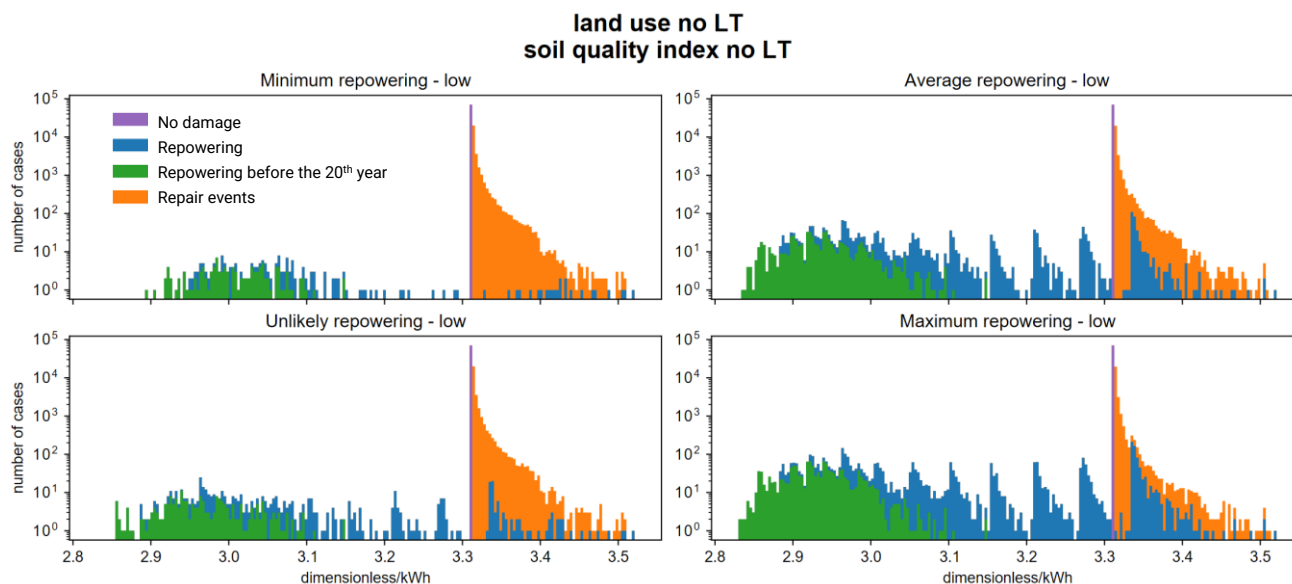


Figure v. Résultats de l'ACIV pour les scénarios décisionnels avec seuil de remise en puissance faible, catégorie d'impact de l'utilisation des sols

Les résultats de l'analyse de l'impact qui comparent les différents scénarios décisionnels visent à fournir des informations pertinentes aux décideurs potentiels impliqués dans le développement d'un projet d'infrastructure critique.

## Conclusions et Perspectives

Pour permettre de prendre en compte les conséquences de l'évolution des risques de catastrophes sur la performance opérationnelle et environnementale des infrastructures critiques à moyen et long terme, cette thèse de doctorat a abordé trois questions scientifiques à travers trois tâches principales. Premièrement, un cadre conceptuel multidisciplinaire pour guider la formulation d'un problème spécifique a été établi. Deuxièmement, une méthode de définition de scénarios qui aide à évaluer les conséquences potentielles de l'évolution des risques de catastrophes sur la performance des infrastructures critiques a été conçue, appelée DRUID. Et troisièmement, la méthode a été développée et appliquée en tant que module compatible avec l'ACV à travers une étude de cas illustrative sur une centrale PV, où les scénarios décisionnels utilisés pour présenter les résultats de l'ACV comme éléments de soutien à la décision ont été testés.

Certaines limites et opportunités de développement de la méthode DRUID sont liées à l'inclusion de risques complexes, à l'élargissement de la portée de la dimension de résilience, ainsi qu'à une description plus explicite des profils de décideurs avant l'étude de la résilience. Dans le domaine de l'ACV, la méthode devrait inclure les processus de fin de vie pour mieux représenter les résultats d'impact, ainsi que les inventaires prospectifs, bien qu'ils puissent introduire plus d'incertitudes dans

le modèle. De plus, en raison de son approche de définition de scénario, la méthode DRUID peut être utilisée dans d'autres évaluations qui souhaitent inclure la perspective du risque de catastrophe, telles que les évaluations économiques (analyse coût-avantage) et les évaluations liées à la résilience.

Le développement de la méthode DRUID a été conçu comme une contribution méthodologique à l'ACV. En tant que tel, il propose une approche exceptionnellement différente de la phase traditionnelle d'analyse de l'inventaire dans l'ACV en introduisant la perspective du risque de catastrophe. En tant que méthode exploratoire, elle ouvre la voie à la conception de nouvelles méthodes et d'approches visant à relever le principal défi de recherche. De plus, l'application de la méthode DRUID au développement des systèmes de production d'énergie ouvre de nouveaux débats sur la manière dont les impacts environnementaux potentiels sont abordés par les organisations du monde entier. Cela est d'autant plus nécessaire au regard des risques de perturbations de l'opération de ces systèmes de production d'énergie par des événements disruptifs de plus en plus fréquents et intenses.

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## List of Acronyms

Acronym	Description
ALCA	Attributional Life Cycle Assessment
CDF	Cumulative Density Function
CLCA	Consequential Life Cycle Assessment
DRUID	Disaster Risk-gUided scenario Definition Method
ERA	Environmental Risk Assessment
FU	Functional Unit
GHG	Greenhouse gas
GMA	General Morphological Analysis
GWP	Global Warming Potential
IAM	Integrated Assessment Model
IEA	International Energy Agency
ILCD	International Life Cycle Data system
ISO	International Organization for Standardization
JRC	Joint Research Centre
KPI	Key Performance Indicator
kWh	Kilo Watt Hour, energy production and consumption measurement
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LULC	Land Use and Land Cover
MWp	Mega Watt Peak, installed power measurement
NATECH	Natural-Technological risk
PACA	Provence-Alpes-Côte d'Azur
PDF	Probability Density Function
PV	Photovoltaic
PVPS	Photovoltaic Power Systems Programme
RA	Risk Assessment
RCP	Representative Concentration Pathway
RTE	Réseau de Transport d'Electricité (electricity transmission network operator in France)
SA	Sensitivity analysis
SETAC	Society of Environmental Toxicology and Chemistry
SQI	Soil Quality Index
SSP	Socio-Economic Pathway
UA	Uncertainty analysis
UNEP	United Nations Environmental Programme

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# Introduction

## Context

The heat and electricity demand have experienced a continuous growth in the last two decades that is still ongoing, with final energy consumption almost doubling across the globe and electricity consumption nearly quadrupling since the year 2000 (Enerdata, 2023). To fulfill this growing demand the installed capacity of energy production systems will continue increasing. Unfortunately, these activities have adverse impacts on human and environmental health (IPCC, 2022), and play a significant part in the accelerated change of global average temperatures and climate in general (IPCC & Core Writing Team, 2023). Therefore, present and future energy production systems must prevent such adverse impacts whilst being sustainable, reliable, and affordable, as stated in the 7<sup>th</sup> Sustainable Development Goal of the Agenda 2030 (United Nations General Assembly, 2015). Renewable energy production systems contribute to this call for action. Their primary advantage is their capability to generate energy from natural resources that can be used and reused in human time scales, e.g. photovoltaic (PV) systems that produce electricity from sunlight. Many countries have committed to developing projects that will increase the contribution of renewables in their national energy mix. Notable examples are the Directive 2018/2001 of the European Union, the European Green Deal (European Commission, 2019), and the REPowerEU Plan (European Commission, 2022b).

Ensuring the suitability of these renewable energy projects, as for any other energy production project, involves taking technical decisions about their geographical locations, the characteristics of the system such as the technical specificities, sizing, the expected electricity production, and profitability, among others. Equally relevant are the strategic decisions that concern the social acceptability of the project in the region, compliance with national and international norms, agreements with the institutions in charge of the electrical network, insurance and financial contracts, and the alignment with political objectives regarding the installed capacity of renewable energy sources and the minimal environmental impacts such projects should have. The importance of considering these factors in decision-making at the infrastructure level is further highlighted when considering their expected operational lifespan, for example, 25 to 35 years for PV power plants (Frischknecht et al., 2020). Taking this perspective whilst considering the influence of other issues requires the aid of comprehensive decision-support methods and tools.

When it comes to the assessment of environmental impacts through technical and technological aspects, the most used decision-support method is Life Cycle Assessment (LCA). It is a standardized method established by ISO standards 14040 and 14044 (ISO 14040, 2006a; ISO 14044, 2006b), widely used for the multi-criteria evaluation of the potential environmental impacts of a product or service, also called product system. What sets LCA apart from other environmental impact assessment tools is that it considers and assesses the whole life cycle of the product system, from the raw material extraction, component manufacturing, transportation, installation, and the operation phases, to the dismantling and waste management (Hauschild, 2018). This allows for a comprehensive view of the potential sources of pollutants and environmental consequences of the product system. In the electricity and heat production sector, LCA has been used to compare the greenhouse gas (GHG) emissions and other environmental impacts of different energy technologies and sources, focusing on the manufacturing and operations stages. For example, in PV technologies, many studies have focused on comparing the environmental performance of different cell technologies and module configurations (Laurent et al., 2018).

LCA is usually applied to product systems according to their average operation conditions, meaning deviations from this normal operation are not considered in the life cycle inventory (LCI) assessment phase. Unfortunately, these assumptions could present situations that may not be realistic to decision-makers, especially in complex energy production systems where deviations from average conditions are bound to happen. For example, considering the expected growth of solar PV systems to fulfill the energy transition objectives for the Net Zero Scenario (IEA, 2024), between 375 - 672 GWp should be installed yearly, corresponding to a surface area of approximately 170,000 – 300,000 hectares. A development of this scale increases the exposure of these systems to environmental hazards that could severely disrupt the expected standard operation of PV plants, especially in the context of climate change.

Therefore, to enable more comprehensive and useful LCA applications in decision-making, such deviations need to be considered in the assessment. Finkbeiner et al. (2014) identified this research challenge in LCA, using the term of “improbable events” for the causes of possible deviations. Moreover, the consequences of those events could go beyond deviations and translate to actual and deep damages to the system. For example, it is not the same to have a temporary interruption of electricity production in a PV production plant because some electrical components require maintenance after a storm, as it is to have several modules and an inverter that are rendered useless because of a flood. If these types of damage and their associated uncertainties were to be considered in LCA at the inventory level, they would undoubtedly change the impact assessment results.

The relevance of pursuing this research challenge is further highlighted when considering that among the sources of possible deviations and damages to energy production systems, we have the consequences of evolving disaster risks. Disasters involve hazardous events that seriously disrupt critical infrastructures and the functioning of a society (UNDRR, 2007), for example, hurricanes and tornadoes razing buildings, or chemical explosions triggering (wild)fires. Unfortunately, accelerated climate change has and will likely continue to increase the frequency and intensity of natural disasters (Lee et al., 2023), and with more complex and interconnected energy systems, the number of critical infrastructures that are exposed to disasters will likewise increase.

In conclusion, the present and future planning and development of energy production systems, both renewable and non-renewable, and critical infrastructures in general, must consider the potential impacts of evolving disaster risks on their environmental performance throughout their lifespan. Addressing these issues as early as the planning phase is key for them to provide reliable decision about the deployment of energy production services for a sustainable energy transition. LCA is a relevant decision-support tool to comprehensively estimate the potential environmental impacts of these infrastructures (Laurent et al., 2018). However, its current application does not account for the consequences of improbable events (Finkbeiner et al., 2014) such as disaster risks. This has been identified in this PhD thesis as a relevant LCA research challenge that if addressed at the inventory level, could enable more comprehensive and realistic environmental impact results. The development of such research could significantly contribute to the comprehensive estimation of potential environmental impacts of renewable energy systems considering the consequences of the evolution of disaster risks.

To address these research challenges, it is necessary to adopt a multidisciplinary approach that links concepts, methods, and tools from the domains of LCA, disaster risks, energy systems, and future-oriented studies.

## Scientific Objectives

This PhD thesis presents a methodological contribution to integrate the disciplines of LCA and disaster risk evaluation. The central objective is to enable the consideration of the consequences of evolving disaster risks on the operational and environmental performance of critical infrastructures in the mid- to long-term. Specifically, the critical infrastructures addressed in this project are energy production installations.

By considering evolving disaster risks it can be acknowledged that global trends like climate change have played a role in increasing the intensity and frequency of occurrence of natural disasters. Consequently, this has rendered technological systems more exposed and vulnerable to external disruptions, increasing the likelihood of technological or industrial disasters. Because of these considerations, the study performed adopts a future-oriented approach.

In order to pursue the central objective of the thesis and address the research challenge, an approach based on the development of a novel inventory module for LCA is proposed. This module presents a methodological approach to guide the definition of 1) a group scenarios representative of the potential evolution of disaster risks and their effects on a territory and the studied infrastructure, and 2) for each scenario, specific pathways describing the consequences of different decision-making alternatives on the operational and environmental performance of the critical infrastructure.

To pursue this methodological development, the following scientific questions are addressed:

1. How could the formulation of the specific problem that contemplates concepts from different domains for knowledge be cohesively guided?
2. How could representative scenarios of possible evolutions of disaster risks be elaborated? In the context of these scenarios, how could the consequences of disaster events be addressed in the analysis of the performance of the critical infrastructure over its lifespan?
3. How could the results from the disaster risk-guided scenarios be included at the Life Cycle Inventory level so that they represent relevant decision-support elements? How can LCA results produced using these scenarios be presented so that they are useful and relevant to decision makers?

## Approach

The novel inventory module for LCA proposed in this PhD thesis is called the **Disaster Risk-guided scenario Definition (DRUID) Method – LCI Module**, consisting of four general steps, as shown in Figure 6.



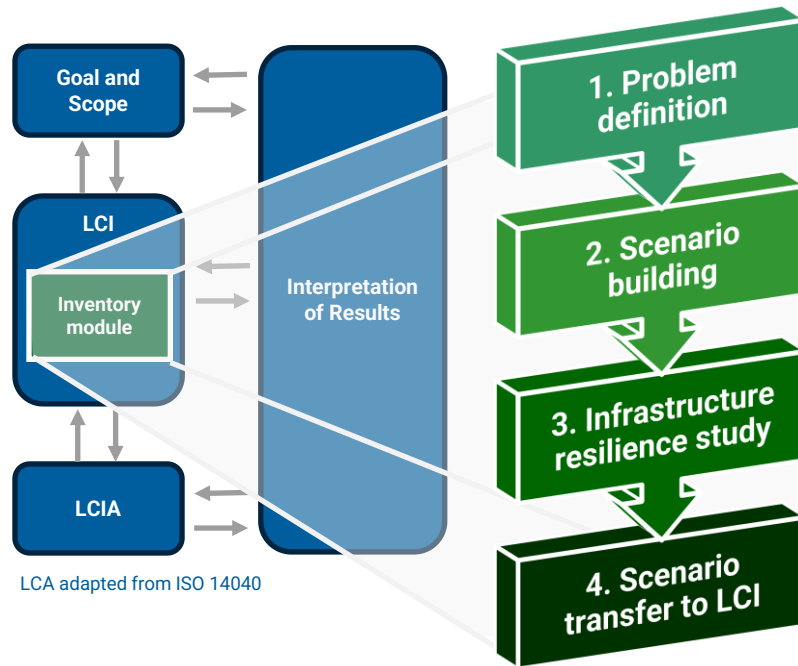


Figure 6. DRUID LCI: Disaster Risk-gUided scenario Definition Method – LCI Module

The development of the *DRUID method* is guided by a case study named *FuturePV* based on the photovoltaic (PV) energy sector in France. The main purpose of *FuturePV* is to provide concrete examples that illustrate the abstract concepts and elements that DRUID LCI proposes. It also aims to demonstrate the applicability, feasibility, opportunities, and limitations of the *DRUID method*. Specifically, *FuturePV* presents the comparative LCA case study for a single PV infrastructure in the context of the PV energy sector development in a mountainous territory with Mediterranean climate in the south of France, in a 2050 horizon. The study compares the LCA results obtained from a baseline scenario study versus results obtained using DRUID scenarios that consider the risk of strong winds. A more extensive contextualization and justification of *FuturePV* is presented in the next section.

The four steps of the *DRUID method* are based on the development of three essential elements:

- I. An application-specific ontology that links essential concepts from the domains of critical infrastructure resilience and disaster risks, the prospective scenario design, and LCA. The ontology will facilitate the design of the *DRUID method* by providing added value to create a shared understanding of the domains involved, facilitate the communication between actors involved in a DRUID study, and ease the interoperability between support tools.
- II. A method that guides the construction of multiple scenarios for a given spatial area, each scenario describing the possible evolutions of the territory, disaster risks, and the infrastructure sector context. The method is based on the approach called General Morphological Analysis for modeling scenarios (Ritchey, 2022; Zwicky, 1967). This will support the Problem Definition (1<sup>st</sup>) step, the Scenario Building (2<sup>nd</sup>) step and the Infrastructure Resilience Study (3<sup>rd</sup>) step.
  - a. Scenarios represent the potential evolutions of a territory, the infrastructure sector, possible disaster risks, the capacity of the infrastructure to face certain disaster risks,
  - b. For each of these scenarios, specific pathways describe the consequences of different decision-making alternatives on the resilience and the operational performance of the

infrastructure. For an energy production infrastructure, such decisions could involve repairing damaged components to recover the production capacity, or to replace the entire installation with better performing technology to increase energy production, which is also known as repowering.

- III. A scenario transfer approach that enables the association of a given scenario and its decision pathways to the LCI of the PV infrastructure for its subsequent life cycle impact assessment (LCIA). The LCA modeling for the foreground PV system is built from *PARASOL\_LCA* (Besseau et al., 2023), a parametric model that is based on *Brightway2* (Mutel, 2017) and *Ica\_algebraic* (Jolivet et al., 2021). This will support the Scenario Transfer to LCI (4<sup>th</sup>) step.

## Case Study Justification

Of the solar-based technologies available, the PV sector is the most important in the electricity generation sector given its enormous potential to reduce atmospheric pollutants and its present and future penetration into the energy mix. According to the most recent report by the IPCC Working Group III (IPCC, 2022), the energy generation sector significantly contributes to the global net GHG emissions, around 34% in 2019 (20 GtCO<sub>2</sub>-eq), and solar PV represents an important technology in mitigating these emissions, as shown in Figure 7. Moreover, the price of solar energy and PV modules has decreased -by 85% between 2010 and 2019 (IPCC, 2022)- and will continue to do so, bringing the technology at competitive prices in the energy market. Alongside better policy implementation, its possibility for its parallel use with agriculture, important technical contributions from industry and research, and the pressure to meet the Agenda 2030 objectives (SolarPower Europe, 2021), it stands as a strong asset for renewable energy plans.

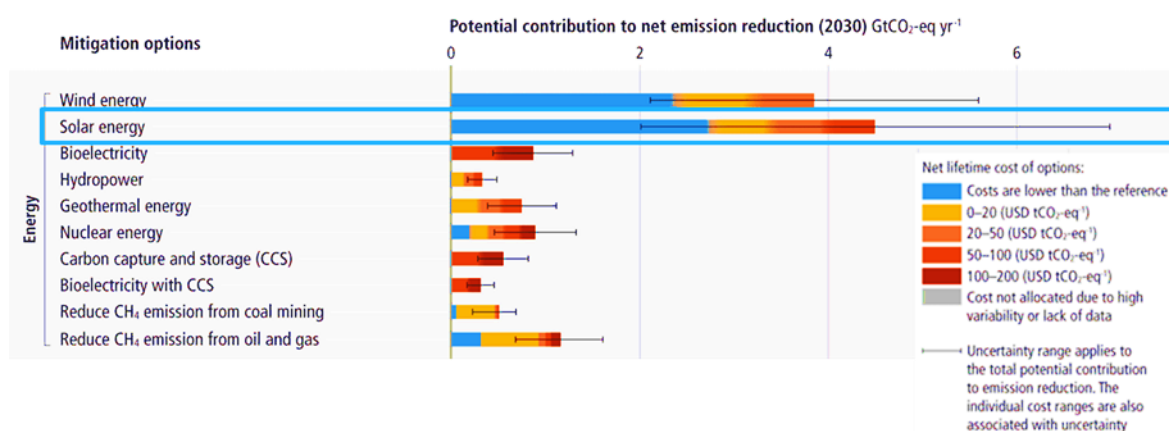


Figure 7. Overview of mitigation options and their estimated ranges of costs and potentials in 2030, adapted from IPCC (2022)

The size of an installation ranges from a few modules arranged on a suitable rooftop, to dozens of panel arrays spanning several hectares, opening the possibilities for both small and large actors to benefit from this resource. Moreover, the price of solar energy and PV modules has decreased by 85% between 2010 and 2019 (IPCC, 2022) and will continue to do so, bringing the technology at competitive prices in the energy market. Alongside better policy implementation, its possibility for its parallel use with agriculture, important technical contributions from industry and research, the pressure to meet the Agenda 2030 objectives as well as the REPowerEU plan (European Commission, 2022b) and the Solar Energy Strategy (European Commission, 2022a), it stands as a strong asset for the renewable energy transition.

The PV energy production sector on a global scale has gained significant momentum in the past decade, with cumulative capacity increasing with each year, and this trend is expected to continue. For example, in France, the electricity mix will undergo major changes towards technologies that rely less on fossil fuels. The electricity transmission network operator, RTE, has explored six different energy production mix scenarios with three consumption trajectories, and in all of them, PV plays an important part, between 13-36% (~70-208 GW of installed capacity) of the national generation mix in 2050 (RTE, 2021).

Such a widespread development in a relatively short amount of time will most likely incite decision makers to push forward PV projects as economically as possible. This means that concerned territories will probably look for inexpensive land, such as forested regions, to develop large-scale installations in order to fulfill their PV installed capacity goals, especially if they are behind in their planning. For example, the Alpes-Maritimes -which is part of the Provence-Alpes-Côte d'Azur (PACA) region in the south of France- is among the top 6 French departments with the highest solar potential in the country, with more than 1620 kWh/m<sup>2</sup> yearly average Global Horizontal Radiation (Solargis, 2024). Unfortunately, this potential is not as exploited as it should be, and both the Alpes-Maritimes department and the PACA region are behind in their objectives regarding renewable energies, specifically the target installed capacity of PV. Plans to develop this underexploited potential are on their way (DREAL Provence-Alpes-Côte d'Azur, 2019), suggesting that rooftop installations and projects in degraded areas are prioritized, although this necessitates significant time and effort.

The development of these kinds of projects requires economic, social, and environmental considerations. The latter is particularly critical when considering that it is likely that economically speaking the option of modifying some natural spaces is more attractive in terms of direct costs and speed of development than making the effort to explore other alternatives. But upon considering the case where the decision has already been made, it is equally important to accurately analyze and communicate the potential environmental impacts of PV systems in a territory, especially when considering the changes that will happen throughout its lifespan due to global trends like climate change. A territory will not be the same in ten or twenty years from the moment the PV infrastructure is installed, because the climate is expected to change to provoke more intense and frequent hazards that are sources of disaster risks.

The interest of assessing the potential environmental impacts of PV systems under disaster risks lies with the possible consequences of the disaster risks on the physical system itself and the type of decisions that such consequences could induce. For example, if a PV power plant is exposed to a certain disaster, and it is not prepared to face it, a possible outcome is the partial destruction of the installed capacity, meaning that several PV modules are unable to continue providing electricity. Therefore, non-routine maintenance, recovery, and replacement activities must take place to return the PV installation to feasible operating conditions. However, it is plausible that if an important amount of PV modules and inverter(s) were damaged, the corresponding decision-makers could opt for replacing the whole plant with newer and better performing technologies, thus increasing the electricity production capacity of the plant. In a context of significant decrease of PV module cost along with a significant increase of their efficiency (IEA, 2020), this possibility of replacing PV modules of old generations by new ones, named repowering, is already considered by the PV developers (Fishman, 2018; Herceg et al., 2022), even independently of any damage events. Note that the processes that contribute the most to the overall environmental impacts of PV systems are those

related to the PV module production, therefore replacing damaged modules is expected to significantly increase the overall environmental impacts of the system.

This presents complications and issues on the technical, economical, and environmental performance of the system, which enrich the discussions surrounding the application and results of the proposed methodological framework.

## Manuscript Structure

The present manuscript is structured in six chapters.

In Chapter 1, the objectives are to explore how disaster risks could be considered in LCA and to suggest a comprehensive contribution to the identified research challenge. The chapter consists of a literature review that covers the following topics: an overview on the LCA method, exploring its origins, current practices, and the research challenge; a disaster risk overview, including its relevant elements and means of evolution; and existing LCA studies that consider risks and disaster risks to a certain extent. The chapter concludes with a preliminary proposition for the methodological contribution of this PhD thesis.

In Chapter 2, the objective is to explore future-oriented approaches in the literature to identify the methods and tools that will help in bridging the gap between the inputs and outputs of the proposed disaster risk-driven inventory module. Section one consists of a literature review that addresses how the future is studied, specifically through the prospective approach, scenario building methods, and their applications in LCA, followed by a discussion on the implementation of scenarios in the methodological proposal. Section two is an in-depth description of a specific scenario building method relevant to the project: the General Morphological Analysis. Finally, section three incorporates the findings from both literature reviews to identify the research challenges of the project, and then presents an overview of the methodological proposal for the inventory module: the Disaster Risk-Guided scenario Definition (*DRUID*) Method – LCI Module.

In Chapter 3, the objective is to develop and present an ontology specific to a problem addressed by the *DRUID method*. This chapter aims to answer the first scientific question. An ontology is a structured framework to organize information and define the relationships between concepts within a specific domain or application. The design of an ontology is motivated by the interdisciplinary nature of a problem addressed by the *DRUID method* and the necessity to transfer data with specific performance assessment modules such as LCA. The proposed ontology, named *OntoDRUID*, aims to provide the fundamental concepts and relationships that will support the formalization of the phases of the *DRUID method*, the design of the associated technological solution, and the communication between analysts, experts, and practitioners. Section one briefly introduces what is an ontology. Section two poses the formulation of competency questions which support the identification of the domain and scope of *OntoDRUID*. Section three presents the essential concepts supporting the answers to the questions that were defined. Section four shows how the *OntoDRUID* hierarchy of classes was modeled.

In Chapter 4, the objective is to define and present the *DRUID method*, establishing its core methodological structure and performing the illustrative case study in parallel to provide a specific and clear example of the application of the method. This chapter aims to answer the second scientific question. Section one addresses the problem definition, using the concepts developed in the ontology, and likewise posing the data collection guidelines. The results from the data collection are

used to define the problem-specific trends, each with a set of possible values or conditions. Section two consists of the scenario definition, which uses the previously defined trends to establish groups of possible scenarios, and for each group choose representative scenarios to evaluate. It is based on the General Morphological Analysis approach for modeling scenarios, which enables the inclusion of both quantitative and qualitative data in the scenario building process. Section three concerns the study of the resilience of the infrastructure under the representative scenarios, which consists of the evaluation of the effects of disaster risks on the performance of the infrastructure in its lifespan.

In Chapter 5, the objective is to present a practical and illustrative application of the *DRUID method* and the scenario transfer approach that enables the association of a representative scenario and its decision pathways to the LCI of the PV infrastructure for its subsequent Life Cycle Impact Assessment (LCIA). This chapter aims to answer the third scientific question. The chapter is structured as a comparative LCA study to test the *DRUID method* and evaluate the different results obtained when using the *DRUID method* versus a baseline scenario without considering disaster risks. Section one develops the goal and scope of the study. Section two develops the LCI and LCIA, including the specifications required to implement the *DRUID method* in the study, with details about the scenario transfer step. Section three presents the interpretation of results.

The final Chapter presents the conclusions of the PhD thesis, together with perspectives and possible future developments.

# Chapter 1. Exploring Life Cycle Assessment in a World of Evolving Disasters

## Introduction

Life Cycle Assessment (LCA) is a normalized environmental impact assessment tool ([ISO 14040, 2006](#); [ISO 14044, 2006](#)) that quantitatively estimates the potential environmental impacts and resources used throughout the life cycle of a product system, i.e., from the raw material extraction, transportation, manufacturing, and use phases to the waste management and recycling processes ([Hauschild, 2018](#)). The results obtained provide information on the estimated potential environmental impacts relative to a determined function of the system, as well as the contribution that each life cycle stage has on the different environmental impact categories evaluated, such as the global warming potential, depletion of minerals, ground and water acidification, land use, and tropospheric ozone levels, to name a few. Comparative analyses are among the most common uses of LCA, and their purpose is to aid in choosing between options of the characteristics of a product system or between different product systems that fulfill the same function.

Because of the broad scope of LCA, it is considered as a systemic method that aids in science-based decisions relative to the product system under analysis, ([Owsianiak et al., 2018](#)) providing decision-makers in industries and organizations with information about infrastructure, product or process design, prioritization, and strategic planning, to name a few. The insights obtained from the environmental impact results could show aspects of a project that a decision-maker might not have contemplated before, or they could confirm and/or deny hypotheses about preconceived notions.

The conventional application of LCA usually focuses on evaluating situations describing a product system operating at average or steady state conditions, meaning that situations that may induce possible deviations are not considered in the assessment. Even though these assumptions are done to facilitate the understanding of the environmental impact results, they may present situations that are unrealistic for decision makers, especially in complex product systems where deviations from normal operations are expected, which could lead to assessments not being used for their intended purpose.

Among the research challenges of LCA and the opportunities to provide more comprehensible and realistic results for decision-makers, the inclusion of such deviations caused by improbable events has been identified as a relevant aspect ([Finkbeiner et al., 2014](#)). Although some attempts have been made to account for such aspects through the integration of LCA with risk assessment methods, a gap remains regarding the consequences of disaster risks on the operations of the product system and their performance. The pertinence of considering disaster risks is related to the expected increase of frequency and intensity of disaster events because of climate change, among other global trends.

The objective of Chapter 1 is to explore how disaster risks could be considered in LCA, and through the insights obtained, propose a comprehensive contribution to the research challenge. Therefore, this chapter is divided into three parts, starting with the exploration of LCA, followed by disaster risks, and finally the combined approaches that have been thus far conceived.

## 1.1. LCA Origins, Current Practices and Challenges

Before proposing how to tackle the research challenge of considering disaster risks in Life Cycle Assessment, it must be understood why LCA is done in the first place. The purpose of LCA is inevitably linked to its origins, so some historical background is presented, followed by a general view of the LCA methodology as it is used today, and finalizing with its possible applications and the research challenge that this PhD thesis addresses.

### 1.1.1. A little bit of history

Life Cycle Assessment emerges as a response to a need to estimate the environmental impacts in a more complete, representative, and quantitative way. Therefore, to understand how LCA came to be, it is important to first comprehend where environmental assessment methods come from.

#### 1.1.1.1. Of environmental concerns and sustainability

It cannot be precisely said when concerns for environmental health in parallel with human health began, at least from non-spiritual or religious practices. Among the first clues that we do have are of historical records of forest management and protection practices, dating back to ancient Greece and Rome (Hughes & Thirgood, 1982). Perhaps it is safe to say that people understood what the depletion of forests meant for their livelihoods, especially with cities becoming increasingly populated, and they tried to avoid this tragedy of the commons (Hardin, 1968) with the help of their contemporary political and religious systems.

A very important event in recorded history when human activities caused negative impacts to both human and environmental health and legislative action was taken as a direct response was in the 1950s. In 1952 the people of London suffered from the black smoke emerging amid an industrial revolution (Martinez, 2023). Even though this is not the first time a human society realized that civilizational development had consequences on their livelihoods and their overall well-being, that event set an important precedent that pushed forward environmental conscience and policies (Greater London Authority, 2022). The Clear Air Act, passed in 1956, was perhaps the first document that emerged as a direct response to an issue related to both human health and the environment.

Similar actions continued to gain traction in the 1960s and even more people in the Anglo-Saxon world were made aware of these issues after the publication of *Silent Spring* by Rachel Carson in 1962, which documented the harmful effects of pesticides on the environment and to humans (Carson, 2002). It was in 1969 when the United States approved the National Environmental Policy Act, which introduced one of the first frameworks to aid in the estimation of environmental impacts of a project (Cutaia, 2016) and include such considerations in decision-making processes by “detailing the impacts of the proposed project, as well as project alternatives, on the physical, cultural and human environments” (Burdge, 1991). Furthermore, with the publication of the *Limits to Growth* report by the Club of Rome, the possible reality of human activities depleting natural resources to a critical point (Meadows et al., 1972) fueled the discussions about resource management for mankind’s long-term well-being.

As this movement was gaining traction, in Europe the Directive 85/337/EEC (EU, 1985) the Environmental Impact Assessment (EIA) was established as a method to consider the effects of public and private projects in the environment and ecosystems. Alongside this movement came concerns linked to social issues projects were also being neglected, which came together on 1987 through the Brundtland Report, *Our Common Future*, introducing the concept of **sustainable development**, encompassing the environmental, social, and economic dimensions: “Humanity has

the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission On Environment and Development, 1987).

The following years saw the mobilization of the international community towards sustainable development and environmental protection. Among the most successful historical agreements is the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer, which regulates chemicals that damage the stratospheric ozone layer that protects the planet from the dangerous levels of ultraviolet radiation from the Sun, which had been severely depleted in previous decades (UNEP, 2018). In 1997, during the third Conference of the Parties (COP3 3), the Kyoto Protocol followed by addressing the contribution of greenhouse gas emissions to the rise of average global temperatures, and urging countries to reduce their greenhouse gas emissions through collective international efforts (UNFCCC, 2020). After the turn of the century, in 2002, the United Nations established the Millennium Development Goals, a plan that aimed at achieving eight goals towards human welfare by 2015 (UN, 2015). These served as the basis for the 17 Sustainable Development Goals established in at the COP 21 Paris Climate Change Conference, product of the 2030 Agenda for Sustainable Development that seeks to stimulate actions that promote prosperity, peace, and partnership for the well-being of people and the planet (United Nations, 2015).

#### 1.1.1.2. *Introducing the life cycle perspective*

What sets apart LCA from other environmental impact assessment methods is the consideration of the **life cycle thinking** approach, looking at a product from its “cradle” to its “grave”, taking inspiration from how natural organisms function (Mazzi, 2020). This involves the consideration of the materials and energy used, as well as the water and emissions produced, at each stage involved in the “life” of the product of system analyzed, i.e. from the raw material extraction, transportation, manufacturing, and use phases to the waste management and recycling processes. Life cycle thinking principles go hand in hand with the 12 principles of green chemistry<sup>1</sup> (Anastas & Warner, 1998) and the 12 principles of green engineering (Anastas & Zimmerman, 2003), striving to design efficient chemicals and processes that fulfill their purpose while making degradation and end-of life processes as harmless as possible, among other key characteristics. Moreover, LCA is a method that allows the potential environmental impacts to be evaluated considering different impact categories, a multi-criteria dimension that also sets it apart from other methods.

LCA as we know it is deeply connected to sustainability principles and concerns for the environment and human health. The first documented study that resembles LCA, the Resource and Environmental Profile Analysis, was performed by the Midwest Research Institute under the sponsorship of the Coca-Cola Company in 1969. It compared containers throughout their production chains to determine which one’s effects on the environment and natural resources were the least impactful (Hunt et al., 1992). Efforts of the same institute on the United States for the Environmental Protection Agency and a study in Switzerland in the 1970s are considered the first steps to develop LCA in its current standardized form (Guinée et al., 2011).

The ISO norms 14040 and 14044, first published in 1997, set the basic principles of what LCA is. Despite the debates and criticisms regarding the openness to interpretation of the standards, the

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<sup>1</sup> Synthesized information in the ACS website (last accessed: November, 2024): <https://www.acs.org/greenchemistry/principles/12-design-principles-of-green-engineering.html>



importance of having a standardized basis to rely on is undeniable: without an international consensus, it would have been difficult to accurately communicate and compare different LCA studies. Moreover, this sets the stage to launch LCA into the global community. Programs such as the Life Cycle Initiative (Udo de Haes et al., 2002) -supported by the United Nations Environmental Programme (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC)-, and The European Platform of Life Cycle Assessment (EPLCA, 2018) promoted the application of life cycle thinking from business to policymaking. Such support, not to mention individual contributions by certain countries and regions, has allowed the LCA community to produce valid and meaningful results and further develop the methodology towards new horizons.

All this is reflected in what LCA is as a method today, how it is used in different decision-making contexts, and the different approaches the LCA scientific community has developed throughout the years.

### 1.1.2. LCA in the present

#### 1.1.2.1. The methodological framework

LCA was first standardized in 1997 by the International Standards Organization (ISO) through the norm ISO 14040 (ISO 14040, 2006), with the complimentary norm 14044 (ISO 14044, 2006). It has since been updated to its current 2006 version, which is reviewed every five years (Hauschild, 2018). The iterative methodological framework of LCA as established in the standard consists of four phases (see Figure 1. 1):

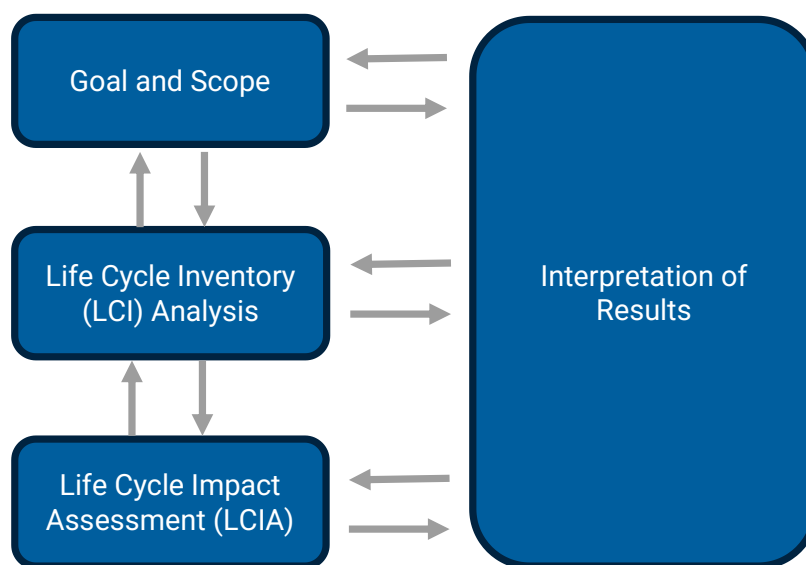


Figure 1. 1. General methodological framework of LCA, adapted from ISO 14040:2006

1. **Goal and scope:** The objective is to define the purpose of the study, its applications and context, the intended audience, and how the results will be presented at the end of the project. Key aspects of this phase are the definition of the product system, the functional unit, the system boundaries, and the modeling approach (Bjørn, Laurent, et al., 2018; Bjørn, Owsianiak, et al., 2018).
2. **Inventory analysis (LCI):** The objective is the collection of data on the material and energy flows of the system, meaning the inputs and the outputs of each process involved. All these flows should be eventually linked to a reference flow, which describes the functional unit. Information is usually obtained from primary data sources (foreground processes) and LCI databases (background processes) (Bjørn, Moltesen, et al., 2018).

3. **Impact assessment (LCIA):** The objective is the transformation of the LCI into quantifiable information on potential environmental impacts. It involves 3 mandatory and 2 optional steps: 1) Selection of impact categories, 2) Classification of elementary flows, 3) Characterization, 4) Normalization, and 5) Grouping or weighting (Rosenbaum, Hauschild, et al., 2018).
4. **Interpretation of results:** The objective is to answer the questions posed in Phase 1, considering all the information from previous phases. Uncertainty and sensitivity analyses are performed to better understand and represent the results, to better determine the robustness of the conclusions, and to identify areas of opportunity for future evaluations (Rosenbaum, Georgiadis, et al., 2018). The end goal is to present the information in a comprehensible and objective way so those who need these results, and their conclusions, can better understand and exploit them.

Given the iterative nature of LCA, each phase is subject to modification after new insights and feedback arise throughout the study. After each iteration, better understanding of the system is gained, uncertainty is reduced, and more refined results are obtained (Hauschild, 2018).

#### 1.1.2.2. LCA and Beyond

Historically, research in LCA has always strived to expand the methodology to reduce uncertainty and deliver the best possible assessment, presenting results that make sense to the intended audience and can serve as strong basis for decision-making and sustainable development goals. The intention of this PhD thesis is to contribute to the coherent broadening of the scope of LCA to have more comprehensive environmental assessment results. Some existing LCA approaches are presented in the following paragraphs to show the broad panorama the LCA community has built through the years, what can be expected from future developments, and which subdomains the contribution of the thesis can address.

Some LCA approaches address the question of broadening the scale of the assessment, going beyond products and product systems. A relevant example is the Territorial LCA, which addresses geographically defined systems by either contextualizing the LCA of an activity that is bound to a territory and depends on its geographical context, or it enables an LCA of the territory itself by considering all the activities within said territory. Its purpose is to better identify environmental hotspots that aid decision-making aiming to improve future regional policies (Loiseau et al., 2018). Territory-specific LCAs can aid in studying specific phenomena that could be otherwise missed through a general application of the method.

Since LCA encompasses the life cycle and the lifespan of product systems in its model, the concepts of temporality are also a subject of concern. An LCA approach that considers systems modeled with inherent variations or evolutions within the temporal scope of the components that make up the model is Dynamic LCA, making clear temporal distinctions for each of the flows that are defined (Beloin-Saint-Pierre et al., 2020). Identifying flows this way allows for a more detailed study of the environmental impacts throughout distinct moments of the lifespan of a product system.

When addressing temporality in LCA, the environmental impact assessments that are usually performed are of product systems that already exist and sufficient information is available to make good estimates, otherwise known as ex-post assessments. However, LCA also possesses the potential to estimate the environmental impacts of future or emerging product systems. This approach is known as prospective LCA, which “models the product system at a future point in time relative to the time at which the [LCA] study is conducted” (Arvidsson et al., 2023). They often consider product systems that involve technologies that are in course of development and/or

commercialization. The purpose is to anticipate the consequences of the decisions made at early stages of development and make the best possible decisions and perform course corrections before it is too late (Cucurachi et al., 2018; Olsen et al., 2018). Currently, prospective LCA studies and approaches are being supported and developed by an important part of the LCA scientific community, notably communicating through the Prospective LCA Network<sup>2</sup>. Given the interest in this type of LCA approach, significant progress and research is expected to continue.

The intention behind conceiving multiple variations and approaches to perform LCA studies is to provide information that is as pertinent and as accurate as possible for its intended application to support decisions. It is not the same to perform an LCA on the packaging options of gaseous drinks than on the alternative configurations for a photovoltaic power plant in a certain region. Therefore, to determine which is the best LCA approach to use, the nature of the decisions related to the intended application must be well understood.

### 1.1.3. LCA for decision making

LCA applications depend on a multitude of factors, but the most important one is probably the decision-making context. Defining this context happens in the first phase of LCA, namely the Goal and Scope Definition, where the LCA practitioner determines the intended uses of the results, the limitations, the decision context and the reasons for performing the study, the target audience, what will be communicated to the public, as well as the parties (stakeholders) involved in the study (Bjørn, Laurent, et al., 2018).

Decisions occur at various levels, therefore, they have vastly different scopes and impacts. Owsianiak et al. (2018) address three possible perspectives, corresponding to how the information given by LCA results might be used.

First, the *government perspective*, which focuses on policy formulation, implementation, and evaluation. Second, the *citizen perspective*, which focuses on the criteria used by consumers to choose one product over another, as well as how the aftermath of political discussions on infrastructure and public policies will impact them. Third, the *industry perspective*, which focuses on marketing, competitive advantages, strategic planning, and the development, follow-up and selection of products, processes, suppliers, etc. (Owsianiak et al., 2018) This is perhaps the LCA perspective that is easier to understand for non-LCA practitioners because results are often presented as comparative analyses between two or more choices that are being evaluated under certain criteria. For example, between two types of photovoltaic module technologies that could be installed to produce electricity in a 3 kilo-Watt peak (kWp) power plant under the same operating conditions in a certain region.

LCA applications related to the latter perspective face a particular challenge: visions and end goals may conflict between the academic LCA practitioners that perform the assessment, and the industrial actors who fund the LCA studies and make decisions based on their results. On the industry side, faster and simpler models are desired because they are cheaper to carry out and the results can be available more quickly for their intended use. On the other hand, the objective of academics is to expand the field and provide more comprehensive assessments, which would consume more time and resources to perform, but the results provided would have enhanced credibility and reliability

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<sup>2</sup> Website, last recovered in February 2024: <https://prospectivelcanetw.wixsite.com/prospectivelcanet>

(Pryshlakivsky & Searcy, 2021). Mutual understanding between stakeholders and their needs would allow the execution of a balanced assessment since both visions have their own strengths and limitations.

In this regard, both industrial actors/decision-makers and LCA practitioners have responsibilities to fulfill. On the decision-makers side, these relate to the acknowledgement of how LCA results are produced, which affect the way they are interpreted and presented. To make better use of the information, they should understand that there is uncertainty and variability involved in the LCA calculations, meaning that environmental impact results are interpreted with statistical analyses that go beyond single scores. On the LCA practitioners' side, developing and performing more complex and complete assessments involves making several compromises to produce coherent results. However, such decisions could unfavorably affect the credibility and usability of the results. For example, some assumptions made about the product system, i.e. considering no changes in production capacity and no potential disruptions due to changes in policies, the market and/or the environment, may present situations that are unrealistic for decision makers (Pryshlakivsky & Searcy, 2021). The unfavorable consequence of such assumptions may be that decision-makers opt not to rely on the LCA results to avoid potentially conflicting information.

Through this panorama, it can be comprehended that to enable better and more comprehensive LCA applications there are still several challenges to overcome. Finkbeiner et al. (2014) addressed this topic in detail, identifying 34 LCA gaps and challenges that involve aspects related to the inventory, the impact assessment, data, modelling, uncertainty analysis, and others. Among these research gaps, an important point is made on the usual application of LCA: despite its versatility and global scope as a decision aid tool, studies usually focus on evaluating product systems using models and scenarios that describe average operating conditions or steady states. Therefore, deviations from those standard conditions or procedures are not considered in the assessment, specifically on the inventory phase. Finkbeiner et al. use the term "improbable events" to refer to the causes of these possible deviations, which could have important effects on the LCI flows and the impact assessment results. They go as far as stating that: "For a comprehensive and realistic assessment of potential environmental impacts of e.g. technologies, improbable events need to be taken into account within LCA. Exclusion of the effects of improbable events could lead to wrong conclusions." (Finkbeiner et al., 2014) This means that there could be major issues if the low-impact alternative chosen after performing an LCA study produces flows with high environmental impacts when adversely affected by an improbable event. Moreover, the consequences of such improbable events could go beyond deviations (e.g., interruption of PV electricity production because of additional cleaning after a dirt storm or a faulty component) and translate to actual damages to the system (e.g., an inverter rendered useless after a centennial flood). If these types of damages were to be considered in LCA, they would undoubtedly change the impact assessment results.

In the same publication, Finkbeiner et al. (2014) shared that the potential impacts of improbable events can be evaluated through generic risk assessments, and that LCA even considers risks at the impact assessment level through human toxicity or ecotoxicity potential. This approach suggests that improbable events are caused by system failures or internal accidents, in other words, industrial or technological disasters. However, these considerations could also be made for improbable events that happen outside the product systems and can disrupt their operations and performance, such as natural disasters (e.g. hurricanes) and external technological disasters (e.g. explosion from an adjacent industrial facility). This academic subject is further discussed in section 1.3.

Taking all of this into consideration, the aim of the present PhD thesis is to contribute to this research gap in LCA by including the effects and potential consequences of disaster risks on the environmental performance of product systems. To explore how this could be achieved, it is necessary to identify the nature of these phenomena, how they are analyzed, and their possible evolutions.

## 1.2. Disaster risks

Natural and technological disasters are events that have had direct and indirect effects and consequences on infrastructure projects, such as the Lothar and Martin storms in 1999 (Sanson et al., 2000), the AZF factory disaster in 2001 (Terssac & Gaillard, 2008), the Xynthia storm in 2010 (Anziani, 2010), and the Alex storm in 2020 (Carrega & Michelot, 2021). Furthermore, said disasters also have serious environmental impacts, affecting the quality of the air, soil, and water. Additionally, the damage suffered by infrastructures induces repair and maintenance operations that also have non negligible environmental consequences, which are so far not considered in conventional LCAs. These situations are considered as improbable events and their inclusion in LCA represents a research and development challenge (Finkbeiner et al., 2014). Tackling this challenge is all the more important because global trends, such as climate change, the densification of territories, and the increase in interdependences between technological systems, seem to be contributing to an important increase in the frequency and intensity of disasters.

This section aims to explore the nature of a disaster and the essential concepts to consider during environmental assessments. First, the diversity of disasters is presented and illustrated through examples of past events. Then, the essential concepts for studying a disaster are characterized. Finally, the factors that influence the evolution of disaster risks are discussed.

### 1.2.1. Disaster definition

In 1961, the sociologist Charles Fritz defined **disaster** as "an event, limited in time and space, in which a society, or a relatively autonomous subdivision of a society, comes into serious danger and suffers such losses to its members and its material heritage that the social structure is disrupted and that the accomplishment of all or part of its essential functions is prevented" (Fritz, 1961; Giry, 2023).

Thus, disaster can be understood as a sudden event that occurs within a short period, affecting a limited space and causing considerable damage to human societies, the natural environment, and infrastructures. Initially triggered by natural phenomena, such as earthquakes, storms, floods, or volcanic eruptions, these disasters can be exacerbated by potentially vulnerable technological installations, such as chemical factories or nuclear power plants, or by the consequences of slower and progressive trends, such as climate change or economic crises. A disaster puts to the test the limits of the adaptation capacities of organizations and territories. The significant human, material, and economic losses incurred highlight the intrinsic weaknesses and inequalities of the systems in place. In addition, a disaster causes significant psychological repercussions on the affected population, such as post-traumatic stress and emotional distress, and disrupts relationships of trust between individuals and authorities (Quarantelli, 1998).

To characterize disasters, two major classification schemes are through a triggering agent-based approach, or according to the intensity of its consequences. These two classifications are discussed in the following paragraphs.

### 1.2.1.1. Triggering agent-based classification

A traditional approach to distinguishing disasters relies on identifying the agent or hazard causing the event. Thus, disasters are generally classified into several categories, including natural, technological, health, and social and political disasters (Dauphiné & Provitolo, 2013). More recently, a new category has emerged: NATECH disasters (Necci & Krausmann, 2022), which combine natural and technological elements.

Natural disasters result from natural events such as storms, hurricanes, earthquakes, tsunamis, landslides, avalanches, severe thunderstorms, wildfires, heat waves, cold waves, hail, lightning, and flash floods. In France, according to data from the Statistical Data and Studies Service (SDES), from 1900 to 2021, 520 natural events caused damage and more than 32,000 deaths. Between 1982 and 2023, 17,500 events have been officially recognized as natural disasters. Among them, 56% were floods, 17% were linked to land movements and the shrinkage-swelling of clays, and 8% were due to atmospheric phenomena. Over the past 40 years, insurance companies have paid around €50 billion in compensation under the natural disaster regime (CGDD, 2023).

Technological disasters result from failures, accidents, or faulty practices associated with industrial technologies, infrastructure, or processes. They can occur in a variety of contexts, including major industrial accidents, nuclear incidents, toxic chemical spills, explosions at industrial facilities, transportation accidents such as train derailments or maritime accidents, system failures in critical areas such as power grids or computer systems, or even massive cyberattacks. These disasters can result in human losses, significant environmental damage, and long-lasting economic and social repercussions. Notable examples of technological disasters in France include the failure of the Malpasset dam in 1959 (423 casualties and 7,000 injured) and the explosions and fires in the LPG storage area of the Feyzin refinery in 1966 (18 casualties and 84 injured), as well as the explosion in the AZF factory in Toulouse in 2001 (31 casualties and several thousand injured) (Dauphiné & Provitolo, 2013).

Health-related disasters are those that have impacts on human health, often associated with a significant increase in mortality. They are triggered by various pathogens such as fungi, bacteria, viruses, or parasites, as well as by chemical contaminants such as heavy metals, hydrocarbons, or dioxins, and physical phenomena such as ionizing radiation, ultraviolet rays, electromagnetic fields, noise, and extreme temperatures (UNDRR, 2007b). The pandemics of the Black Death (1347-1352), the Spanish Flu (1918-1920), AIDS, and COVID-19 are all examples of major health disasters that have had a significant impact on public health throughout the world.

Social and political disasters often emerge from economic, political, religious, and cultural circumstances. They can manifest themselves in armed conflicts, terrorism, organized or diffuse crime, and urban riots (Dauphiné & Provitolo, 2013). The current tensions between Ukraine and Russia, the conflicts in the Middle East, and the terrorist attacks in Paris and Nice in France illustrate examples of social and political catastrophes having a profound and lasting impact on the societies concerned.

A NATECH disaster occurs when a natural disaster triggers a technological accident or industrial disaster. These events occur when natural phenomena, such as storms, floods, earthquakes, or landslides, interfere with industrial facilities, critical infrastructure, or storage sites for hazardous substances, leading to severe environmental and public safety consequences. NATECH disasters can be particularly devastating because they combine the destructive effects of natural phenomena with

the dangers associated with industrial facilities, increasing the risk of human loss, environmental damage, and socio-economic disruption. NATECH disasters include chemical leaks during floods, explosions of oil installations during earthquakes, or power plant fires sparked by lightning (INERIS, 2023; Necci & Krausmann, 2022). Notable historical examples of NATECH disasters are the failure of the Malpasset dam in 1959, and the earthquake plus tsunami that triggered the nuclear accident at Fukushima in 2011.

1.2.1.2. Intensity of consequences-based classification

An alternative to the classification of disasters according to the nature of the triggering agent is based on the intensity of the damage disasters cause.

In France, events are classified based on human and material damage. One typology is available for events caused by natural hazards and another for events having a technological origin (see Table 1. 1).

Table 1. 1. Typology of natural and technological disasters, adapted from Dauphiné and Provitolo (2013)

Class		Natural disaster		Technological disaster	
		Human damage	Material damage	Human damage	Material damage
0	Incident	No injuries	Less than 0.3 million Euros	No victims	Less than 0.05 million Euros
1	Accident	1 or more injured	0.3 to 3 million Euros	1 death	0.05 to 0.1 million Euros
2	Serious accident	1 to 9 deaths	3 to 30 million Euros	2 to 5 deaths	0.1 to 0.5 million Euros
3	Very serious accident	10 to 99 deaths	30 to 300 million Euros	6 to 19 deaths	0.5 to 2 million Euros
4	Disaster	100 to 999 deaths	300 million to 3 billion Euros	20 to 49 deaths	2 to 10 million Euros
5	Major disaster	1000 deaths or more	More than 3 billion Euros	59 deaths or more	More than 10 million Euros

Scales specific to hazards, the sources of disasters, make it possible to characterize the events causing disasters. In the following paragraphs four examples are presented for wind, hurricanes and cyclones, earthquake and nuclear and radiological events.

The Beaufort scale measures wind force based on its observable effects on the sea surface or land. It represents the mean wind speeds averaging over 10 minutes at a 10-meter elevation, without wind gusts. It was designed in 1805 by British Admiral Sir Francis Beaufort and was initially used to help sailors estimate wind strength at sea (Encyclopaedia Britannica, 2024). The Beaufort scale has 13 levels (see Table 1. 2), ranging from 0 (calm) to 12 (hurricane), each associated with specific descriptions of observed conditions, such as wind speed, effects on the sea, foam formation, and damage to land structures. Although the Beaufort scale was developed for observation at sea, it is also used to estimate wind strength on land, particularly in meteorology.

Table 1. 2. The Beaufort scale for strong wind (Météo-France, 2024a)

Force	Description	Wind speed		Sea conditions	Land conditions
		knots	km/h		
0	Calm	< 1	< 2	Sea like a mirror	Smoke rises vertically with little to no drift.
1	Light air	1–3	2–5	Ripples with appearance of scales are formed, but without foam crests	The direction of wind is shown by smoke drift, not by wind vanes. Little if any movement with flags. Wind barely moves tree leaves.
2	Light breeze	4–6	6–11	Small wavelets still short but more pronounced; crests have a glassy appearance but do not break	Wind felt on face. Leaves rustle and small twigs move. Ordinary wind vanes move.
3	Gentle breeze	7–10	12–19	Large wavelets; crests begin to break; foam of glassy appearance; perhaps scattered white horses	Leaves and small twigs in constant motion. Wind blows up dry leaves from the ground. Flags are extended out.
4	Moderate breeze	11–16	20–28	Small waves becoming longer; fairly frequent white horses	Wind moves small branches. Wind raises dust and loose paper from the ground and drives them along.
5	Fresh breeze	17–21	29–38	Moderate waves taking a more pronounced long form; many white horses are formed; chance of some spray	Large branches and small trees in leaf begin to sway. Crested wavelets form on inland lakes and large rivers.
6	Strong breeze	22–27	39–49	Large waves begin to form; the white foam crests are more extensive everywhere; probably some spray	Large branches in continuous motion. Whistling sounds heard overhead or nearby power and telephone lines. Umbrellas used with difficulty.
7	High wind, moderate gale, near gale	28–33	50–61	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind; spindrift begins to be seen	Whole trees in motion. Inconvenience felt when walking against the wind
8	Gale, fresh gale	34–40	62–74	Moderately high waves of greater length; edges of crests break into spindrift; foam is blown in well-marked streaks along the direction of the wind	Wind breaks twigs and small branches. Wind generally impedes walking.
9	Strong/severe gale	41–47	75–88	High waves; dense streaks of foam along the direction of the wind; sea begins to roll; spray affects visibility	Structural damage occurs, such as chimney covers, roofing tiles blown off, and television antennas damaged. Ground is littered with many small twigs and broken branches
10	Storm, whole gale	48–55	89–102	Very high waves with long overhanging crests; resulting foam in great patches is blown in dense white streaks along the direction of the wind; on the whole the surface of the sea takes on a white appearance; rolling of the sea becomes heavy; visibility affected	Seldom experienced inland. Considerable structural damage occurs, especially on roofs. Small trees may be blown over and uprooted.
11	Violent storm	56–63	103–117	Exceptionally high waves; small- and medium-sized ships might be for a long time lost to view behind the waves; sea is covered with long white patches of foam; everywhere the edges of the wave crests are blown into foam; visibility affected	Very rarely experienced. Widespread damage occurs. Larger trees blown over and uprooted.
12	Hurricane	>64	>118	The air is filled with foam and spray; sea is completely white with driving spray; visibility very seriously affected	Severe and extensive damage. Roofs can be peeled off. Windows broken. Trees uprooted. RVs and small mobile homes overturned. Moving automobiles can be pushed off the roadways



The Saffir-Simpson scale is a measurement scale used to classify the intensity of hurricanes and tropical cyclones based on potential damage and the maximum wind speeds. This scale was developed in the 1970s by civil engineer Herbert Saffir and meteorologist Robert Simpson. The Saffir-Simpson scale has five categories, ranging from Category 1 to Category 5, depending on the maximum sustained wind speed at a 10-meter elevation averaged over a 1-minute interval. Each category is associated with estimates of potential damage and impacts on infrastructure, homes, and populations. Category 3 to 5 hurricanes are considered significant due to their capacity to cause catastrophic damage (see Table 1. 3) (NOAA, 2021).

Table 1. 3. The Saffir-Simpson scale for hurricanes and cyclones (NOAA, 2021)

Category	Wind speed	Damage
Category 1	Winds from 119 to 153 km/h	Very dangerous winds will produce some damage
Category 2	Winds from 154 to 177 km/h	Extremely dangerous winds will cause extensive damage
Category 3	Winds from 178 to 208 km/h	Devastating damage will occur
Category 4	Winds from 209 to 251 km/h	Catastrophic damage will occur
Category 5	Winds over 252 km/h	Catastrophic damage will occur

The Richter scale, developed in 1935 by seismologist Charles F. Richter, is a logarithmic scale used to measure earthquake magnitude, that is, the amount of energy released by an earthquake. This scale is based on recordings of seismic waves detected by seismographs. Contrary to what many believe, the Richter scale does not have a fixed upper or lower limit, although it is generally used to measure earthquakes of small to moderate magnitude. Each increase of a point on the Richter scale corresponds to a 10-fold increase in the amplitude of the recorded seismic wave. For example, a magnitude 6.0 earthquake releases approximately 31.6 times more energy than a magnitude 5.0 earthquake. The Richter scale is widely used in seismology to quantify and compare the intensity of earthquakes worldwide (see Table 1. 4) (Rafferty, 2024).

Table 1. 4. The Richter scale for earthquakes (GNS Science, 2021)

Magnitude	Description	Effects
1.0–1.9	Micro	Microearthquakes, not felt. Recorded by seismographs
2.0–2.9	Minor	Felt slightly by some people. No damage to buildings.
3.0–3.9	Slight	Often felt by people, but very rarely causes damage. Shaking of indoor objects can be noticeable.
4.0 – 4.9	Light	Noticeable shaking of indoor objects and rattling noises. Felt by most people in the affected area. Slightly felt outside. Generally, causes zero to minimal damage. Moderate to significant damage is very unlikely. Some objects may fall off shelves or be knocked over.
5.0 – 5.9	Moderate	Can cause damage of varying severity to poorly constructed buildings. Zero to slight damage to all other buildings. Felt by everyone.
6.0–6.9	Strong	Damage to a moderate number of well-built structures in populated areas. Earthquake-resistant structures survive with slight to moderate damage. Poorly designed structures receive moderate to severe damage. Felt in wider areas; up to hundreds of kilometers from the epicenter. Strong to violent shaking in the epicentral area.
7.0–7.079	Major	Causes damage to most buildings, some to partially or completely collapse or receive severe damage. Well-designed structures are likely to receive damage. Felt across great distances with major damage mostly limited to 250 km from the epicenter.
8.0–8.9	Great	Major damage to buildings, and structures likely to be destroyed. Will cause moderate to heavy damage to sturdy or earthquake-resistant buildings. Damaging in larges areas. Felt in extremely large regions.
9.0–9.9	Extreme	Near total destruction – severe damage or collapse to all buildings. Heavy damage and shaking extend to distant locations. Permanent changes in ground topography.

The International Nuclear and Radiological Event Scale (INES) is an international scale used to classify and communicate the significance of nuclear and radiological events. Developed by the French Nuclear Safety Authority (ASN) and the International Atomic Energy Agency (IAEA), the INES scale is designed to provide a rapid and uniform assessment of the severity of nuclear incidents and accidents to inform the public and the competent authorities. The INES scale has seven levels, ranging from 0 to 7, each associated with a specific description of the importance of the event. Each level of the INES scale is defined according to specific criteria linked to nuclear safety, radiation, and the consequences for human health and the environment. The INES scale is used by nuclear regulatory authorities worldwide to assess and classify nuclear and radiological events and coordinate appropriate responses and actions in the event of an incident (IAEA, 2019).

Table 1. 5. INES scale for nuclear and radiological events (IAEA, 2019)

Level	Description
0	No sign of significant impact on safety
1	Minor anomaly with little or no risk to safety
2	Anomaly with low safety risk
3	Serious incident involving limited radiological risks off-site
4	Serious accident with radiological risks extending off-site
5	Accident with wider health and environmental consequences
6	Major accident with significant impact on health and the environment
7	Major accident with regional or global consequences

## 1.2.2. Concepts and models of disaster management

### 1.2.2.1. Concepts of disaster management

Since 1990 and the UN Resolution 44/236, the United Nations developed four programs for disaster risk reduction: 1) the International Decade for natural disaster reduction (19994 – 1999), 2) The Yokohama Strategy for a safer world (1999 - 2005), 3) the Hyogo framework for action (2005 – 2015) and 4) the Sendai framework for disaster risk reduction (2015 – 2030). **Disaster Risk Reduction** is defined as “the conceptual framework of elements considered with the possibilities to minimize vulnerabilities and disaster risks throughout a society, to avoid (prevention) or to limit (mitigation and preparedness) the adverse impacts of hazards, within the broad context of sustainable development” (UNESCO, 2010). Within this context, the United Nations Office for Disaster Risk Reduction (UNDRR) defines essential concepts to manage disaster risk, which are presented in the following paragraphs.

A **disaster** is “a serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability, and capacity, leading to one or more of the following: human, material, economic, and environmental losses and impacts” (UNDRR, 2007a).

**Disaster management** consists in “the organization, planning, and application of measures preparing for, responding to and recovering from disasters” (UNDRR, 2017).

These tasks rely on the concept of **disaster risk** defined as “the potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period, determined probabilistically as a function of hazard, exposure, vulnerability, and capacity”

(UNDRR, 2009b). Thus, hazard, exposure, vulnerability, and capacity are the four factors that determine the risk of a disaster.

A **hazard** is “a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation” (UNDRR, 2007b).

**Exposure** is “the situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas” (UNDRR, 2009c).

**Vulnerability** pertains to the “conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards” (UNDRR, 2007d).

**Capacity** is “the combination of all the strengths, attributes and resources available within an organization, community or society to manage and reduce disaster risks and strengthen resilience” (UNDRR, 2009a).

Finally, the concept of **resilience** is defined as “the ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management” (UNDRR, 2007c). It supports the development of several models related to disaster management.

#### 1.2.2.2. Models of disaster analysis

Models for disaster analysis differ from each other because of how the different concepts are integrated and how they relate to one another. In the following paragraphs three examples that use different disaster risk management concepts are presented.

The Disaster Resilience of Place (DROP) model (see Figure 1. 2) presents a relationship between resilience and vulnerability at a local level that aims to improve comparative assessments of communities (Cutter et al., 2008), which are also applicable to localized systems and infrastructures. The DROP model considers the prevention and preparation measures that could be taken before a hazard event arrives, i.e. the antecedent conditions, the possible responses after the event, the impact/consequences on the community, and the degree of recovery depending on the capacity to absorb the impact and the adaption measures taken in the long term, i.e. resilience.

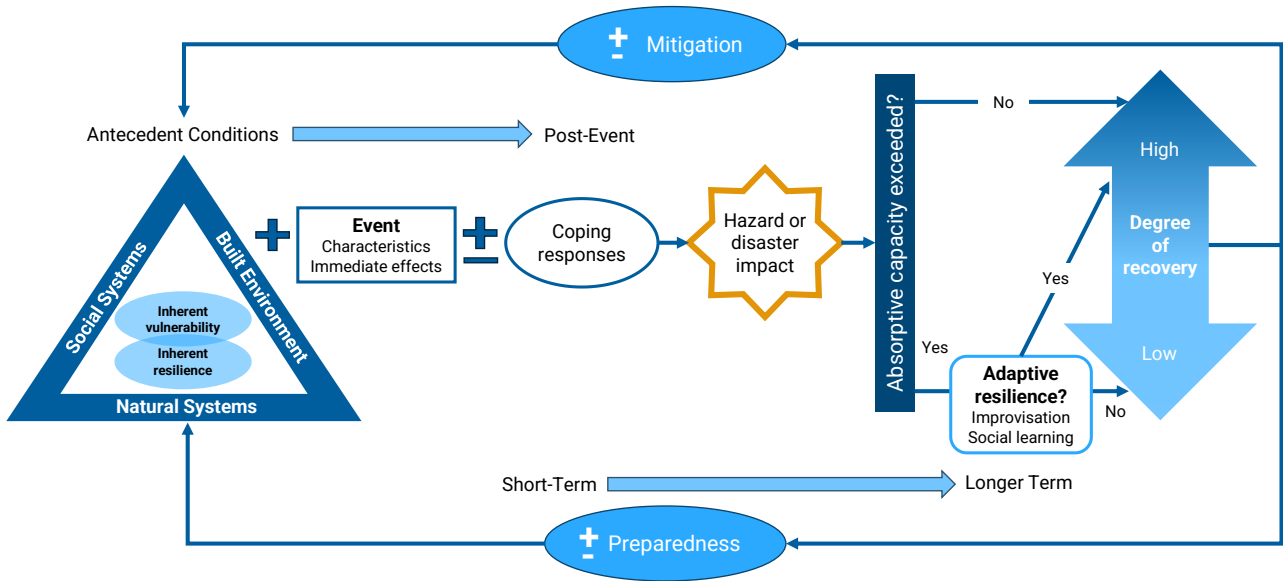


Figure 1. 2. Disaster Resilience of Place (DROP) model (Cutter et al., 2008)

Resilience, independently of vulnerability, was first conceived in the ecological sphere by Holling (1973) as “a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations and state variables”. Its definition and modeling have since been the subject of debate. In this PhD thesis the suggestion of Mentges et al. (2023) is followed, thus restricting resilience to capacity, as defined previously. A graphical way to understand resilience is through the hypothetical performance curve of a product system (see Figure 1. 3), which can be divided in four phases (Mentges et al., 2023): 1) planning before the disruptive event, 2) absorbing the impact from the disruptive event, 3) recovering from the disruptive event, and 4) adapting after the disruptive event. Resilience management implies the consideration of these four steps to strengthen the capacity of a system to deal with disruptions, meaning that systems should aim to become better at recovering, learning, and adapting.

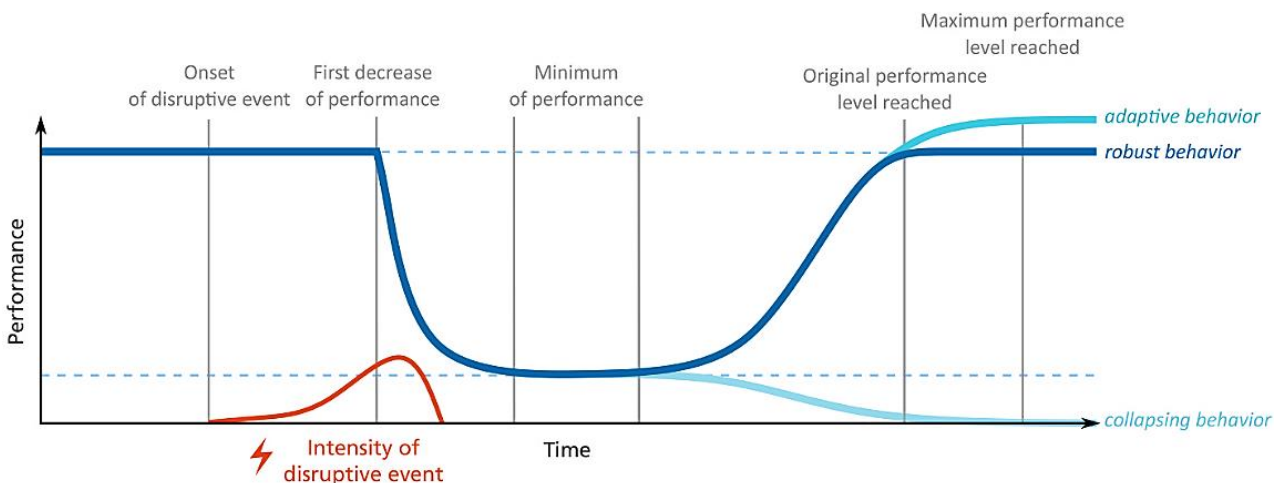


Figure 1. 3. Representation of resilience through the performance curve (Mentges et al., 2023)

Finally, a model that considers hazards, exposure, and vulnerability is Risk Assessment. It is a part of the Risk Management process, and it is defined as the overall process of identifying, analyzing, and evaluating risk. According to the norm ISO 31000 (ISO 31000, 2018), it should be conducted in a systematic, iterative, and collaborative manner, drawing on the knowledge and views of the related

stakeholders. Moreover, it should make use of the best available information, and further supplemented as it becomes necessary. The general steps of Risk Assessment are briefly described in the following points: (Poljansek et al., 2017)

1. *Risk Identification*: It has the purpose of finding, recognizing, and describing risks that might help or hinder an organization in achieving its objectives.
2. *Risk Analysis*: It aims to comprehend the nature of risk and its characteristics, including the level of such risk. It considers in detail the uncertainties, risk sources, possible interactions, consequences, likelihood, events, scenarios, controls, and their effectiveness. Inputs to this stage could be historical (experience, records, documentation, etc.), predictive (modelling and experimentation) or a mix of both.
3. *Risk Evaluation*: Risks and their consequences are leveled against the permissible limits determined by the decision-makers, and if the risks are unacceptable/intolerable then the management actions that must be taken to reduce this risk and/or mitigate its consequences are decided.

The purpose of the information obtained from analyzing disaster risks is to use it in decision-making activities to act more efficiently and avoid possible adverse consequences to systems and communities. The models for hazards, exposure, vulnerability, and resilience serve this purpose, and they are used for disaster risk management (DRM) processes. DRM aims to increase knowledge that will aid in the enhancement of the prevention and mitigation, preparedness, response and recovery capabilities of regions faced with disaster risks (Poljansek et al., 2017).

### 1.2.3. Evolution of disaster risks

Disaster risk, as the hazards that cause them, change and evolve as the world around them does. Unfortunately, disaster risk evolution trends suggest that there is an increased frequency and intensity of disasters around the world.

For example, the international Emergency Events Database (EM-DAT)<sup>3</sup>, maintained by the Centre for Research on the Epidemiology of Disasters (CRED), provides records on natural and technological disasters since 1900. Their records highlight an increase in the number of natural and technological disasters from 44 in the year 1960 to more than 500 in 2022 and 2023. Note that an event is recorded if it satisfies at least one criterion: 10 fatalities, 100 affected people, a declaration of a state of emergency, or a call for international assistance. In 2023 EM-DAT recorded a total of 399 disasters related to natural hazards. These events resulted in 86,473 fatalities and affected 93.1 million people, and the economic losses amounted to 202.7 billion US dollars (CRED, 2024).

This section explores the possible changes disaster risks can undergo because of major global trends, and also due to the interaction between natural and technological risks.

#### 1.2.3.1. Global trends-driven disaster risk evolution

Major global trends or mega-trends refer to phenomena and lines of development with worldwide influence over large periods of time. The European Strategy and Policy Analysis System has identified the top seven prevailing mega-trends in Europe that are also applicable around the globe: climate change, demographic densification, urbanization, (uneven) economic growth, energy consumption,

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<sup>3</sup> EM-DAT website (Last accessed May 2024): <https://www.emdat.be/>

connectivity, and geopolitics (Gaub, 2019). These trends are interconnected and will inevitably affect each other's development.

From the findings in the IPCC Sixth Assessment Report, it is clear that climate change is one of the most important topics of the century, and the increase of global average temperatures that contributes to this trend has been heavily influenced by anthropogenic activities (Lee et al., 2023). Moreover, there is strong evidence to suggest that this is the driving force behind the present and future increase in frequency and intensity of natural disasters and extreme events, both from the hazard and exposure perspective, and by rendering ecosystems and human societies more vulnerable to these events (IPCC, 2023).

A way to study climate change and its consequences in the distant future is through scenarios, and among the most used scenarios are the Representative Concentration Pathways (RCP). These describe pathways of greenhouse gas emissions and atmospheric concentrations, air pollutant emissions, and land use changes in the 21<sup>st</sup> century, up to 2100 (IPCC, 2014). More recently, these pathways have been analyzed alongside the Shared Socioeconomic Pathways (SSP) (O'Neill et al., 2016) to understand the plausible social risks and response operations when faced with climate change. The SSPs are presented as narratives, as shown in Table 1. 6.

Table 1. 6. SSPs and RCPs, adapted from (O'Neill et al., 2017; Rogelj et al., 2018)

SSPs	RCPs	Description
SSP1	RCP 1.9, RCP 2.6	Sustainability: The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries.
SSP2	RCP 4.5	Middle of the road: The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns.
SSP3	RCP 7.0	Regional rivalry: A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues.
SSP4	RCP 3.4, 6.0	Inequality: Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries.
SSP5	RCP 8.5	Fossil-fueled development: This world places increasing faith in competitive markets, innovation, and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated.

These scenarios were developed with the help of Integrated Assessment Models (IAMs), which represent the complex interactions between physical and social systems in a relatively simplified way through computer-aided modeling (IAMC, 2022). IAMs let scientists study scenarios with a large variety of hypotheses. These can reflect through their modeling scheme, to some extent, the effects of other mega-trends. For example, IMAGE<sup>4</sup> is one of the important IAMs that simulates the environmental consequences of human activities around the globe, taking into account complex

<sup>4</sup> IMAGE website (Last accessed May 2024):  
[https://models.pbl.nl/image/Welcome\\_to\\_IMAGE\\_3.3\\_Documentation](https://models.pbl.nl/image/Welcome_to_IMAGE_3.3_Documentation)

biophysical processes and an economic model including agricultural and energy systems, as some policy instruments, among others (Stehfest et al., 2014).

1.2.3.2. Coupling-driven disaster risk evolution

If climate change contributes to the increased frequency and magnitude of natural hazards, other global trends, such as the densification of territories or the complexification of industrial society, affect nature and the consequences of disasters. The 2011 Japan triple disaster, where a submarine earthquake event -induced a Tsunami that provoked a nuclear disaster, illustrates the changing nature of disasters from a single threat to multiple hazards and cascading effects (World Nuclear Association, 2024).

Thus, the need to consider disaster events that are not caused by a single simple hazard but by the interaction between natural hazards and technological systems is highlighted. To consider these relationships, four new paradigms to study and analyze risks and their impacts have emerged (see Figure 1. 4). Compound risks address the interaction of extreme events or their sources, such as climate change, sea-level rise or events that merely happen at once. Interacting risks address environmental drivers that directly or indirectly provoke other impacts, such as seismic activity that induces mass movements. Interconnected risks address the interaction of natural and technological systems, which includes NATECH events. Finally, cascading risks address the disruption of critical infrastructure and related organizational systems (Alexander & Pescaroli, 2019).

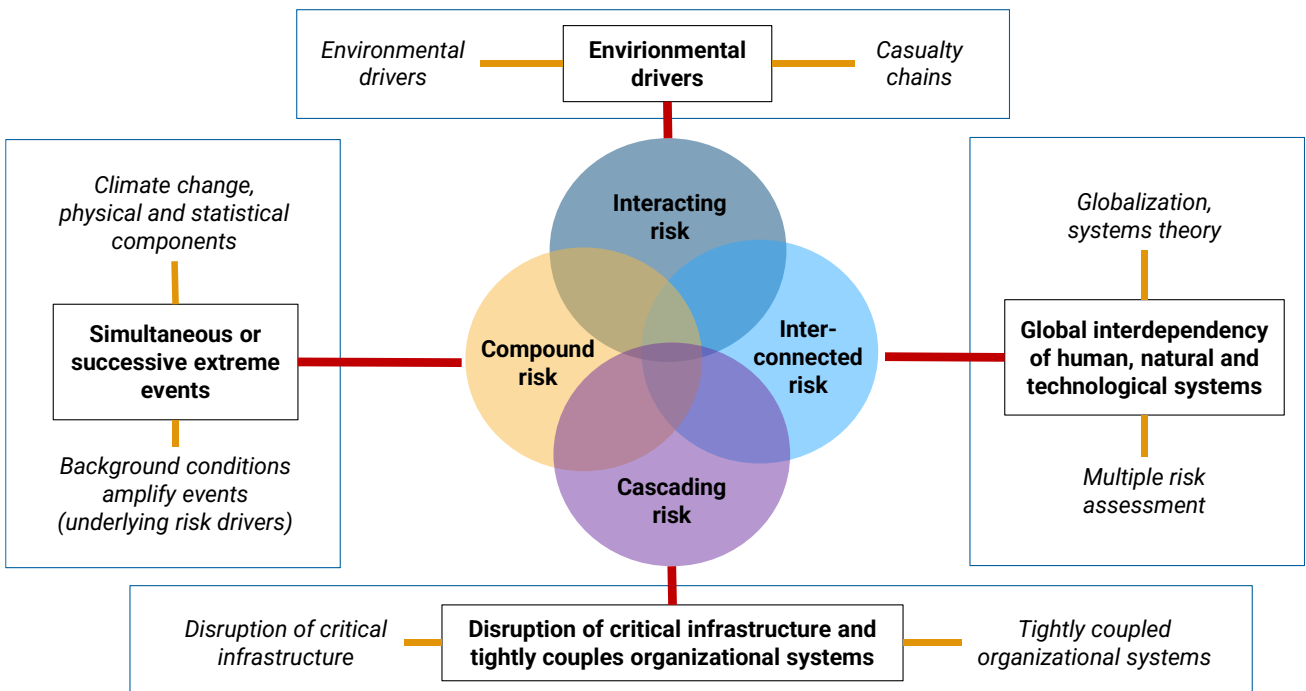


Figure 1. 4. Compound, interconnected, interacting and cascading disasters, adapted from (Alexander & Pescaroli, 2019)

Natural-Technological (NATECH) accidents refer to the fact that “natural hazards, such as earthquakes, floods or storms, can trigger the release of toxic substances, fires and explosions when impacting industrial installations that process, store or transport hazardous materials”. (Necci & Krausmann, 2022) Climate change is having a remarkable impact on the frequency and intensity of some natural hazards, therefore it has become an increasingly important topic in disaster risk management, which should seriously consider the TECH dimension that is often overlooked when looking into consequences of natural hazards. For example, in France, data from the ARIA database

demonstrates that there has been an increased number of events caused or aggravated by intense natural phenomena, such as rain-floods, extreme heat, or wind (see Figure 1.5).

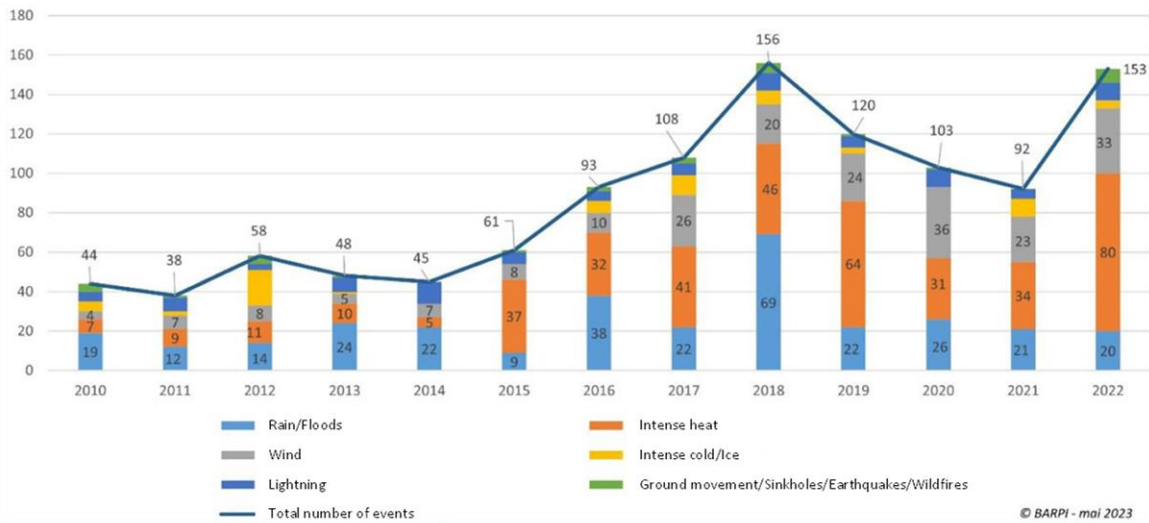


Figure 1. 5. Evolution of the occurrence of NATECH events in France (INERIS, 2023)

### 1.3. LCA Considering Disaster Risks

Considering disaster risks in Life Cycle Assessment presents an opportunity to provide a more comprehensive assessment of the environmental impacts of product systems. It also presents a research challenge because including disaster risks involves their consideration at different levels of the LCA, from the goal and scope definition, the LCI and the LCIA, to the interpretation of results (Finkbeiner et al., 2014). Moreover, the results of the assessment must be presented in a way that is understandable and useful for the intended application, i.e. the decision-making context. Otherwise, the “messages” that the inclusion of disasters in LCA is trying to send might get lost and not taken into account due to a lack of understanding and acceptability. This could come to the detriment of the stakeholders.

Finkbeiner et al. (2014) addressed this as the consideration of improbable events in LCA. The scientific community has made several contributions towards this research challenge, specifically through the combination of LCA and risk assessment methods. However, disaster risks have seldom been part of the improbable events considered at the inventory level. This is an area opportunity because the effects of disaster risks on the product systems do correspond to the research challenge signaled by Finkbeiner et al.

To elucidate the way of contributing to this research challenge, this section explores what has already been done, followed by a discussion about how to address the consideration of improbable events at each level of the LCA, and concluding with the proposition of the present thesis project.

#### 1.3.1. Existing approaches

The integration of LCA and risk is a topic that has been explored in the last decade. The most common way researchers have explored this is by using LCA and Risk Assessment methodologies as complementary techniques (Kobayashi et al., 2015; Muazu et al., 2021). This is in line with the publication by Finkbeiner et al. (2014), who stated that the potential impacts of improbable events can be evaluated through risk assessments. Other approaches have considered the influence of risk factors on the structural performance of buildings and infrastructure whilst performing impact



assessments (Caruso et al., 2020; di Filippo et al., 2022, 2023; Salgado & Guner, 2021), and climate-related risk scenarios for crop production and infrastructure (Guest et al., 2020; Niero, Ingvordsen, Peltonen-Sainio, et al., 2015; Roux et al., 2016).

The following paragraphs present an overview of said approaches in the reviewed literature.

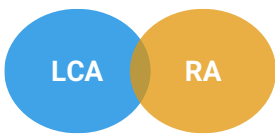


### 1.3.1.1. LCA plus RA

The methodological integration of Life Cycle Assessment (LCA) and Risk Assessment (RA) usually considers Environmental Risk Assessment (ERA), which it is concerned with the risk posed by the release of chemicals into the environment and what effects they have on human and environmental health (Udo de Haes & Heijungs, 2009).

The reasoning behind the integration of LCA and ERA is that they use similar baseline information to perform their respective assessments. Various attempts have been made to hybridize the tools in different ways. The most recent review on the topic is by Muazu et al. (2021). The authors observed that the integration of LCA and RA varies greatly in terms of methodology and assessment indicators, thus no universal LCA plus RA method exists. What works and what doesn't for a project depends on the objectives of the evaluation and what results are useful for the target audience to make relevant decisions (Kobayashi et al., 2015; Muazu et al., 2021).

The types of methods to integrate LCA and RA observed throughout the literature, adapted from two reviews (Kobayashi et al., 2015; Muazu et al., 2021), are presented in Table 1. 7.

Table 1. 7. General classification for LCA and RA combined methodologies, adapted from Kobayashi et al. (2015) and Muazu et al. (2021)

Method	Key features	Advantages	Disadvantages
<p>Parallel LCA and RA</p> 	LCA and RA done separately, combing the analysis of results	<ul style="list-style-type: none"> <li>More information</li> <li>Requires no complex integration</li> <li>Use of multi criteria analysis tools for interpreting the results</li> </ul>	<ul style="list-style-type: none"> <li>Time consuming</li> <li>Higher costs</li> <li>Conflicting information in results (e.g. opposing impact conclusions, burden-shifting)</li> </ul>
<p>LCRA<sup>5</sup></p> 	Performing RA with a life cycle perspective	<ul style="list-style-type: none"> <li>Easy identification and management of problems</li> <li>Efficient implementation</li> <li>Reduced costs and time</li> </ul>	<ul style="list-style-type: none"> <li>Limited indicators and scope</li> <li>Assessing many impact contributors is difficult</li> <li>Risk of double counting</li> </ul>
<p>ERA in LCA</p> 	LCA that includes ecotoxicological and toxicological parameters	<ul style="list-style-type: none"> <li>More impacts are considered</li> <li>Spatially differentiated, more dynamic and realistic</li> <li>Easier identification of problems and trade-offs</li> </ul>	<ul style="list-style-type: none"> <li>Some qualitative indicators, ERA</li> <li>Uncertainty: incomplete ERA</li> <li>Risk of double counting</li> <li>Difficult to assess multiple processes and products</li> </ul>

<sup>5</sup> A relevant example is the PhD thesis of L. Aissani (2008), who developed an LCRA methodology to compare the risk across the life cycle of two fuel sectors, gasoline and hydrogen, identifying and quantifying the risk transfers of transportation, storage, handling, etc., using expert opinions and semi-quantitative risk identification throughout the whole life-cycle (Aissani et al., 2012).

The main challenges towards a cohesive integration of LCA and RA concern the assessment of uncertainty and variability, the local scale of RA and ERA versus the global scale of LCA, the differences in temporal scales, and the harmonization of indicators and analysis of results (Breedveld, 2013; De Luca Peña et al., 2022; Muazu et al., 2021). All these potentially conflicting factors would make it difficult for decision-makers to take the results of the combined methodologies into account. Of course, there is great merit and value in understanding the information and the insights that both LCA and RA have to offer on the same level. However, considering that it is possible to look at the results and the conclusions that each study provides separately and contemplate them side by side, it begs the question: do the benefits of adapting and integrating the methods from these two different tools outweigh the disadvantages?

#### 1.3.1.2. Other approaches

A relevant characteristic of the LCA and RA approaches is that the identified hazards, which are the inputs for the risk assessment, are situated inside the system under evaluation (inside-out impacts (Cimprich et al., 2019)). In other words, the system has control over these risk sources to a certain extent because they come from a material/product used or in a process (production, transformation, packaging, transportation, etc.) in the system. Therefore, the places to implement control measures to mitigate or prevent the consequences of these potential risks are relatively straightforward to identify and apply.

However, hazards and improbable events may also come from external phenomena (outside-in impacts) that the system and its operators have no direct control over, such as natural disasters. LCA-based approaches that have adopted this perspective are relatively new. Relevant examples pertain to the estimation of the environmental impact of risks in the LCA of buildings, which address and assess the damage caused by seismic activity (Hasik et al., 2018).

These LCA-related approaches consider the structural damage as the main impact of risks from natural hazards on buildings, which have been developed for earthquakes (Caruso et al., 2020; di Filippo et al., 2022; FEMA, 2018; Hasik et al., 2018), tsunamis (Salgado & Guner, 2021), and fire risks (di Filippo et al., 2023). The structural and the environmental performances are studied relative to each other, focusing on the climate change potential of activities related to repair, reconstruction, and/or maintenance that occur after damages caused by a particular natural hazard. Structural analyses and probabilistic methods are used to estimate the response of a building to a hazard load, which adds another layer of uncertainty that needs to be addressed in the assessment (Hasik et al., 2018; Salgado & Guner, 2021).

Other approaches that consider the implementation of risk factors as scenarios in LCA do so by addressing the risk of the changing climate that will progressively evolve into “new normal” conditions that product systems should prepare to face. From the reviewed studies (Guest et al., 2020; Niero, Ingvordsen, Jørgensen, et al., 2015; Niero, Ingvordsen, Peltonen-Sainio, et al., 2015; Roux et al., 2016), two used RCP-based scenarios to study the climate change impact on the infrastructure performance (short-, medium-, and long-term) in a single family house (Roux et al., 2016) and for roads (Guest et al., 2020). These studies did not consider impacts due to extreme hazards or weather events, although Guest et al. (2020) did signal this as a limitation and an area of opportunity for their study. On the other hand, Niero et al. (Niero, Ingvordsen, Jørgensen, et al., 2015; Niero, Ingvordsen, Peltonen-Sainio, et al., 2015) directly considered heat wave events with specific parameters to simulate climate

in an experimental facility in their research about the effects of future climate scenarios on crop production. The limitation of this kind of assessment is that it depends on the availability of primary measurable data to estimate the crop performance under altered climatic conditions.

Although far from perfect, these approaches set the stage to develop more complex frameworks and methodologies to address the specific needs of prospective studies for decision making. One of the most important challenges to overcome is the interpretation of the uncertainty these prospective models introduce to the LCA results, who already has multiple sources of uncertainty that render the results difficult to interpret.

Finally, a study that addresses the possible integration of RA with Environmental Impact Assessment (EIA) was conducted by Fuentes-Bargues et al. (2020). Using the norm ISO 31010:2019 as a reference, they evaluate which RA techniques could be the most useful to analyze the vulnerability to severe accidents or disasters in the Environmental Impact Study of a project, arguing that this incorporation will increase the objectivity of the EIA process. The main limitation for the application of these qualitative and semi-quantitative techniques is the required participation of experts in the project to be evaluated (with deep knowledge on the systems, procedures, etc.) as well as specialist in the RA technique to use. Moreover, the authors recommend the use of these risk appreciation techniques over the quantitative and probabilistic ones due to their more functional and simpler application. An additional reason is that RA is used in the initial phases of a project and at that stage there is not enough information about how the systems and the subsystems work to provide reliable data for the quantitative approaches (Fuentes-Bargues et al., 2020).

### 1.3.2. Discussion

When comparing what has been done in the literature versus the research challenge signaled by Finkbeiner et al. (2014), four possible levels of considering improbable events in LCA have been identified. These correspond to the four phases of LCA: goal and scope definition, LCI, LCIA, and interpretation of results.

#### 1.3.2.1. At the goal and scope definition level

This means making the impact of the disaster risks a fundamental part of the objective of the study, explicitly stating the limitations, the reasons for inclusion, the modeling framework, the system boundaries, and all aspects that this step entails (Bjørn, Laurent, et al., 2018; Bjørn, Owsianiak, et al., 2018). In the reviewed literature, this has included scenario identification at a global (Roux et al., 2016) or specific (Sauve & Van Acker, 2021) scale to study expected changes in the product system, as well as identifying risk throughout the lifecycle of a product system.

The latter means that risk identification, characterization, and prioritization are considered fundamental steps to be addressed at this level because they will provide the necessary information to feed the product system inventory. For example, in the case of LCA of buildings that address the environmental consequences of structural damage caused by natural hazards, it is not the same to identify the main risk as an earthquake (Hasik et al., 2018), a tsunami (Salgado & Guner, 2021), or a hurricane because the kind of stress they have on the building is different, therefore the information that needs to be recovered for the inventory and the specific damage assessment method will also change.

Moreover, depending on whether the study aims to only assess impacts from damages or if it includes building renovation strategies after disasters (Caruso et al., 2020), modeling specificities and the data collected will be different.

#### 1.3.2.2. At the LCI level

This implies adopting the assumptions and objectives set on the goal and scope to include risks and their consequences on the product system in the data necessary to build the inventory of the product system. If the inventory that considers the consequences of risk events is well defined and the involved uncertainties are well propagated, then the effects these disturbances should be reflected on the posterior impact assessment results. This has been done to some extent by considering damage assessment and the reinforcement activities necessary for buildings under earthquake risk (Caruso et al., 2020; Hasik et al., 2018).

Another option is to treat the “risk inventory” (Aissani, 2008) as a separate entity altogether, although this approach is more suited for risk assessment-centered methods. At this level, risks can also be evaluated qualitatively in order to simplify the possible scenarios, (Aissani, 2008; Aissani et al., 2012) but some studies have attempted to do so also quantitatively for their specific case studies (Gargiulo et al., 2021; Sauve & Van Acker, 2021), relying heavily on historical information and expert knowledge, which can nevertheless have a complimentary qualitative assessment. Also, RCP scenarios have been used to consider the strains that future climate put on the product systems and how the impacts of the product system will change because of this, which are the bases for considering the evolution of climate hazards and risks in LCA (Gargiulo et al., 2021; Guest et al., 2020; Roux et al., 2016).

#### 1.3.2.3. At the LCIA level

The most common approach that has been considered in the literature involves the inclusion of toxicological and ecotoxicological parameters in the assessment (related to environmental /chemical risk analysis), which are already included in some impact assessment methods, e.g. IMPACT 2002 (Jolliet et al., 2003). There are some limitations regarding the characterization models for chemical substances because they involve significant uncertainties regarding, for example, their exposure and effect models, and impact pathways. Moreover, large uncertainties are inherent to these impact categories because of the large amount and variety of substances with toxicity potential that are assessed, all which have different orders of magnitude in their impact potential. Despite these uncertainties, the inclusion of these impacts is relevant to avoid burden shifting between impact categories and development of better models and parameters is important (Muazu et al., 2021; Rosenbaum, Hauschild, et al., 2018).

#### 1.3.2.4. At the interpretation of results level

In general, attempts to do the methodological integration of LCA and RA have rendered the interpretation of results and their communication more difficult, which might hinder rather than help decision-making processes. In this regard, there has been debate over the pertinence of the integration of RA and LCA for certain applications and decision-making contexts (Linkov et al., 2017).

Both methods fulfill very different purposes and answer questions that, although linked, are distinct. On one hand, RA aids in assessing specific environmental hazards that could be focused on a local level, while LCA aids in assessing an ensemble of environmental impacts caused by processes throughout the life cycle of the product system. Because of this, integration at a results and analysis level has been suggested as appropriate for complex systems, since all the advantages of what both methods offer are gained and the disadvantages of a complex methodological integration are

avoided (Muazu et al., 2021). The significant disadvantage of this approach is the time and resources required to perform both assessments and the analysis work necessary to provide decision-makers with comprehensible and useful information.

The research by Gargiulo et al. (2021) is a relevant example, where they first perform an LCA to identify the life cycle stages of a geothermal power plant project with the most important environmental impacts and more prone to risks. Then, they used a Multi-Risk Assessment to identify the risk pathways at each life cycle phase of the project, and structured scenarios through fault and event tree approaches (bow-tie structure) to go from the source of the risk (seismic activity and extreme weather) to the flows that will provoke the environmental impacts (probability distributions for each event related to the volume of diesel spilled).

Another aspect relates to the choices that must be made after a disaster risk causes severe disruptions to the product system to the point of causing destruction of important components. For example, in Salgado and Guner's (2021) study, such choices are related to the retrofitting or demolition of a building after they suffered certain damage caused by a natural hazard event. Choices are guided by the defined decision variables and thresholds, which are related to the performance of the given product system.

When confronting the literature with the research challenge on the inclusion of improbable events, with special emphasis on disaster risks in LCA (Finkbeiner et al., 2014), it is observed that most are LCA plus (E)RA approaches that focus on inside-out impacts (Muazu et al., 2021). Although important, this focus tends to omit the influence of external phenomena on the product system, i.e. outside-in impacts. In this regard, LCA approaches with infrastructure/building damage assessments (Hasik et al., 2018) do consider such impacts and address the inclusion of improbable events at the inventory level, which is key to considering the missing impacts from disruptions on the product system that such events cause (Finkbeiner et al., 2014). However, few of these studies address uncertainties related to the environmental impacts of the production of materials and components to be replaced, most also lacking communication of their results via probabilistic data. As Hasik et al. remarked, "although the task of presenting probabilistic results can be challenging, it is essential for studies aiming to compare many design alternatives and influence decision making from both seismic loss and life cycle assessment perspective, as there is limited value in such studies relying on deterministic results" (Hasik et al., 2018). Studies like Gargiulo et al. (2021) and Sauve and Van Acker (2021) implement such probabilistic models related to risk through structured and cohesive methodologies, but the inventory flows related to the repair and replacement of equipment and what does that mean for the end of life of components in the product system is missing.

Considering the latter discussion, projects that aim to contribute to this research challenge ought to address it from all four levels, at least covering the goal & scope definition and the inventory levels. These insights provide important information for the development of the present thesis work.

### **1.3.3. A new contribution**

The purpose of this PhD thesis is to tackle the discussed research gap in LCA and provide a relevant methodological contribution that, through the consideration of evolving disaster risks and their likely consequences on the environmental performance of the critical infrastructure, enables a comprehensive evaluation of the potential life cycle environmental impacts of critical infrastructures, specifically energy production plants.

The following paragraphs address the core contributions that aim to fill the research gaps, followed by the positioning of the methodological contribution in the methodological framework of LCA.

#### 1.3.3.1. Consequences of disaster risk

So far, we have explored how improbable events and disaster risks have been addressed and included in LCA studies. Although some attempts have been made to consider improbable events as risks through the integration of LCA with risk assessment methods, a gap remains regarding the consequences of disaster risks on the operational phase of a product system, especially related to the repair and replacement/reconstruction of damaged components after a disaster event. In critical infrastructures like energy production plants, carrying out those activities might mean halting the essential services provided to surrounding communities, which likewise represent non-negligible financial and production losses.

In infrastructure projects, existing strategies that are implemented after disaster events where several components are severely damaged or destroyed opt for the replacement of entire systems by newer technologies because it is financially and technically beneficial. In energy production systems this is known as repowering (Herceg et al., 2022). For example, imagine the case of a ground mounted PV power plant with a 30-year operational lifespan, and on its 13<sup>th</sup> year of operation a windstorm induces severe mechanical stress on most PV modules, causing important and irreversible damages, meaning they cannot produce electricity as before. Because of the constant technological progress in PV technologies, the performance of modules produced 10 years after the plant was installed has significantly improved<sup>6</sup>. When the relevant actors are faced with the choice between replacing the damaged modules with the same technology or changing the whole installed capacity with a newer and more efficient technology, the latter is a good opportunity from a financial and operational point of view. However, replacing/reconstructing an entire system means that the environmental assessment needs to consider the whole life cycle for all the components that are being replaced, i.e. from raw material extraction to the end-of-life processing, which significantly increases the potential environmental impacts. In the case of systems that were approved and certified due to their low impacts, such as renewable energy production systems, this represents an important aspect to address.

The methodological contribution includes decision-making challenges of this nature because of their relevance in the possible different outcomes of the performance of the product system and its life cycle environmental impacts.

#### 1.3.3.2. Evolution of disaster risk

Disaster events that put critical structures at risk of being damaged are going to happen more often. As it has been discussed, the effects of global trends, notably driven by the average increase of global temperatures, are already manifesting in all aspects of human societies and in nature. According to the IPCC, such trends will contribute to the increased frequency and intensity of disaster events and the severity of the impacts on human communities and infrastructure. However, the intensity, frequency, and severity of several natural phenomena will depend on how much or how little regional climate changes. Information between an SSP2 and SSP4-based model provide different estimations for future climate, and the differences these changes represent for disaster events should be

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<sup>6</sup> NREL's Best Research-Cell Efficiency Chart (Last accessed May 2024): <https://www.nrel.gov/pv/cell-efficiency.html>

accounted for as possible evolutions and subsequent consequences on the infrastructure performance.

The consideration of the possible evolution of disaster risks related to global trends needs the study of the potential future states of the region the product system is in. This means looking beyond the climate change trend and including the future context in multiple terms, i.e. political, normative, economic, geographical, social, etc. Naturally, this will also affect the situation of the product system studied in the future. In the case critical infrastructures like energy production systems with decades-long operational lifespans, the inclusion of disaster risk evolution and the consequences of varying disaster event intensities on the performance of the critical infrastructure, plus the post-disaster alternatives about the repair, replacement, and reconstruction of system components, will provide an ensemble of possible alternative future states of the product system.

Through LCA, each alternative would reveal different results for the potential environmental impacts, therefore they need to be defined and introduced at the inventory (LCI) level. In this regard, an important challenge to address is the significant variability that disaster events and their consequences introduce to the assessment.

#### 1.3.3.3. *The methodological contribution*

The effects of evolving disaster risks on one hand, and the consequences of post-disaster decisions on the other, could adversely affect the operational and environmental performance of a critical infrastructure throughout its life cycle. Information on the potential environmental impacts of critical infrastructures in a world of evolving disaster risks, especially in the energy production sector, is potentially key to decision-makers at the forefront of the renewable energy transition. Thus, to provide meaningful LCA results that comprehensively and coherently consider these aspects, they need to be addressed as early as the goal and scope definition of the LCA study and implemented at the inventory level.

The proposed methodological contribution consists of the development of a **disaster risk-guided inventory module** that enables the estimation of the consequences of evolving disaster risks in LCA studies of critical infrastructures.

The inventory module for the LCA study of a critical infrastructure requires information given by:

- a. The goal and scope definition, especially concerning the system boundaries, the inventory regionalization, the characteristics of the actors that the study is meant for, for what purpose will they use the results and their insights, and the elements included and excluded in the LCA study, for example, the life cycle stages, and the components and processes of the system.
- b. The list of processes, elementary and intermediate flows that make up the unit processes of the product system.

Therefore, it is essential that a complete baseline LCA study of the product system is performed beforehand. The baseline LCA should follow the recommendations of the ISO 14040 standards and the suggestions of the ILCD Handbook on LCA (EC-JRC, 2010). Additionally, depending on the studied energy production system, complementary LCA methodological guides or handbooks with best practices and recommendations could be used. For example, in the case of LCA of PV technologies, the IEA PVPS Task 12 has published documents on Methodological Guidelines (Frischknecht, Stolz, Health, et al., 2020) and Life Cycle Inventories (Frischknecht, Stolz, Krebs, et al., 2020).

The expected outputs of the module are twofold. First, it defines a group of plausible future situations representative of the potential evolutions of the studied disaster risks that can affect the infrastructure and the territory it is situated. From this group of scenarios, a few representative future situations are selected. Each chosen situation describes a specific context with information about the possible disaster events, the current and future state of the territory, and the sectorial panorama. Second, from this context, the possible changes to the performance of the critical infrastructure are derived according to the different decisions made after studying its resilience versus certain disaster risks. For each chosen situation with its respective alternatives, the associated inventory to be used in the life cycle impact assessment is provided.

## Conclusion

Life Cycle Assessment has many virtues as a decision aid tool for the estimation of the environmental impacts of product systems. For critical infrastructure projects that aim to be environmentally responsible in compliance with regional requirements, national policies, and international agreements, the environmental performance information provided by LCA is crucial.

Despite its broad scope, LCA still has important research gaps to address. Among these is the methodological consideration of improbable events as introduced by Finkbeiner et al. (2014), and specifically evolving disaster risks in the context of climate change. The latter have an important influence on the LCA results because of their variable disturbances on the operational phase throughout the lifespan of the product system.

The consideration of evolving disaster risks in LCA must happen from the goal and scope definition and life cycle inventory phases for a more comprehensive inclusion and propagation of the related uncertainties. This poses challenges in all the LCA phases and the decisions made within the product system.

To contribute to the identified research gap and address these challenges, this PhD thesis proposes a methodological contribution in the form of a disaster risk-driven inventory module that defines: a universe of plausible future situations representing evolutions of disaster risks that may affect a critical infrastructure throughout its lifespan, and situation-specific contexts from which the possible operational lifespan alternatives of the critical infrastructure can be derived. These alternatives depend on the decisions made after a likely disaster event, such as repair, replacement, or reconstruction of the damaged infrastructure components. Chosen alternatives and situations help determine the different life cycle inventories for posterior comparative life cycle impact assessments.

At this stage, the inputs and outputs of the proposed contribution according to the research needs and the research challenges have been determined. To derive a structured approach, it is necessary to determine how this group of future situations will be defined. To do so, inspiration was taken from contemporary applications of LCA, specifically looking at future-oriented LCA. This guided the research towards future-oriented approaches and specifically the prospective approach, which is the subject addressed in the next Chapter.





## Chapter 2. Representing the Uncertain Future

### Introduction

The development of the disaster risk-guided inventory module for LCA, which is the main aim of this PhD, requires knowledge about possible future situations to have a more comprehensive view of the potential environmental impacts related to the studied product system, which in this case is a critical infrastructure. This is because the aim is to explore the evolution of disaster risks guided by major global trends, most notably climate change, that influence the trajectories of social, economic, territorial, environmental, and political global trends, as well as the decisions made throughout the lifespan of the product system. To do so, it is fundamental to understand how the future can be systematically studied whilst considering all these factors.

The realization of this project represents a multidimensional challenge that requires tools, methods and approaches that permit the organized and systematic integration of all the factors involved. Since looking towards the future is an important part of the contribution of this PhD thesis, it is necessary to explore future-oriented approaches and determine which ones are the most useful for this purpose.

The objective of Chapter 2 is to explore future-oriented approaches in the literature to identify the methods and tools that will help in bridging the gap between the inputs and outputs of the proposed disaster risk-driven inventory module.

Because an inventory module for LCA has been developed, future-oriented approaches specific to LCA were the cornerstones for the literature review that led to the topics addressed in this chapter. However, while the exercise of discovering future-oriented approaches and their related methods occurred from a specific case to a general context, this chapter presents concepts from a general view to a specific context, concluding with a discussion leading to the proposed methodological contribution.

### 2.1. Studying the Future

Actors in charge of strategic planning and decision-making activities that look to the future must understand that there is a lot of unpredictability and uncertainty involved in this exercise. Therefore, these factors ought to be accepted, studied, and understood. Of course, studying the future is not a straightforward exercise, and it has taken different paths and forms in the past century. Godet (1994, p. 33) and Weidema et al. (2004) provide a glossary of terms for future-oriented research that make clear distinctions between forecasting, predictions, futures research, prospective, etc. Among the existing future-oriented approaches, prospective studies are the ones more aligned with the strategic planning perspective. It must be noted that adopting one future-oriented approach does not mean that others are automatically excluded, meaning that tools, concepts, and methods are used across approaches and even complement one other. The prospective approach also consistently appears in the future-oriented LCA discourse and in methods used to estimate future situations. Therefore, the aim is to explore where the prospective approach comes from, understand which methods and approaches are available to conduct a future-oriented study, concretely address how these kinds of approaches have been applied to LCA (Bisinella et al., 2021; Olsen et al., 2018), and finally discuss about how these approaches can be used for the methodological contribution of this PhD thesis.

### 2.1.1. The prospective approach

Thinking strategically and planning for the future stem from our human instinct for survival, which has historically relied on collaboration and organization as unified communities of different scales and natures. Strictly speaking, strategic prospective has been studied as a discipline in the fields of economy, science, technology, and society, since the decade of 1940 after the Second World War (Godet, 2007b; Voiron-Canicio & Garbolino, 2020; Weidema et al., 2004). From there, the early development of prospective and future-oriented approaches happened on two fronts. In America, the focus was on quantitative forecasting in the service of the military and technological development. In France, the transition towards a more industrialized economy spawned a more positive vision of the future and how it is analyzed to reach an end goal, notably through the mind of the philosopher Gaston Berger in the 1950s. He called this concept “*la prospective*”, which involves a more qualitative, voluntarist, proactive, and global approach to address complex phenomena (Godet, 1994). In the following decades, this French-based prospective approach was continued by Bertrand de Jouvenel in the 1960s who founded the *Futuribles* international association, and since 1970s this work has been continued by economist Michel Godet<sup>7</sup> (Godet, 2007c, 2007a) through its methodological and institutional structuring. In more recent decades, prospective approaches have explored diversifying avenues, addressing topics such as territorial prospective, environmental prospective, hybridized approaches (e.g. geopropective), integration of cultural aspects, and shock scenarios (Futuribles, 2022; Voiron-Canicio & Garbolino, 2020).

Both the prospective approach and forecasting aim to look into possible futures using information of the present. However, there are fundamental differences. For one, the quantitative nature of forecasting provides an assessment of the future that is based on probabilistic estimates built from historical data and several assumptions (Godet, 1994). In contrast, the prospective approach considers parameters that are unquantifiable and qualitative in nature, such as societal changes and the possible impacts of decisions on the development of societies, with the purpose of preparing informed actions and decisions (Voiron-Canicio & Garbolino, 2020).

This is not to say that one approach is better than the other. Each one has its specific purpose and realm of applications. Therefore, the most appropriate approach should be chosen for each case. For this PhD thesis, given that a planning and decision-making problem with highly uncertain information is being addressed to base the assumptions of the future, the prospective approach is aligned with these goals, although quantitative data will also be used to estimate certain aspects of the future.

The prospective approach, also known as strategic prospective and strategic foresight, has evolved significantly since its conception to the present day. Godet (1994) recounts the voyage that prospective and strategic approaches have had from separate views and schools of knowledge that ultimately converge and synergize to build comprehensive visions of the future. This integration has made the prospective approach a discipline that integrates various branches of knowledge, and that can be applied to many fields of study.

In a later publication (*Manuel de Prospective Stratégique*) Godet (2007a) presents the strategic prospective approach as having the objective to propose strategic orientations and actions based on the competencies of the company, according to the scenarios of its general and competitive environment. In this sense, it is a nine-step integrated approach (Figure 2. 1) focusing on a corporate

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<sup>7</sup> Webpage *La prospective* (Last accessed May 2024): <http://www.lapropective.fr/>

vision to project planning. Although this presentation leans more towards the strategic side of the approach, the tools and methods that are used throughout the process can be used and applied according to the needs of the project to be developed. Thus, for the thesis project, there is an interest in using tools and methods that are related to the prospective side of the approach, as defined based on the French perspective (steps 1, 3, 4, and 5, shaded in blue on Figure 2. 1).

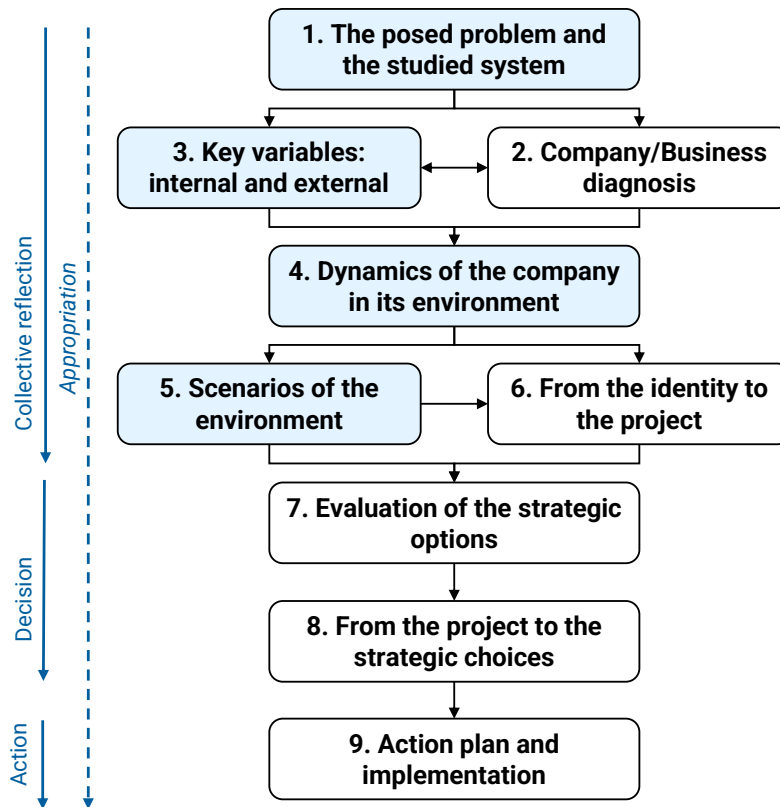


Figure 2. 1. The strategic prospective approach, adapted from Godet (2007a)

The prospective approach studies the future by looking into the realm of possibilities, and they should fulfill three essential characteristics for them to be helpful for decision-making activities. First, the variability of the proposed alternatives should be significant to reflect the possible evolutions the system under study can undergo, which requires the identification of key variables and a long-term perspective. Second, there should be a significant contrast between alternatives to permit insightful discussions, which involves the integration of breakdowns or breakthroughs. And third, the alternatives presented should be pertinent to the problematic addressed throughout the study (De Jovenel, 2000; Voiron-Canicio & Garbolino, 2020).

Voiron-Canicio and Garbolino's (2020) present a succinct and accurate interpretation of what the prospective approach is:

Whatever the field of study, prospective consists in seeing far and wide in order to assess the consequences of decisions, carrying out an in-depth analysis so as to go beyond analogy and extrapolation, and anticipating potential breaks. On the other hand, it broadens the representations of the future to qualitative approaches and data that are not solely quantified. For example, it gives a dominant place to the points of view of stakeholders in the future. (Voiron-Canicio & Garbolino, 2020, p. 3)

Considering this definition, the use of past data, collective thinking, debates, and stakeholder participation are key parts of the prospective approach. These elements coalesce in an exploration



The **first phase** is the definition of the goal and scope of the future scenarios. This requires a clear statement of the problem to address, as well as determining the temporal horizon (De Jouvenel, 2000). Moreover, this involves identifying the type of future scenario to build, since it will guide the later development of multiple future scenarios (Bisinella et al., 2021). Scenarios can be classified in three categories, which are based in what the scenario developer would like to know about the future (Börjeson et al., 2006):

- *Predictive scenarios*, which involve estimating the probability or likelihood of occurrence of the outcome. These scenarios are useful for planning and adapting to situations that are expected to happen, but they can contribute to preserving past and present trends, both desired and undesired. There are two subtypes:
  - Forecasts: *What will happen, on the condition that the likely development occurs?* Where the scenario generated is considered as the most likely development and is more suited for short term predictions.
  - What-if: *What will happen, on the condition of some specified events?* It consists of a group of forecasts, where no particular scenario is considered as the most likely development.
- *Explorative scenarios*, which look at situations that are seen as possible from many perspectives, more often in a long-time horizon that considers more profound changes on the product system. They are especially useful when looking into future alternative developments of a well-understood system.
  - External: *What can happen to the development of external factors?* These external factors are beyond the control of the relevant actors and the generated scenarios are more general.
  - Strategic: *What can happen if we act in a certain way?* It describes the possible consequences of strategic decisions, and it can consider related external aspects.
- *Normative scenarios*, which are divided into:
  - Preserving: *How can a target be reached, by adjustments to the current situation?* In these scenarios, (cost-) efficiency towards reaching the target is key, therefore optimization and modeling are well used approaches.
  - Transforming: *How can a target be reached, when the prevailing structure blocks necessary changes?* These focus on finding options to fulfill long-term targets, to change the current schemes in order to satisfy the image that we have of the future.

The **second phase** involves the identification of key aspects and associated parameters for the scenarios and determining their possible future states. These aspects are specific to the project or study carried out, describing its present and future values or states in function of those relevant aspects. This identification can be done quantitatively through sensitivity analyses, or qualitative through workshops, Delphi surveys, expert panels, and other participatory methods (Bisinella et al., 2021).

The **third phase** involves the combination of the key aspects and values to develop consistent future scenarios with the help of some methods and techniques (Bisinella et al., 2021). Methods that can help in this development have been inspired by technology foresight analyses<sup>8</sup> and social-science

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<sup>8</sup> Prospective methods used for technology analysis. *Quantitative*: S-curve analyses, analogies, experience curves, and extrapolation of time-series. *Qualitative*: literature reviews, expert panels, scenarios, futures workshops, and Delphi surveys (Olsen et al., 2018).

research (Olsen et al., 2018). Notably, futures studies<sup>9</sup> methods offer quantitative and qualitative alternatives to generate a description of the future situation. Weidema et al. (2004) presented six groups of futures studies methods, which can be applied in parallel to complement each other, meaning that a practitioner is not restricted to using only one method:

1. *Extrapolating methods*: They are based on quantitatively representing the future through a linear or non-linear prolongation of past relations based on historical data, using tools such as trend analysis, simulation modeling, and time series regression.
2. *Exploratory methods*: They are based on qualitatively describing and structuring possible futures, combining analytic techniques to develop sub-themes or consequences to identify and structure the entire scope of possibilities. A relevant example is the general morphological analysis, which is a conceptual modeling approach that is used in the identification, investigation, discovery, and structuring of all possible relationships contained in complex and multi-dimensional problems with a large number of key identified variables (Ritchey, 2011a).
3. *Dynamic modeling methods*: They present an analysis of the interactions of several causal mechanisms over time, according to their relative strengths and probabilities of occurrence. They are quantitative in nature. However, they may require the participation of relevant experts for the identification of key mechanisms, interactions, and probabilities of occurrence involved in the model.
4. *Cornerstone scenario methods*: They aim to present a broad set of plausible outcomes, which can serve as a basis for sound and viable conclusions about the broad set of possible futures. These methods are based on the fact that uncertainties linked to the long-term future will yield an ensemble of possibilities, therefore they are better suited to describe scenarios with a long-term horizon dealing with complex situations.
5. *Participatory methods*: They use the knowledge, insights, and opinions of experts and stakeholders to infer the possibility and/or probability of future events, their mechanisms, and their interactions. They are qualitative in nature.
6. *Normative methods*: They are based on organizational planning. They enable an organization to orchestrate and focus its resources to achieve a goal.

Once the scenarios have been developed, a consistency check is necessary, thus ensuring that the alternatives generated are plausible and possible.

The **fourth phase** involves looking at the scenarios developed in the third phase and selecting a few representative scenarios for the study that is being carried out (Bisinella et al., 2021).

Finally, the **fifth phase** involves transferring the scenarios to the specific application. In this thesis project, the scenarios are used to complement the Life Cycle Assessment carried out for a critical infrastructure.

### 2.1.3. Future-oriented view in LCA

Life Cycle Assessment has been considered valuable as a decision support tool, which extends to decision-making activities that concern the future, such as the development of products and new technologies, as well as strategic planning (Olsen et al., 2018). Thus, the need for future-oriented

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<sup>9</sup> Futures studies: “Exploration of what might happen and what we might want to happen. Futures studies is subject- or question-oriented” (Weidema et al., 2004). This is often used as a direct translation of *la prospective*, although it lacks the explicit strategic aspect.

elements in LCA concerns the unknowns related to the product system, the conditions and factors surrounding it, and how its environmental impacts will manifest themselves in the future.

Considering the latter, future-oriented LCA is defined by Olsen et al. (2018) as “a systematic assessment of future events and developments in society, technology, economy and policy that in the long-term could considerably influence the product system (and/or functional unit) and its societal conditions and hereby the environmentally relevant flows”. The future elements that concern this assessment can be treated at the level of each LCA phase. In general, long-term scenarios in LCA have been considered as necessary for strategic and policy planning, and they are a prevalent element of future-oriented studies in LCA (Bisinella et al., 2021).

In the following paragraphs, the role and applications of scenarios in LCA at different levels are presented. Afterwards, prospective LCA is addressed, which is a particular conceptual approach for future-oriented studies in LCA that has been briefly introduced in Chapter 1.

#### 2.1.3.1. Scenarios in LCA

The concept of scenario analysis has been present in LCA for a couple of decades and it can be described in many ways. In general, scenarios refer to the discretization of a sensitivity analysis, since scenario analysis “evaluates the change in the result for each alternative considered (or meaningful) for a given choice.” (Rosenbaum, Georgiadis, et al., 2018) It is worth mentioning that scenario analysis is but one type of sensitivity analysis. Thus, the purpose of scenario analysis is to represent different possibilities of results that are subject to different parameters, such as future developments in territorial management, politics, climate change, etc.

For the scenarios to yield useful results for a given LCA, they must be appropriately identified, developed, and implemented. Naturally, some techniques are more useful than others to develop different scenario types, and some recommendations are given in Höjer et al. (2008). A guide to design scenarios for LCA was proposed by Weidema et al. (2004), which deals with the issue of developing systematic scenario approaches as a basis for future studies of product systems and environmental impacts. Here, a scenario is defined as “a description of a possible future situation relevant for specific LCA applications, based on specific assumptions about the future and, when relevant, a description of a path from the present to the future”.

Scenarios are considered at different levels in LCA because they fulfill different roles depending on the LCA phase (Weidema et al., 2004). Table 2. 1 presents a summary of the role that scenarios have at each LCA phase. Note that, as LCA itself, developing scenarios is an iterative process that requires verification and carrying out changes across LCA phases and the scenario building steps.



Table 2. 1. Role of scenarios in each phase of LCA, information from (Weidema et al., 2004)

LCA Phase, ISO 14040	Role of scenarios
1. Goal and scope definition	Definition of the scenario type and its framework Explicit description of assumptions for each scenario Scenarios guide the definition of data quality requirements and related aspects
2. Inventory analysis (LCI)	The development of scenarios, consistent with the relevant parts of the future technological system
3. Impact assessment (LCIA)	Characterization and weighting are linked to scenarios representing elements of the ecosphere and the technosphere <sup>10</sup> .
4. Interpretation of results	Scenarios are checked for completeness, sensitivity, and consistency Uncertainty analysis and data quality assessment are also performed

**At the goal and scope definition level**, the purpose of using scenarios in the assessment is explained, alongside the scope of the use, the temporal and system boundaries. First, the type of scenarios to develop and analyze are chosen. According to Weidema et al. (2004), scenarios in LCA are mainly built using two approaches based on futures studies methods: a) *what-if scenarios* used for comparative assessments between at least two alternatives to resolve an established decision problem, where the scenarios can be defined based on well-known knowledge and data; and b) *cornerstone scenarios* used for strategic planning purposes and guidance for future developments (e.g. technological). Here, the chosen scenarios are varied, and the purpose is to obtain an overview of the studied problem or field. With this information, the outline or general description of the scenarios is given, alongside the specific assumptions that will guide the study.

**At the inventory analysis (LCI) level**, the choices of scenarios are evaluated, and the scenarios themselves are fully developed. A different inventory must be used for each scenario, so different data is collected to fulfill the requirements. The scenarios can be developed using the LCI scenario development guidelines proposed by Weidema et al. (2004), who suggested the application methods for futures studies to investigate product systems, also discussing about modeling issues and possible default scenarios. The guidelines to study product systems and develop scenarios are presented in five steps:

1. *Identifying relevant parts of the product systems*, by looking at the speed of development of relevant factors, the environmental significance of these developments, the possibility or radical or abnormal developments, the time horizon of the study, and the position of the process in the life cycle of the product system.
2. *Determining the necessary precision*, related to the direction and speed of the development to study, going from a general view to an analysis at specific points in time and for specific technologies.
3. *Choosing the futures studies method*, and this decision depends on the time horizon of the scenario, and on the predictability and complexity of the system, which is the object of the

<sup>10</sup> Ecosphere: everything that is not man-made or man-manipulated; what is referred to as "nature". Technosphere: man-made or man-manipulated processes (Hauschild, 2018).

scenario. Six different futures studies methods have been proposed by Weidema et al. (2004), and are presented in section 1.2.

4. *Scenario development by the chosen future-studies method*, and the recommendations provided in the text are divided into the six above-mentioned methods, providing insights on the limitations of each approach.
5. *Consistency check*, which involves keeping in mind that the use of different methods may be more appropriate for certain parts of the product system. This consistency check is done between the assumptions and the justification of the methods used, and it is also done between the results obtained and its interactions with other parts of the product system.

**At the impact assessment (LCIA) level**, the characterization and weighting steps are concerned by the scenarios related to the environmental and the technological context. These scenarios concern the potential environmental effects of the product systems, which are related to the geographical context and the temporal horizon considered (Weidema et al., 2004). This is to say, for example, that a product manufactured in China will not have the same environmental impacts than the same product manufactured in France because the background and foreground<sup>11</sup> processes concerned have very different emissions. The same goes for differences between a product manufactured in the present and an analogous one manufactured in a certain year in the future. Moreover, the estimations of the environmental impacts of emissions depend on the LCIA method used for each impact category assessed; depending on the time horizon determined (long-term vs short-term) the characterization of certain substances will change, so this should be clearly stated and applied (Rosenbaum, Hauschild, et al., 2018).

Finally, **at the interpretation of results level**, the objective is to scan the scenarios, checking for potential issues that should be treated iteratively in previous phases, in accordance with the ISO 14040 standard (ISO 14040, 2006). Uncertainty and sensitivity analyses are key in the study of scenarios, especially when comparing the environmental impact results from one scenario to another. These analyses are performed to better represent the results and determine how robust the conclusions are, as well as identify the areas of opportunity for better future evaluations. Uncertainty analyses estimate how uncertain and variable data affect the results of the LCA and what that implies when interpreting the impact assessment outcome (Igos et al., 2019). Uncertainty is categorized in two types: pure uncertainty or stochastic, which recognizes the intrinsic variability of some phenomena and cannot be reduced by performing further research; and variable or epistemic, which results from the lack of knowledge and can be reduced by performing further research, gathering more data, refining established models, improving the sampling techniques, etc. On the other hand, sensitivity analysis aims to understand the main sources of uncertainty, and how variations in the output values of a model are affected by changed in their inputs (Igos et al., 2019). The goal is to present the information in a comprehensible and objective way so those who need these results, and their conclusions, can better understand and exploit them. Figure 2. 3 shows a graphical representation of the essential differences between an uncertainty and sensitivity analysis.

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<sup>11</sup> Foreground processes are those specific to the product system studied and they are largely modeled using primary data. Background processes are more generic since they appear in other product systems and they are usually modeled using LCI databases (Bjørn, Owsianiak, et al., 2018).

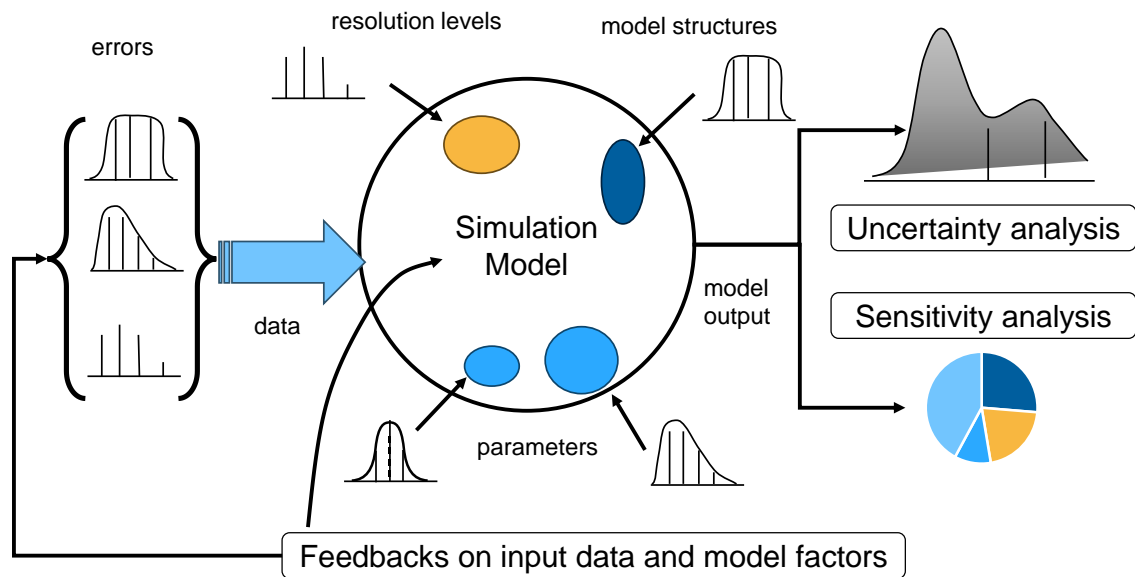


Figure 2. 3. Idealized uncertainty and sensitivity analysis, adapted from Karim and Mohammad (2023)

A study published by Bisinella et al. (2021) systematically reviews the use of future scenario approaches in LCA to provide pertinent recommendations. The authors emphasize that throughout the studies reviewed there are problems related to the lack of consistent terminology used in LCAs involving future studies, namely on the definition of ‘scenario’ itself, the types of scenarios used, and the references to the future scenario theories and approaches used. Moreover, the scenario development phases are generally not clearly stated.

### 2.1.3.2. Prospective LCA

When talking about future-oriented LCA, the term prospective LCA is often understood as a synonym. The development and terminology of this LCA type have been cause of extensive research and debate in the LCA community (Arvidsson et al., 2023).

Based on observations of interactions with individuals within the LCA community, when an LCA practitioner hears the term ‘prospective LCA’, they often think of LCA that focuses on assessing product systems that are at early stages of development, meaning that some part of the process includes non-mature technologies. Ex-ante LCA is a term that is also used to refer to this approach. (Cucurachi et al., 2018). Traditionally, LCAs have been ex-post, making evaluations on the performance of mature, marketable, and operational systems. The assessment allows for informed decision-making, but there is a limitation: the more developed a technology is, the more difficult is to make changes to its design and development to transform them into more efficient and sustainable products. This is the problem ex-ante LCA tackles. By assessing technology at early readiness levels, it is easier for scientists and designers to make influential and functional changes to the technology at lower costs and in shorter timescales. In short, LCA will have a more significant impact in the reduction of potential environmental burdens of product systems if it is applied on these early stages of technological development (van der Giesen et al., 2020).

Coming back to the terminology, as Arvidsson et al. (2023) pointed out, some authors do not mention the concept of new and emerging technologies in their definition of prospective or future-oriented LCA, like the one presented by Olsen et al. (2018), but the temporal positioning of these LCAs is clear in relation to ex-post LCA.

Thus, following Arvidsson et al.'s (2023) recommendations, the definition of prospective LCA that is used in this PhD thesis is the following: "LCA that models the product system at a future point in time relative to the time at which the study is conducted". In this context, to properly report the scope of a prospective LCA study to perform, the following aspects should be defined: the temporal positionality, technology maturity, technology selection, technology upscaling (if applicable), the scenario development approach(es), and the background data (Arvidsson et al., 2023).

With this information, it can be stated that this thesis project is aligned with the prospective view of LCA. Therefore, the definition of the key aspects to include in a prospective LCA study is included in the methodological proposition.

#### **2.1.4. Discussion**

The objective of this PhD thesis is to explore the consequences of evolving disaster risks on the environmental performance of a critical infrastructure throughout its lifespan. Said consequences represent future situations the critical infrastructure might encounter and through the methodological proposal of this PhD thesis and LCA they could be translated into potential environmental impacts. To achieve the established objective, a disaster risk-driven inventory module whose outputs provide the ensemble of future situations to be used in LCA is proposed. However, the future situations must be properly described so they can provide the information needed to perform a comprehensive environmental impact assessment through LCA.

From what has been explored in this section, the prospective approach (see §2.1.1) permits the description, estimation, and analysis of different future situations through the mobilization of scenario building approaches, which involve quantitative and qualitative methods enabling the representation and analysis of various aspects of the future situation. This aligns with the purpose of the disaster risk-driven inventory module designed in this PhD thesis. Moreover, scenarios are already considered in future-oriented LCA, meaning that including scenario building methods in the inventory module would be within the realm of what the LCA community knows, which is beneficial for acceptability and integration into existing LCA tools.

Therefore, in the PhD thesis project, a scenario development approach to define the future situations, i.e. the prospective scenarios, is proposed and implemented in the inventory module. Said approach has a two-fold purpose.

The first purpose is to define a universe of scenarios that describe the potential evolutions of disaster risks that can affect the territory and the infrastructure related to the studied product system, meaning the critical infrastructure. For each scenario contained in this universe -named hereinafter the context scenario- there is a specific description of the disaster events, the state of the territory, the available technologies, the possible evolution of these factors, and the expected standard performance of the system throughout its operational lifespan, i.e. without the influence of disaster risks.

The second purpose of scenario development is, for each context scenario, to define different possible decision scenario alternatives according to the consequences of the decisions made after a disaster event disrupts the operational performance of the critical infrastructure.

Thus, the scenario development process happens in two distinct steps, one for each described purpose. Given the multidimensionality of the problem and the elements that the approach developed in the thesis aims to consider, explorative scenario approaches have been chosen to guide scenario

development for both purposes. Specifically, the use of external explorative scenarios for the scenario universe definition, and of strategic explorative scenarios for the scenario alternatives in a specific context scenario. Some elements used to describe what-if predictive scenarios and dynamic modeling will be implemented, especially when addressing the likelihood of disaster risks versus the resilience of the critical infrastructure. Because the proposed methodological approach intervenes in LCA, it is also determined that scenarios will be cornerstone scenarios for the scenario universe definition, and a type of what-if scenarios for the decision scenario alternatives in a specific context scenario (see Figure 2. 4).

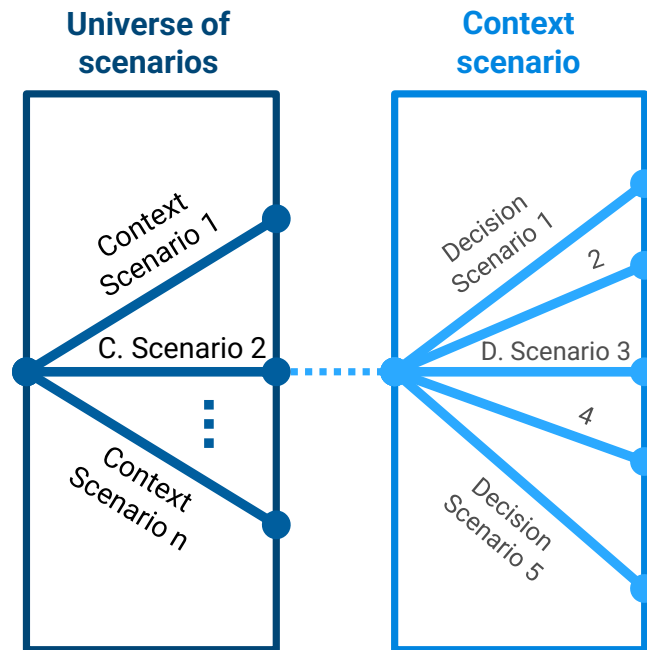


Figure 2. 4. Simple representation of the two levels of scenarios envisioned for the methodological proposition of the thesis

To address the development of external explorative scenarios an assumption is required, namely that the evolution of disaster risks and the trends need to be studied at the same time scale as the operational lifespan of a critical infrastructure, which spans decades. Moreover, as discussed in Chapter 1, disaster risks are complex phenomena that depend on many uncertain factors, and no two disaster risks are the same. Plus, when interacting with other complex and uncertain factors such as socio-economic and climate trends, they become even more challenging to address and analyze. Quantitative approaches (i.e. dynamic modeling) for these kinds of elements involve probabilistic estimations with deep uncertainty, which require significant time and resource investment. Additionally, non-quantifiable elements are difficult to represent in such approaches, thus explorative scenarios that can deal with said elements are a more appropriate option. This does not mean, however, that other tools from quantitative approaches are ignored. For example, data and models obtained from Representative Concentration Pathway (RCP) scenarios represent important references to estimate the future of certain climate phenomena<sup>12</sup> for specific regions<sup>13</sup>.

<sup>12</sup> Copernicus Climate Change Service (C3S) provides authoritative information about past, present and future climate in the world (accessed April 2024): <https://cds.climate.copernicus.eu/>

<sup>13</sup> Climate projections in France are provided by the DRIAS portal (accessed April 2024): <https://www.drias-climat.fr/decouverte>

From the exploratory methods and approaches available in scenario development literature, for both general and LCA applications (Bisinella et al., 2021; Börjeson et al., 2006; Weidema et al., 2004), General Morphological Analysis has been identified as a relevant tool that can be used for the project. This is the subject of the following section.

## 2.2. Scenarios with General Morphological Analysis

General Morphological Analysis (GMA) is a tool used for non-quantitative modelling, problem structuring and analysis that uses discrete category variables to identify and investigate all the possible relationships that are contained in a complex problem (Ritchey, 2022). GMA has been designed to study the structural relationships between factors that are difficult to quantify contained in complex problems (Zwicky, 1967), which aligns with the description of the issue that this PhD thesis aims to address.

In well-cited scenario development literature (Börjeson et al., 2006), GMA has been suggested as a technique used to check the internal consistency among different scenarios that already have been defined, but its capabilities are not limited to this application. GMA has a complete and structured methodology that allows for comprehensive scenario definition and development, especially in situations that involve genuine uncertainty<sup>14</sup> and with data that is difficult to systematically quantify, for example, in studies of the future that include complex social and political issues (Ritchey, 2011b).

The objective of this section is to present the General Morphological Analysis (GMA) methodology, its origins, its most used method, and how it has been applied. This exploration is done with the purpose of understanding how GMA could contribute to the proposed methodological approach.

Throughout this section, publications by Tom Ritchey (2003, 2011b, 2011a, 2018, 2022) will be repeatedly cited because of his important and widespread contributions to the field of GMA.

### 2.2.1. GMA for complex problems

Modeling the future involves the inclusion of factors that are not easily or at all quantifiable. And even when we have mathematical models (e.g. climate models) that estimate possible future states of some factors, how these factors will interact with other possible evolutions that concern social, political, and technological dimensions is complicated to estimate. Considering these complex factors involves going beyond quantitative approaches, thus mobilizing more participative and judgmental processes. However, these are not easy to incorporate and systematically implement, so the question remains: how can we put these processes on a coherent methodological basis? General Morphological Analysis is one such method that attempts to answer this question.

#### 2.2.1.1. Brief historical background

As a structured methodology, GMA has had an interesting development. In his book, *Wicked Problems – Social Messes*, Tom Ritchey (2011b) recounts this story, starting with his own experience in the field. As a social anthropologist who worked for the Swedish Defense Research Agency, Ritchey dealt with what he calls ‘wicked problems’, referring to “complex, ever changing societal and organizational planning problems that are difficult to define and structure properly” (Ritchey, 2011b). His work necessitated the development of computer-based tools and methods that would aid long-term planning in an international context that continued evolving in uncertain ways. In this context, an

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<sup>14</sup> This refers to the cases when “there is no way to calculate the probability of something happening, and for the most part we are not even sure what might happen” (Ritchey, 2011b, p. 1).

infinite number of possible scenarios exist that are evidently impossible to account for, not to mention the irreducible uncertainties that these issues contain. This led Ritchey to think about typology analysis, a concept-structuring technique that inter-relates simple concepts to explore more complex concepts that arise from these relations. The idea was to go bigger and better and treat a multi-dimensional problem, thus developing an extended typology analysis that could deal with more inter-relations and connections between concepts and variables, aided by computer-generated tools.

The answer that Ritchey sought came from across the sea. Fritz Zwicky, an astrophysics professor at the California Institute of Technology had already conceived the extended typology analysis in the 1940s, later called morphological research, and then morphological analysis. Zwicky's morphological analysis -what Ritchey coined as General Morphological Analysis<sup>15</sup>- was conceived to categorize and raise hypothesis for astrophysical objects, assist in the development of jet and propulsion systems, and for the study of the legal aspects of space travel, all through a general qualitative and dimensional analysis of structural relationships between hard to quantify factors (Ritchey, 2011b).

After Zwicky, Ritchey can be considered as the main figure in the field that has developed GMA to what it is today through his work in the Swedish Morphological Society, which he founded in 1998<sup>16</sup>, and as the Director of the Morphologics<sup>17</sup> consulting company. His work has supported over 100 projects using computer-aided GMA since 1995 for various companies, non-government agencies, and government authorities<sup>18</sup>.

#### 2.2.1.2. Characteristics and key components

In brief, GMA is a conceptual modeling approach used in the identification, investigation, discovery, and structuring of all the possible relationships contained in complex, multi-dimensional, and non-reducible problem spaces (Ritchey, 2011a). Typically, this implies the intervention of mainly social and political factors that involve normative and/or judgmental processes that are not well suited for quantification or causal modeling.

General Morphological Analysis (GMA), as first presented by Zwicky (1967), has the ambition to explore all the possible interrelations among the established concepts or variables, encouraging practitioners to abandon prejudice and pre-evaluations, thus allowing for a complete exploration of the possible and the plausible. This means that GMA aims to perform unbiased totality research, which involves exploring further than other studies would, trying to include all the aspects possible. In Zwicky's own words: "But the morphologist will not let himself be stopped by any of the conventional objections. He will emphasize the importance of one of the most fundamental directives of the morphological mode of life which holds that nothing should be accepted as impossible unless it is clearly proved to be impossible" (1967). In practice, the length and exhaustiveness of this kind of research depends on the resources available to perform it, the most influential being the temporal and the financial resources.

Another key component to carry out such exhaustive research is the participation of stakeholders. Among the most important outcomes of GMA studies is the knowledge and understanding that

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<sup>15</sup> Ritchey made this distinction because morphological analysis as a term is used in other areas of study for specific identification of terms and relations, for example, in botany, geology, and linguistics (Ritchey, 2011b).

<sup>16</sup> Swedish Morphological Society website: <https://www.swemorph.com/index.html>

<sup>17</sup> Morphologics website: <http://www.morphologics.se/>

<sup>18</sup> Source: ResearchGate (recovered March 2024): <https://www.researchgate.net/profile/Tom-Ritchey>

concerned actors and stakeholders acquire about the complex problems they face on a large-scale project. GMA mobilizes participatory tools to achieve the objectives of the project, which requires effective communication between the different actors involved. This may be achieved through guided, structured, and organized GMA workshops. Ritchey points out that besides a deeper understanding of the problem, through this process the stakeholders could better understand the reasoning and the positions of other stakeholders regarding the concerned issues. Moreover, he recommends that any project involving complex planning issues and stakeholders/actors with complex positions should engage in a 2-day GMA workshop at the very beginning (Ritchey, 2011b).

To achieve the ambitions of GMA, Zwicky presented six methods: the morphological box method, the systemic field coverage method, the negation and construction method, the method of the extremes, the confrontation of perfection and imperfection, and the method of generalization (Zwicky, 1967). However, according to the literature reviewed, only the morphological box method is systematically used by GMA practitioners.

### 2.2.1.3. The morphological box method

The morphological box method is the most used and developed GMA approach, to the point that it is almost synonymous with GMA itself. Thus, throughout the rest of this document, whenever GMA is mentioned, it refers to GMA that uses the morphological box method. This method follows a similar structure as scenario building methods (see §2.1.2) with five iterative steps, as shown in Figure 2. 5.

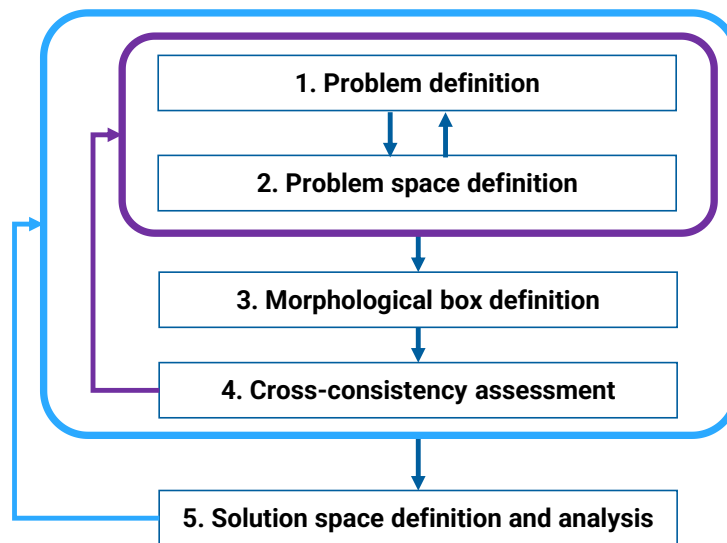


Figure 2. 5. Iterative steps of the GMA morphological box method, adapted from (Ritchey, 2011b; Zwicky, 1967)

**The first step is the problem formulation**, where the problem is precisely posed, described, and formulated with as many details as possible. It is generally agreed that a comprehensive integration of all the elements contained in the problem is unlikely, but an attempt relevant to the problem addressed is necessary. Ritchey recommends a 2-day workshop with stakeholders for everyone to understand the problem formulated (Ritchey, 2011b).

**The second step is the problem space definition**, where the most critical elements of the problem are identified and described as parameters that have a set of conditions, which can be states or values. It is also possible to determine parameter classes or groups for those that share similar characteristics. The parameters are intended to set the frame of the problem defined. The possible conditions related to each parameter should be exhaustive and mutually exclusive. For example, in a



scenario modeling exercise for Norwegian defense planning, the defined parameters are Actor, Goal, Method, and Mean. For the Actor parameter, the possible states, which represent the kind of actor involved in the defense scenario, are State, Network, Business Enterprise, and Individual(s) (Johansen, 2018). To complete this step, a small group of Subject Matter Specialists and stakeholders involved should be assembled for a short series of guided workshops. These workshops are a direct follow-up to those carried out for the first step.

**The third step is the morphological box definition**, where a multidimensional matrix -called the morphological box or morphological field- is constructed with the parameters and all their possible conditions, setting the entire problem space in a visual format. The morphological box is usually built in the context of the workshops with the Subject Matter Specialists. It is possible for a practitioner to build a preliminary morphological box but using it afterwards in a workshop might induce biases and hinder the purpose of the GMA workshop as a creative exercise. Despite this disadvantage, building a preliminary morphological box could be the best alternative to use the time of the workshops more efficiently to define the elements of morphological box.

The morphological box is constructed by  $x$  number of  $P_x$  parameters and each one can take a  $v_{nx}$  number of conditions in the given value range or states (see Table 2. 2) (Ritchey, 2011b). The morphological box helps to determine a certain number of configurations that are defined by selecting one condition per parameter. Each configuration represents a scenario. The total number of these scenarios ( $T_{SC}$ ) is shown in (Equation 2. 1).

$$T_{SC} = v_{n1,P1} * v_{n2,P2} * v_{n3,P3} * \dots * v_{nx,Px} = \prod_{j=1}^x v_{nj,Pj}$$

(Equation 2. 1)

This means that the  $T_{SC}$  increases geometrically with the increase in the number of parameters. For example, in a problem that addresses 5 parameters with 4 values each, the number of possible scenarios is 1,024. Dealing with such cases leaves a practitioner with huge problem spaces that are difficult to deal with without computer-assisted tools.

Table 2. 2. Example of a morphological box

Parameter 1	Parameter 2	Parameter 3	Parameter 4	Parameter 5
V <sub>1</sub>	V <sub>1</sub>	V <sub>1</sub>	V <sub>1</sub>	V <sub>1</sub>
V <sub>2</sub>	V <sub>2</sub>	V <sub>2</sub>	V <sub>2</sub>	V <sub>2</sub>
V <sub>3</sub>	V <sub>3</sub>	V <sub>3</sub>	V <sub>3</sub>	V <sub>3</sub>
V <sub>4</sub>	V <sub>4</sub>	V <sub>4</sub>	V <sub>4</sub>	V <sub>4</sub>

**The fourth step is the cross-consistency assessment (CCA)**, where a consistent problem space analysis aims to remove the impossible scenarios. This assessment evaluates two aspects: (Johansen, 2018)

1. The logical consistency between the conditions, meaning that their internal relationships cannot contradict each other, and
2. The empirical consistency of the conditions, meaning that their relationships do not result in impossible or highly improbable situations according to the specifics of the context.

The problem space can be significantly reduced to a manageable number of possible scenarios when eliminating the inconsistent sets of conditions. This is done by pairing off each condition of each parameter with every other condition in all the other parameters (Ritchey, 2011b) to form a group of two-dimensional parameter blocks, as shown in Table 2. 3.

The number of parameter blocks (*CCB*) in the cross-consistency matrix is shown in (Equation 2. 2):

$$CCB = \frac{1}{2}x(x - 1)$$

(Equation 2. 2)

Considering the latter, the number of parameters and their associated conditions, the total number of pair-wise relationships between all the parameter conditions (*Ct*) can be estimated, which make up the cells in the cross-consistency matrix. This number is calculated using (Equation 2. 3).

$$Ct = \sum_{i=1}^{x-1} \sum_{j=2}^x v_{ni, Pi} \cdot v_{nj, Pj}$$

(Equation 2. 3)

The scenarios that remain after the CCA make up the solution space. Removing scenarios based on a pair-wise comparison facilitates the analysis because it automatically eliminates whole sets of impossible scenarios, thus reducing the solution space from the thousands to the hundreds, or even dozens.

Table 2. 3. Cross-consistency matrix for the example morphological box, adapted from (Ritchey, 2011b)

		Parameter 1				Parameter 2				Parameter 3				Parameter 4			
		V1	V2	V3	V4	V1	V2	V3	V4	V1	V2	V3	V4	V1	V2	V3	V4
P2	V1																
	V2		X														
	V3			X													
	V4			X	X												
P3	V1																
	V2		X	X			X	X									
	V3		X					X									
	V4		X					X									
P4	V1						X	X		X			X				
	V2		X	X			X			X	X		X				
	V3	X		X			X		X	X			X				
	V4	X			X												
P5	V1					X				X		X					
	V2	X		X		X	X			X		X		X	X		
	V3		X	X		X		X			X	X				X	
	V4			X													X

For example, the cross-consistency matrix shown in Table 2. 3 contains 10 parameter blocks and 160 cells, meaning that a working group needs to determine if any of these 160 pairs are possible or impossible depending on specific criteria determined by the group. An x is marked on the cells that

the working group have deemed as impossible or implausible according to the specific criteria, and with the help of a dedicated software tool<sup>19</sup> it is determined that only 13 possible scenarios remain from the original 1,024 alternative scenarios. This makes up the solution space, shown in Table 2. 4.

Table 2. 4. Example of a solution space

Parameter 1	Parameter 2	Parameter 3	Parameter 4	Parameter 5
v1	v1	v2	v1	v4
v1	v1	v3	v1	v4
v1	v4	v2	v1	v1
v1	v4	v2	v1	v4
v1	v4	v3	v1	v4
v1	v1	v3	v2	v4
v1	v4	v3	v2	v4
v3	v2	v4	v4	v1
v4	v1	v2	v1	v4
v4	v1	v3	v1	v4
v4	v1	v3	v2	v4
v4	v1	v2	v3	v4
v4	v1	v3	v3	v4

The leading software tool that supports GMA is MA/Carma (Computer-Aided Resource for Morphological Analysis), developed by the Swedish morphological Society<sup>20</sup>. Through it, the whole GMA process can be carried out. Ritchey (2011b) recommends that this process ought to be supported by qualified facilitation.

Finally, **the fifth step is the solution space analysis**, where the best scenario alternatives for the objectives of the specific case study are chosen from the established solution space and transferred for their subsequent use.

**2.2.2. GMA applications, strengths, and limitations**

Having explored how GMA can be applied in theory in section 2.2.1, this section focuses on how it has been used in the literature Although GMA has thus far been framed as a method meant for scenario development, this is only one of its fields of application.

As shared by the Swedish Morphological Society, GMA has been used in more than 100 projects divided into five general areas: Society, Security and Safety; Commercial; EU Projects; Defense; and for Academic Research Support. The nature of these projects varies, but they can be divided in four broad categories (Ritchey, 2022), described in the following paragraphs, which are mostly based on the literature review done by Álvarez & Ritchey (2015).

- A. Design for engineering, products, architecture, and general design theory: These studies were the main applications of GMA in the mid- and late-20<sup>th</sup> century, especially in engineering and product design. They focus on exploring different design solutions with the potential to enhance an aspect

<sup>19</sup> Tool used for the example: Python implementation of Zwicky's Morphological Analysis (Buchner, 2014/2024). Web tool (accessed March 2024): <https://johannesbuchner.github.io/zwicky-morphological-analysis/#>

<sup>20</sup> MA/Carma website (accessed March 2024): <https://www.swemorph.com/macarma.html>

of the studied problem. Some examples are: product design, the design of product manufacturing and its related processes, architectural design solutions, and training program design, among others (Álvarez & Ritchey, 2015). The end goal is to select the alternative that might yield the best solution for the given study.

- B. *Scenario development and futures studies in general*: Scenario development is among the most conventional and widespread uses of GMA. The idea is to explore the field of plausible, consistent, and relevant scenarios and establish the possible future developments with the objective of using the information to make pertinent decisions. Modeling alternative futures through GMA encompasses a large range of projects and possible applications on different fields and subjects. Some examples of scenario development studies are (Álvarez & Ritchey, 2015; Ritchey, 2011a): human actions affecting nuclear waste storage, climate change scenarios, introduction of electric vehicles in urban traffic, technological forecasting.
- C. *Policy analysis, operational research/management science, and social/cultural modeling*: Studies of this nature use GMA as a method to structure policy spaces and exploring strategy alternatives, as well as in strategic and organizational planning and decision-making (Álvarez & Ritchey, 2015). They complement scenario development through GMA by adding another layer to the model. This means that, in theory, the problem space is divided into two parts: the contextual environment and the strategy space. This way of structuring GMA is especially used when addressing complex policy issues, although it could also be useful for the corporate sector (Ritchey, 2011b).
- D. *Creativity, innovation, and knowledge management*: Studies under this category lean more towards the creative aspects of GMA, emphasizing the perspective of totality research. These studies have used GMA as a methodological and strategic support to generate and organize ideas for innovative business models, co-creation design, and creative thinking and design in general.

Among the virtues that GMA possesses as a method, four general **strengths and advantages** are highlighted, plus two specific advantages for scenario development applications (Johansen, 2018; Ritchey, 2011b):

1. The preparation of the CCA as a collaborative process in an organized and guided group enables the participants to detect poorly defined concepts more easily. This is because they are faced with other concepts in terms of logic and consistency in one-to-one situations. Thus, the CCA can also be used to re-work vague concepts and problems in the terminology. Ritchey (2011b) emphasizes the importance of this point, because even Subject Matter Specialists who have worked in the same area for decades have very different perspectives and experiences. He adds: “These differences – which can make it difficult for them even to agree upon what the “real problem” is – depend on their specific specialties or (more importantly) which “stakeholder” groups they are associated with. In this context, one of the most important results of a GMA workshop is creating among the participants a common conceptual framework, terminology and understanding” (Ritchey, 2011b).
2. GMA is compatible with other modeling tools and procedures, either as a preliminary step that provides a model that can be used in other models, or as a tool for comparing and testing the consistency of posed parameters, concepts, and scenarios. An example is the development of Bayesian Network models, with GMA being a preceding step to determine the variables of the problem, its ranges, and their dependencies (Ritchey, 2011b; Waal & Ritchey, 2007).
3. With the help of the software tools and the documentation generated throughout the process, it is possible to trace the origin of the results generated through GMA, thus enabling reproducibility. Given the complex nature of the problems treated, no two studies will yield the same results, no

matter their similarities. However, it is possible to understand where the information and the derived conclusions are coming from.

4. The systematic exploration used in GMA aids in the discovery of new relationships and configurations that could have been otherwise overlooked. This is supported by the identification and definition of boundary conditions, meaning the limits and extremes of different conditions, contexts, and factors related to the parameters in the problem space (Ritchey, 2018, 2022).
5. For scenario development applications:
  - GMA enables the definition of a generic classification of the morphological field and its solution space. Said classification ensures that all questions posed in the problem definition are addressed and represented in the final scenarios, and that inconsistent scenarios are removed (Johansen, 2018).
  - GMA provides a structured process that leaves a transparent audit trail, which facilitates the scenario verification by the developers and outside parties, and the communication of results. In Johansen's (2018) words: "By establishing firm criteria for the analysis of the morphological field, and making that process transparent, it is possible to communicate results to those who may apply results in practice as well as to the wider scientific community".

Likewise, GMA has **limitations and challenges** to be addressed. The most important ones to be highlighted are (Johansen, 2018; Ritchey, 2011b):

1. GMA requires strong and experienced guidance. To create comprehensive and non-trivial morphological models, the aid of a facilitator is crucial, as Ritchey (2011b) shares from experience. It is possible for a practitioner to build a morphological field with information collected from literature and expert solicitation, and the results obtained can provide valuable information. This is even encouraged as an initial step. However, a follow-up step that engages collaboration and guided dynamic interactions through workshops is strongly recommended to complete the GMA exercise, because this is the best way one can exploit all that GMA has to offer.
2. GMA is time- and resource-demanding. Depending on the complexity of the problem addressed, the development of morphological models might require several workshop days, plus the time and resources required to treat and analyze the results (Johansen, 2018; Ritchey, 2011b).
3. GMA cannot be effectively carried out in groups larger than 7 to 8 participants. Ritchey (2011b) suggests this number to promote communication between participants as individuals, since a larger group would address each other as a whole.
4. GMA depends on the quality of its inputs. This related to the information required to prepare the working group, as well as the quality of the actors included in the working group itself. A challenge to address at this level is the reliance on judgmental evaluations from start to finish (Johansen, 2018).
5. Proper GMA requires dedicated software support (Ritchey, 2011b). Because of the complex nature of the problems that GMA addresses, building the morphological model with software tools helps reduce potential human errors and the time required to make them.
6. For scenario development, the application of GMA does not guarantee that the solution space is an exhaustive representation of all possible and plausible scenarios. Like any other scientific process, there may be unidentified elements that lie beyond the limits that were defined, and these could be expanded with the appearance of new contributions (Johansen, 2018).

Considering all the latter, the structured approach of GMA is indeed an interesting alternative to guide the scenario development for the disaster risk-guided inventory module developed in this PhD thesis. Specifically, GMA can be used to develop the different context scenarios (see Figure 2. 4) that represent the universe of scenarios, through the definition of the morphological box (see Table 2. 2).

### 2.3. Disaster risk-guided scenario definition for LCA

Continuing the discussion of section 1.4 that addressed the scenario development approach to be used in this PhD thesis, the scenario building approach using the GMA method has been found to be an interesting option to develop the future scenarios for the disaster risk-driven inventory module. It permits the consideration of hard-to-quantify elements while enabling a structured, reproducible, and transparent scenario definition process. Therefore, the development of the inventory module in this PhD will use the scenario development approach and the GMA method as bases.

The challenges related to the development of the inventory module as a comprehensive methodological proposition to define scenarios that respond to the main objective of this thesis project are now addressed. These pertain to enabling the consideration of the consequences of evolving disaster risks on the operational and environmental performance of critical infrastructures over their lifespan.

The objective of this section is to explore the challenges related to scenario building for the project to then present how they are addressed through the methodological contribution proposed in this PhD thesis.

#### 2.3.1. Scenario building challenges

The conceptual development of the inventory module will be based on the scenario building approach and the GMA method to produce future scenarios for their posterior use in LCA. However, because of the multidimensionality of the elements that ought to be considered, these approaches and methods should be adapted.

There are several challenges to address before the main objective of the PhD thesis can be addressed. Said challenges are divided into four general topics, which have been identified with the help of the scenario building and GMA steps (see Figure 2. 6).

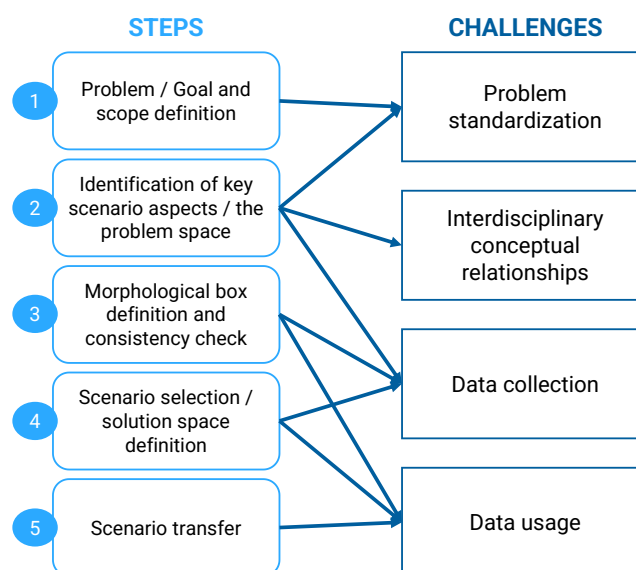


Figure 2. 6. Scenario building and GMA steps vs the challenges

### 2.3.1.1. *The standardization of the problem*

The purpose of establishing a methodological approach is to facilitate the reproducibility of similar case studies, and therefore enable their fair comparison and aiding decision-making. Regardless of the nature of the methodology, the process begins with the definition of the problem it aims to address.

When defining the general problem to be addressed by the methodological approach, we must consider that there are many elements from different disciplines that come into play and are often in conflict with each other. As previously discussed in this manuscript, the issue of evolving disasters risks and their effects on a given territory and on the environmental performance of a critical infrastructure is related to various elements from several fields of knowledge: LCA, disaster risk modeling (hazard, vulnerability, and resilience), scenario modeling, etc.

The main difficulty of having a multidimensional problem when faced with the purpose of a methodological approach is that each field of knowledge has its own concepts and ideas, and in a sense, the experts on different fields do not speak the same language. Each field interprets a problem from a different perspective based on the knowledge and tools at their disposal. This makes communication and information gathering difficult. It is even more complicated when a particular concept is understood differently depending on the field of knowledge. For example, Risk Assessment (RA) has been interpreted as either environmental RA or chemical RA in its conventional integration with LCA (see §1.3.1.1).

Thus, the challenge lies in accurately stating and defining the problem to be addressed, so that it is understood in the same way by the main fields of knowledge and actors involved. In this case, the main objects that should be clearly stated in the problem definition are the evaluation of the environmental performance of the critical infrastructure and the effects of evolving disaster risks. This information will facilitate the identification of the key aspects for scenario development.

### 2.3.1.2. *Conceptual relationships in an interdisciplinary approach*

The identification of the key aspects for scenario development requires a thorough understanding of the elements involved. This becomes a challenging task because of the involvement of complex and multidisciplinary elements needed to identify the problem space. These difficulties are further highlighted when attempting to establish canonical definitions and conceptual relationships between fundamental elements for the problem space definition, which needs to be established before attempting to define the morphological box.

The complex elements that must be addressed in the problem space throughout the established period of the study are:

- **The disaster risks.** In a given territory there can be different types of disaster risks, and depending on the nature of the hazard, these are described at different intensity and temporal scales and through different mechanisms. Moreover, all the four dimensions of disaster risk -hazard, exposure, vulnerability, and capacity (see §1.2.2.1)- must be addressed to fully represent the phenomena, which are represented by different models. This description is further complicated when contemplating the possible interactions between natural and technological hazards (i.e. NATECH, see §1.2.3.2), with territorial trends (i.e. land use change), and socio-economic factors (i.e. vulnerability and resilience of local communities).

- **The critical infrastructure.** As the object of the study, the critical infrastructure is mainly described by the elements that compose it, i.e. the internal components that enable its functions. However, the external elements are as much a part of the critical infrastructure as the internal ones. Its characteristics will depend on the physical location, the socio-economic and political situation of the territory it is in, the attitudes of surrounding communities towards similar critical infrastructures, the state and evolution of all these situations, as well as the evolution of technologies related to the components of the critical infrastructure. Similar to the case of disaster risks, these elements are described through different mechanisms and temporal scales, making their collective analysis difficult. Moreover, in the case of this PhD thesis, a complete description must already include what are the possible consequences for the operational performance of the critical infrastructure after a disturbance, at least in a generalized way. Naturally, a more detailed understanding of these possible phenomena is preferable, but it also requires more time and resources.

Disaster risks and the critical infrastructure are at the center of the problem that is addressed. They are the elements whose relationships will bridge the gap between effects and consequences of uncertain phenomena. If the methodological proposition wants to enable a structured way of studying these relationships and permit reproducibility for similar studies in the future, knowledge linked to multiple fields of knowledge is required: prospective studies, life science, engineering, organizational theory, geography, and environmental impact assessment.

Having this information will facilitate the definition of the morphological box and subsequent steps.

#### 2.3.1.3. Data collection

Also related to the multidimensionality and multidisciplinary of the problem addressed, the information required to establish the problem space and build the morphological box for scenario building needs to come from diverse subjects and topics. Data recollection thus requires consulting a multitude of sources from different domains, which involves several challenges:

- **Diversity of temporal scales.** As evoked in section 2.3.1.2, the models that describe disaster risks, the studied critical infrastructure, and the territorial context do not operate on the same temporal scale, especially when addressing their potential evolutions and the life cycle perspective.
  - The evolution of any structure, building, system, business, or infrastructure will generally rely on internal decisions within an established period. But the evolution of disaster risks, particularly natural risks, is more difficult to address. And by virtue of being related, these difficulties extend to the critical infrastructure, which will affect the potential decisions that are made.
  - For example, the operational lifespan of the critical infrastructure involves a couple of decades, while the return periods of major disaster risks are centuries. Related to this, some models might not describe the phenomena in ways that can be directly interpreted thus additional data treatment is required.
- **Diversity of spatial scales.**
  - For infrastructure, it is not the same to address a single plant or the development of a sector in a given region. The methodological proposition is for now focused on the study of a critical infrastructure, but its use in broader studies that include multiple infrastructures is an interesting development for the future.



- Disaster risks, depending on their nature, will originate in certain geographical regions and have a potential area of impact. For example, in the case of a flood or a dam break, the event could start upstream, outside the territorial scope of a study, and propagate throughout the river until it reaches the concerned territory. With this perspective, how certain risks that the infrastructure may be exposed to are considered becomes a more challenging question.
- **Diversity of risks.** Disaster risks can be straightforward, i.e. hail breaking important equipment, or complex, i.e. a forest fire propagating to a new region because a gas reservoir exploded after exposure. Complex risks (see §1.2.3.2.) complicate the analysis, but it is important to consider them given their potentially cascading and devastating effects.
- **Diversity of trends.** The increase of global average temperatures is a driving force behind many global phenomena, such as stronger and more frequent natural hazards. However, its great importance should not blind us from other important trends that affect the vulnerability and resilience dimensions of disaster risk: regional, national and international political decisions, socio-economic issues, technological development, etc.

These problems raise questions about how to ensure the quality and the pertinence of the data that should be collected, and what are the key sources and experts to consult.

#### 2.3.1.4. Data usage

In this case, scenario building involves using the information that has been collected to construct future situations representative of the problem addressed. From what has been discussed in section 2.1.4, this needs to happen in two distinct steps: one for the context scenarios contained in the scenario universe, and another one for the decision scenarios contained in each context scenario.

The application of GMA for scenario development presents a solid alternative to establish the context scenarios, since it enables the inclusion and systemic analysis of qualitative and quantitative aspects. Moreover, the morphological box and the CCA permit a visual and relatively simple representation of the contents of the scenario universe, which facilitates collaborative work of experts in different fields and the presentation of results to concerned parties. The challenges here are also related to the diversity of information that goes into the morphological space as well as the logistical aspects of the workshops. Such an analysis will never be free from judgmental processes and certain biases; thus, practitioners must be careful and exhaustive when organizing said workshops and the information presented. Finally, both the input and the output information for this exercise may be either of qualitative or quantitative nature. Thus, one must be critical when interpreting this through the morphological box since the tool has been designed to deal with qualitative data.

In the case of decision scenarios, naturally, they rely on specific information related to the context scenario they belong to. Their objective is to present the different alternatives that decisions made throughout the operational lifespan of the infrastructure will yield, given the baseline operational performance and the possible disaster risks that can disrupt it at different periods. The challenges here are related to the representation of the lifespan operational performance model, the temporal scale of the scenario analysis (same as in §2.3.1.3), determining the rules or guidelines of diverging decision scenarios -i.e. how do we determine when a decision must be made, and what kind of decision?-, the presentation of results for their clear understanding, and establishing a clear link with the life cycle inventory.

The latter challenge is related to scenario transfer. The methodological proposition is contained in an inventory module; thus, the results are both descriptive scenarios and a quantitative representation of the changes these scenarios involve for the life cycle inventory. Evidently, there is an inventory per decision scenario, therefore the model used for the inventory should share the same characteristics across decision scenarios, be easily editable, and consistently provide the outputs in the same format. In LCA, parametrized models have the capacity to consider temporal, spatial, and technological variabilities of product systems, using input parameters to represent to describe selected flows (Besseau, 2019; Tannous et al., 2019). With this in mind, parametrizing inventories related to context scenarios is a solution that can ease the evaluation of results.

### 2.3.2. Proposed methodological contribution

To address the challenges related to scenario building for the LCA of a critical infrastructure, the proposed methodological contribution, i.e. the inventory module, consists in developing a scenario definition method at the LCI level that is guided by disaster risks: the **Disaster Risk-gUided scenario Definition (DRUID) Method – LCI Module**. The development of this method is divided into three general tasks: the conception and formalization of the meta-method, the elaboration of the method, and the completion and use of the method in LCA.

#### 2.3.2.1. Conceiving and formalizing the meta-method

The challenges addressed in this task are the problem standardization and the interdisciplinary conceptual relationships. The proposed solution consists of two parts.

The first part is the canonical problem definition, where a general formulation of the problem to address is presented. Its purpose is to facilitate the identification of the main elements that will guide the scenario definition process. These elements are the trends guiding the evolution of risks, the type of risks, the type of performance to be assessed, the critical infrastructure, and the location. In the context of LCA, the performance type addressed is the environmental performance of the critical infrastructure. However, by leaving the performance type as an ‘open question’ the practitioners may include what is important for their particular study, for example, economic performance.

Thus, the canonical problem formulation is: *Will <trends> -driven evolution of the <type> risks significantly affect the <performance type> performance of <critical infrastructure> located in <location> within <time horizon>?*

The second part is the development of an application-specific ontology, which establishes a common vocabulary (Noy & McGuinness, 2000) to be used for the *DRUID method*. The ontology will establish the definitions for the basic concepts that come from the various fields of knowledge used, i.e., the problem definition, disaster risks, the territory, the critical infrastructure, the trends, and the existing relationships between them. Its purpose is to establish a structured terminology that links the different elements consistently, allows the reproducibility of case studies, and facilitates information organization. A secondary purpose is to set the foundations for interoperability between tools supporting the application of the *DRUID method*. Developing the ontology is the subject of Chapter 3.

#### 2.3.2.2. Elaborating the method

The challenges addressed in this task are the interdisciplinary conceptual relationships and the data collection. The proposed solution is the disaster risk-guided scenario definition method as an LCI module (DRUID LCI), that consists of four iterative steps (see Figure 2. 7). Each step is linked to a scenario building step with specific guidelines pertaining to the type of problem the method is meant

to address. This is the subject of Chapter 4, where the conception of the first three steps is explored in parallel with an example of their application through a case study. The fourth step is explored in Chapter 5 for reasons that are explained in later paragraphs.

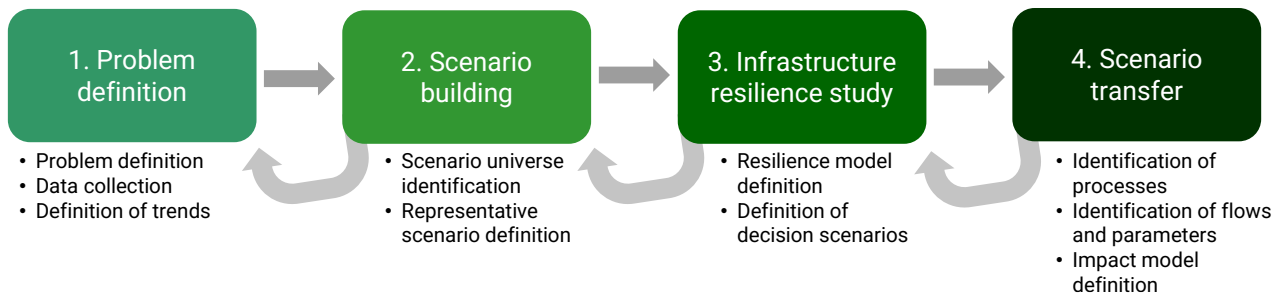


Figure 2. 7. Disaster Risk-guided scenario Definition (DRUID) method – LCI Module

The case study is in the context of the development of a PV infrastructure in a mountainous region in the south of France in a 2050 horizon. Its purpose is to demonstrate the feasibility, opportunities, and limitations of the proposed method.

**The first step** is the problem definition, consisting of two parts. The first part is where the problem to address is posed using the canonical problem formulation (see §2.3.2.1). Through this definition, the essential elements of the problem are identified. The second part consists of following the data collection guidelines, where questions are posed for each identified dimension of the problem: hazards and exposure, absorptive capacity, the infrastructure, and the territory. Responding to these questions will give the user a better idea of the information they require to address their problem and assist in the identification of the possible sources of required data. With the obtained information, parameter classes related to key elements of the problem addressed can be identified: hazard class, territory class, infrastructure absorptive capacity class, and infrastructure technology class. For each parameter class, the related parameters with their respective conditions or values are defined. Said conditions represent the states that the parameter can take depending on the driving trends and the defined time steps of the study.

**The second step** is the scenario building. This step follows the recommendations for the GMA morphological box method. From the information gathered during the first step the morphological box that represents the universe of possible scenarios is defined. The CCA is performed as established in section 2.2.1.3, and the result is the solution space with the possible alternatives that make up the universe of context scenarios. From the established universe of context scenarios, at least one is chosen according to their representativeness to the problem addressed.

For each context scenario selected from the scenario universe, a scenario structure is established. Said structure contains information on:

- *The general context.* It is a narrative description of the global trends related to the territory and the infrastructure sector. These trends are representative of their expected changes and evolutions.
- *The territory context.* It is a narrative description of how specific aspects of the territory could evolve in the period studied, including geographical, political, and demographic aspects, among others relevant to the study.
- *The disaster risk context.* It presents the changes in the main characteristics of the disaster risks considered in the context scenario. These changes are specific to the guiding trends and the

defined period. The main characteristics of disaster risks are the hazards the territory is exposed to, and the absorptive capacity of the critical infrastructure for each hazard it may face.

- *The infrastructure context.* It is a narrative description of the changes related to the infrastructure sector, such the expected changes at the technological level, policies, best practices, etc.

**The third step** involves using the information from the context scenario structure to study the resilience of the critical infrastructure when faced with specific types of disaster risks. It consists of an iterative model that aims to identify the potential consequences of disaster risks on the resilience of the critical infrastructure throughout its lifespan given plausible decision-making alternatives related to maintenance. For critical infrastructures in the energy production sector these maintenance decisions are related to repairing or changing particular components, and repowering, which involves replacing the entire installation with a newly manufactured system to increase the overall energy production output (Herceg et al., 2022). The outputs of the resilience model are the decision scenarios.

**The fourth step** involves an approach to transfer the decision scenarios to LCA. The objective is to provide concrete guidance to link the consequences of decision scenarios to the corresponding changes in the life cycle inventories (LCI) and their subsequent life cycle impact assessments. It consists of defining parameters and processes that represent the results from the resilience study, and cohesively integrating them with the reference parametrized LCA model to develop the DRUID LCI model of the infrastructure. This model can then be used in the LCIA to estimate the environmental impacts of the product system.

In this PhD thesis, the *DRUID method* is presented as an LCI module, thus called DRUID LCI. However, the *DRUID method* could be used in another context that it not an LCA study. In such cases, the fourth step must be adapted specifically to transfer the decision scenarios from the resilience study to the assessment method they would be used it. This is why Chapter 3 introduces the *DRUID method* and the concepts it is built upon form a 'generic' standpoint.

If the *DRUID method* is to be used as an LCI module (see Figure 2. 8), then it is fundamental that the Goal and Scope and LCI phases are first done for the baseline LCA, following the ISO standards (ISO 14040, 2006, p. 14; ISO 14044, 2006), recommendations from the ILCD handbook (EC-JRC, 2010), or any other specific recommendations for the type of product system under assessment.

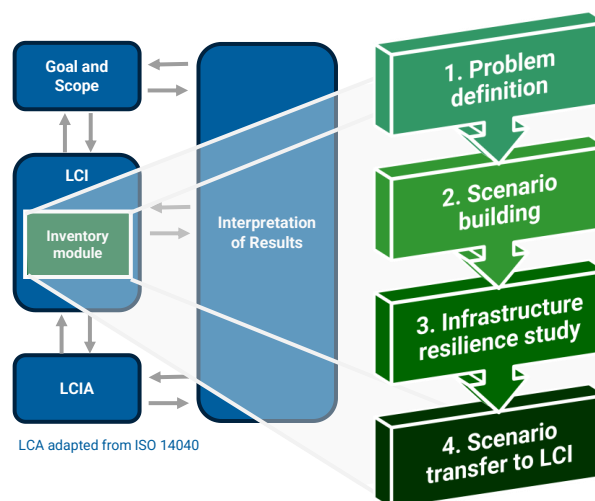


Figure 2. 8. Disaster risk-guided scenario definition (DRUID) Method – LCI Module in LCA

### 2.3.2.3. LCA application of the method

The practical incorporation of DRUID LCI in an LCA study is the subject of Chapter 5, using the application to the case study to guide the development and presentation of the comparative LCA results for one context scenario. This is done using flexible and compatible LCA software tools: *Brightway2*, an open-source Python-based LCA tool for quantitative environmental impact assessments (Mutel, 2017); and *lca\_algebraic*, a Brightway2-based library that uses symbolic calculus to facilitate the parametrization of life cycle inventories and facilitate sensitivity analyses (Jolivet et al., 2021).

After the LCIA has been performed for each identified decision scenario, the environmental impact results are meant to be included in the scenario structure presentation.

## Conclusion

Studying the future is fundamental to complete the methodological proposal, i.e. the inventory module for LCA, if it is to structure the analysis of the possible evolutions of disaster risks and their effects on the environmental performance of the studied critical infrastructure. Specifically, scenario building methods provide guidance and tools for the representation and analysis of future situations. Among these, the General Morphological Analysis (GMA) has been identified as a relevant method to guide scenario development in this case because its conceptual modeling approach focused on exploring relationships between variables facilitates the inclusion of quantitative, semi-quantitative, and qualitative factors in scenario building.

The exercise of going through the existing scenario methods, exploring the principles behind the prospective approach, finding the opportunities GMA presented, and brainstorming how the scenarios in the method could be with the aid of these tools was not as straightforward as it has been presented. Despite not being shown in this Chapter, specificities on the case study were studied and reworked during several workshops that aimed to engage with scenario building and GMA in particular. The discussions and conclusions that arose from these workshops greatly helped to uncover the research challenges and fundamental questions to answer. From this exercise, it has been determined that the inventory module should be a scenario definition method with GMA as its main basis.

To make a comprehensive methodological proposition there are research challenges to confront, which became apparent after comparing the needs of the project with the steps for scenario building. These challenges have been addressed through three general tasks whose objective is to establish the proposed **Diaster Risk-gUided scenario Definition (DRUID) Method – LCI Module**: conception and formalization, elaboration, and application to LCA. Each task is addressed and expanded on one of the following chapters.

## Chapter 3. An Ontology to Support the Design and the Application of the Disaster Risk-guided Scenario Definition Method

### Introduction

The Disaster Risk-guided scenario Definition (*DRUID*) method aims to support the consideration of the potential consequences of evolving disaster risks in the assessment of a given performance type of a critical infrastructure throughout its lifespan. As introduced in Chapter 2, the first step of the methodology consists in collecting data necessary to frame the problem to be studied, step 2 consists in elaborating the prospective scenarios, step 3 pertains to the infrastructure resilience study, and step 4 transfers the scenario results to the critical infrastructure performance study, which in this PhD thesis is Life Cycle Assessment (LCA) to evaluate the environmental performance.

The development of the *DRUID method* raises two challenges that are addressed in Chapter 3. The first challenge is related to the interdisciplinary nature of the *DRUID method*. Indeed, the methodology must integrate concepts, models, and methods from different scientific domains to elaborate representations of critical infrastructures and disaster risks, apply a prospective analysis on this model, and translate the results to enable the comparison of the performance type being assessed. The second challenge is related to the open nature of the *DRUID method*. It aims to support the comparison between types of performances of a critical infrastructure that could be evaluated with and without considering the evolution of the risk of disasters. In the context of this PhD, the performance study refers to the environmental performance evaluated with LCA. Still, the objective is that the *DRUID method* could be applicable to the diversity of critical infrastructure performance types that could be assessed, for example, environmental, operational, and economic performance. Hence, the *DRUID method* must allow the transfer of its results toward specific tools and methods associated with diverse studied performance types.

These challenges motivate the formulation of the first scientific question of this PhD thesis:

*How could the formulation of the specific problem that contemplates concepts from different domains for knowledge be cohesively guided?*

One approach to address these issues is the design of an Ontology (Uschold & Gruninger, 1996). Ontology is originally a discipline of philosophy dedicated to the systematic study of the nature and organization of being (Chaumier, 2007). The knowledge representation research community uses the concept of Ontology to refer to the basic terms and relations that include the vocabulary of a topic area and the rules to combine terms and relations that enable defining extensions to the vocabulary (Neches et al., 1991). Ontology can describe very general concepts but can be dedicated to specific applications (Guarino, 1998), in which case it can be called an “application ontology”. They provide an added value to create a shared understanding of some domains of interest, to solve communication issues between people (e.g. between experts from different domains), interoperability among systems, and system engineering problems (Uschold & Gruninger, 1996).

Thus, to support the design of the *DRUID method* and associated tools, an application ontology named *OntoDRUID* is proposed. It has three aims. The first is to support the integration of elements from risk management, critical infrastructure resilience, and methods supporting prospective studies. The second is to allow the application of the *DRUID method* to different specific domains of assessment,

such as environmental assessments. Finally, the third aim is to facilitate the engineering and interoperability between support tools, and the communication between the actors involved in studies that use the *DRUID method*.

The objective of Chapter 3 is to describe *OntoDRUID* (see Figure 3. 1). The design of *OntoDRUID* follows essential steps in designing an ontology proposed by Noy and McGuinness (2000). The initial step entails delineating the domain and scope of the ontology by formulating the ontology requirements using competency questions. Then, the essential terms of the Ontology are identified based on existing ontologies. The ontology classes, hierarchies, and properties are then designed. Finally, class instances are formulated to meet the requirements.

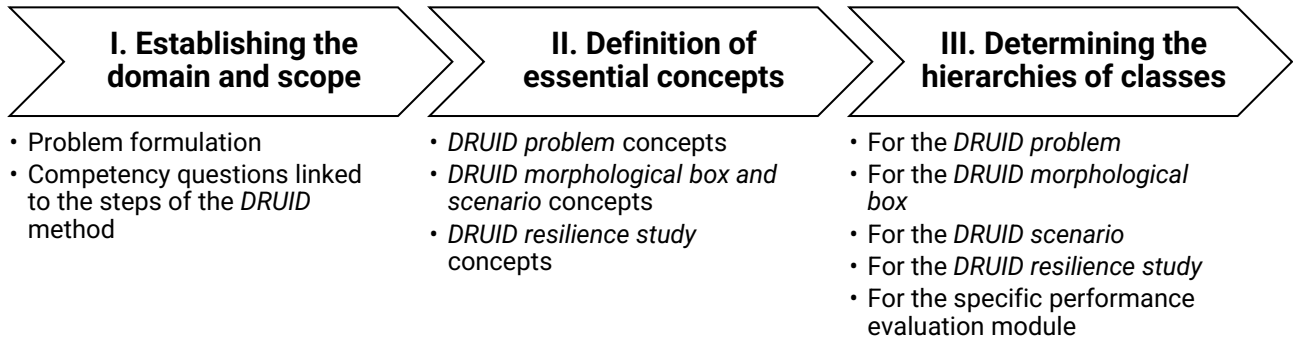


Figure 3. 1. Phases to design the *OntoDRUID* ontology

### 3.1 The Ontology Engineering Domain

Aristotle developed Ontology as a domain of Metaphysics, which explores the nature of existence. The philosophical definition of Ontology is the "*science of being qua being*", the study of attributes that belong to things because of their very nature (Guarino et al., 2009). The origin of the term is the Greek 'to on' from the noun present participle of the verb to be 'einai' and the words 'logia' (theory) and 'logos' (discourse). In computer science, an ontology is a type of information object or computational artifact that formally models the structure, i.e., the relevant entities and relations that emerge from observing a system to be helpful to a dedicated purpose (Guarino et al., 2009; Roche, 2005). Studer et al. (1998) define an ontology as "a formal, explicit specification of a shared conceptualization". A conceptualization is an abstract, simplified view of the world that we wish to represent for some purpose (Genesereth & Nilsson, 1987).

Gruber (1993) distinguishes five components in ontology design: classes, relations, functions, instances, and axioms. Classes are abstract groups, sets, or types of objects or entities that primarily categorize and organize knowledge. Relations are ways in which classes and instances can be related to one another. It includes hierarchies (subclass-superclass relationships) and associative relationships (part-of, connected-to). Functions are particular types of relations where each element in the domain is associated with exactly one element in the range. Instances are specific, concrete occurrences of concepts or classes. Axioms refer to statements or rules that are always true in the domain. They are used to impose constraints and infer new knowledge.

Gruber (1993) also proposed requirements to be considered while designing an ontology. An ontology should provide unambiguous definitions of concepts and relationships. It should be logically consistent, with all definitions and axioms coherently connected. It should be designed to accommodate the addition of new concepts and relationships as needed. It should include only the

most essential concepts and relationships for the intended tasks. It should avoid redundancy by ensuring each concept and relationship is represented only once.

Uschold and Gruniger (1996) promote ontology in five axes:

1. To provide a shared understanding of enterprise activities, facilitating communication between different departments and improving coordination for business process re-engineering and enterprise integration.
2. To enhance the ability to capture, distribute, and effectively use knowledge, improving decision-making and innovation.
3. To enable seamless access to information from diverse sources, allowing for more comprehensive data analysis and reporting.
4. To improve the accuracy of language processing applications such as information retrieval, translation, and user interaction systems
5. To enhance the precision of product searches and comparisons, improving the user experience and operational efficiency in online marketplaces.

Guarino (1998) distinguishes between several types of ontologies and provides a definition of each typology. “Top-level Ontologies” describe general concepts independent of a particular domain or application. They provide a high-level framework to support broad interoperability and shared understanding across various domains. “Domain Ontologies” describe concepts specific to a particular domain of interest. “Task Ontologies” describe the vocabulary related to specific tasks or activities. They provide the terms and structures needed to support particular tasks or processes. “Application Ontologies” describe concepts depending on a particular domain and a specific task or application. They are tailored to meet the requirements of particular applications, integrating domain-specific and task-specific knowledge.

Designing an ontology involves multiple stages, each building on the previous one to ensure that the result is robust, useful, and adaptable. The first step in the ontology design method is akin to laying the foundation by defining its purpose and boundaries. Here, competency questions are formulated, such as “What domains are we representing? What specific problems are we trying to solve?” Answering these questions sets clear objectives and constraints, ensuring that the ontology will be focused and relevant. Next, the raw materials needed for our construction are gathered. This process involves collecting domain-specific knowledge from various sources, such as academic papers, databases, existing ontologies, and expert consultations. This step is crucial as it ensures we comprehensively understand the domain, preventing gaps in our ontology. Key concepts and their relationships within the domain are then identified so the blueprint can be sketched with a solid foundation and materials. This step involves brainstorming sessions and discussions with domain experts to ensure completeness and accuracy. The conceptual model is then created, where the key concepts and their relationships are visually represented using diagrams or flowcharts. This high-level model serves as a guide, providing a clear picture of the overall structure and how different components fit together. Finally, the classes (general concepts) and instances (specific examples) of the ontology are defined (Noy & McGuinness, 2000).

The following sections present the application of these phases to design the *OntoDRUID ontology*.



### 3.2. *OntoDRUID* domain and scope

As previously stated, *OntoDRUID* is an Application Ontology aiming to support the development and use of the *DRUID method*. The development of *OntoDRUID* is motivated by the challenges of developing an interdisciplinary and open method. The *DRUID method* relies on concepts and models from Critical Infrastructure Resilience, Disaster Risks, Prospective studies, and, in the context of the PhD, the LCA domain. Because *OntoDRUID* is an application ontology, it has first to describe the specific problem the *DRUID method* addresses. Then, the ontology must support the *DRUID* steps that consist in collecting data, elaborating prospective scenarios, study the lifespan resilience of the critical infrastructure, and communication with specific performance assessment tools.

The first phase of the *OntoDRUID* ontology design involves formulating competency questions for each of the *DRUID* steps. These questions frame the requirements of the Ontology.

The first dimension considered to define the competency questions is the type of problem addressed by the *DRUID method*. As previously stated, (see §2.3.2.1), a *DRUID problem* follows the following generic formulation:

Will **<trends>**-driven evolution of the **<type>** risks significantly affect the **<performance type>** performance of **<critical infrastructure>** located in **<location>** within **<time horizon>**?

This formulation integrates three dimensions: the critical infrastructure, including the specific performance studied; the disaster risk; and the prospective study. For a given *DRUID problem*, the ontology must be able to support the design of tools such as guidelines, databases or graphical user interfaces. These tools must provide the *DRUID* analysts with the means to answer to the following competency questions:

1. What is the critical infrastructure studied?
2. What are the risks considered within the study?
3. What trends are considered to elaborate on the prospective scenarios?
4. What are the spatial borders of the study?
5. What are the temporal borders of the study?
6. What is the specific performance studied?

The first step of the *DRUID method* is the definition of the problem to study, which is based on the generic formulation of a *DRUID problem* and on the competency questions presented above. Complementary to the problem definition is the data collection. This consists in gathering the data required to apply it. The ontology must support this phase by standardizing the concepts used to collect data and supporting the storage and access to data related to the *DRUID problem*. Consequently, the ontology must consider the diverse and complex nature of critical infrastructures and disaster risks to describe a wide range of problems. The ontology must be able to aid the *DRUID analyst* with the following competency questions:

7. What information about the studied critical infrastructure has already been collected?
8. Which information about the studied critical infrastructure is still to be collected?
9. What information about the risks of disasters has already been collected?
10. What information about the risks of disasters is still to be collected?
11. What information about the considered trends has already been collected?
12. What information about the considered trends is still to be collected?

The second step of the *DRUID method* consists in elaborating prospective scenarios using the General Morphological Analysis (GMA) method (see §2.2.1.3). This approach relies on first constructing a morphological box representing the entire problem space by cross-tabulating the essential parameters to elaborate the scenarios and their associated values. Then, a cross-consistency assessment is performed by systematically evaluating the compatibility of pairs of parameter values to identify which combinations are feasible and which are not (Ritchey, 2022). At the end of this process, a set of possible future configurations are available, and the analyst will select the most representative ones to elaborate on the *DRUID scenarios*. The ontology must be able to support the DRUID analyst with the following competency questions:

13. What are the parameters considered to elaborate the *DRUID morphological box*?
14. For each parameter, what is their universe of values?
15. What are the possible combinations? What are the feasible ones, the incompatible ones, and the contradictory ones?
16. What are the potential configurations? Are there patterns and insights?
17. What is the associated *DRUID scenario* content for each selected configuration?

The third step of the *DRUID method* consists in studying the resilience of critical infrastructure within its lifespan while considering the elaborated *DRUID scenario*. The analyst constructs an algorithm to simulate the lifespan of the infrastructure depending on the evolution of its key performance indicators and its ability to absorb disaster risks. The ontology must be able to support the *DRUID analyst* with the following competency questions:

18. What is the considered duration of the critical infrastructure lifespan?
19. What are the rules of evolution of the considered critical infrastructure Key Performance Indicators (KPI)?
20. What is the evolution of the risk of disasters?
21. What is the evolution of the critical infrastructure absorptive capacity?
22. What are the resilience actions?
23. For each simulation, what are the values of the KPI and of the occurrence of resilience actions?

The fourth step of the *DRUID method* provides results for the initial *DRUID problem*. The analyst translates simulation results to feed the software that will support the evaluation of the critical infrastructure performance type considered within the *DRUID study*. The analyst evaluates the performance with and without considering the *DRUID phase three* results. Then, he provides a result narrative with the comparison results and data used to generate them. Within the context of the *DRUID-LCA approach* (DRUID LCI, see §2.3.2), dedicated software evaluates the environmental impacts over the lifespan of a critical infrastructure with and without considering the environmental impact of reparation and reconstruction processes. The ontology must be able to support the *DRUID analyst* with the following competency questions:

24. What are the Input parameters of the specific DRUID-performance evaluation module?
25. How is the *specific DRUID performance* of the lifespan of the critical infrastructure evaluated without considering the evolution of the risk of disasters?
26. How is the *specific DRUID performance* of the lifespan of the critical infrastructure evaluated, considering the evolution of the risk of disasters?
27. What are the conclusions of the comparison of the two evaluations?

These 27 competency questions structure the requirements of the *OntoDRUID ontology*.

### 3.3. *OntoDRUID* essential concepts definition

The second phase in defining an Application Ontology such as *OntoDRUID* is to define the essential concepts to be considered within the ontology. The following sections provide a conceptualization of essential concepts associated with each step of the *DRUID method*.

#### 3.3.1. *OntoDRUID* problem definition and data collection concepts

The first step of the *DRUID method* consists in formulating an instance of a *DRUID problem* and collecting data necessary to gather information required by the application of the method. The first core concept of this step is the *DRUID problem*. A *DRUID problem* addresses the evolution of critical infrastructure performances with a prospective perspective centered on the risks of disasters. *OntoDRUID* aims to establish a unified vocabulary and conceptual framework that bridges various disciplines in formulating a *DRUID problem*. This conceptualization relies on three concepts: critical infrastructure, disaster risk, and on the domain of prospective scenario design.

##### 3.3.1.1. Critical infrastructure

The first concept of a *DRUID problem* is the **critical infrastructure**. A critical infrastructure is “a company, an institution, an organization, facilities, services, and equipment, whether regional, national, or international, which, if disrupted, damaged, or destroyed, would have a serious impact on the health, safety, security, or economic well-being of citizens or the effective functioning of governments and other infrastructures depending on it” (Gallais & Filiol, 2017). Critical infrastructure characteristics are the core of a *DRUID problem*. Hence, the ontology must cover the diverse and complex nature of critical infrastructures.

To provide the *DRUID method* with a wide scope of application, the ontology must support the description of the diversity of critical infrastructure types. The concepts of **sectors**, **sub-sectors**, and **industrial function** aid in establishing this description. To characterize the different potential critical infrastructure sectors, the typology provided by the European Union directive on the resilience of critical entities (Directive EU 2022/2557) is used (EU, 2022). This directive provides a typology of industrial sectors: energy, transport, banking, financial market infrastructure, health, drinking water, wastewater, digital infrastructure, public administration, space, production, processing, and food distribution. Subsectors support the description of sectors. For example, considering a subsector associated with the origin of electricity (e.g. fossil fuel or renewable resources) enhances the description of the energy sector. Finally, industrial functions, such as production, storage, transportation, or distribution, support the distinction of infrastructure.

Prospective scenario design, resilience studies, and specific performance evaluation require manipulating information about critical infrastructure characteristics. The sociology of an organization provides concepts that allow DRUID users to describe the complexity of critical infrastructure, referring to the multiple interacting elements between an infrastructure and its internal and external environment. For example, Hatch and Cunliffe (2013) offer concepts to describe the internal structure of an organization and its interactions with its environment (see. Figure 3. 2).

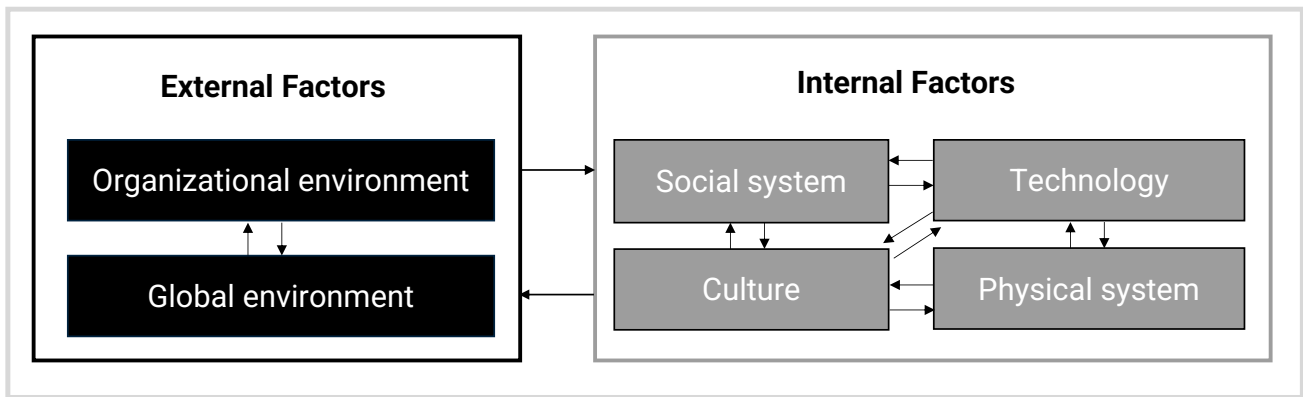


Figure 3. 2. Essential concepts to describe an organization adapted from Hatch and Cunliffe (2013)

The complexity of the structure and of the dynamic of critical infrastructure is described by considering internal and external factors. Four internal and two external factors support the description of the structure and the dynamics of an organization. The internal factors are (Hatch & Cunliffe, 2013):

1. **Technology** concerns all the means the organization uses to enable the production of products and services that justify its activity. It includes the physical objects (products, tools, or equipment) used in production, production methods, and the knowledge necessary to develop and use the tools. The described essential technologies of the studied organization and associated properties such as production rate, reliability, or reparability aids DRUID analysts in selecting specific performance types studied and elaborating simulations. Technologies related to the production objectives of the organization have to be described as the ones associated with risk management.
2. The **social system** describes the hierarchy of authority, the division of labor, and the system of rules and formalized procedures. The described social system of the studied organization will aid DRUID analysts in characterizing risks of failure of the productive system, safety management barriers, and characterizing potential decision-making activities about a specific studied performance.
3. The **physical system** is related to the spatial distribution of locations in which the organization is present and the physical particularities of each area. The described physical system, particularly the location of the critical infrastructure, will support DRUID analysts in characterizing risks of disasters that can affect the infrastructure.
4. **Culture** is associated with the set of shared representations relating to work, technology, functions, relationships, and a code of life, that is, the way of acting to produce, communicate, control, decide, or inform. The described cultural system will support DRUID analysts in characterizing decision-making principles.

The environment includes all the systems outside the organization that influence its functioning. Two systems are distinguished: the organizational environment and the global environment. The organizational environment includes entities that interact with the organization. The global environment includes global entities and phenomena that indirectly influence the organization.

The **organizational environment** directly relates to the systems interacting with the organization (Hatch & Cunliffe, 2013). An organization sells products and services to clients and buys raw materials and equipment from suppliers. It might mobilize subcontractors to support production or manufacturing. Financial actors such as banks or insurance companies follow the activities of the

organization. The described organizational environment will support DRUID analysts in characterizing potential sources of disturbances and constraints to be considered when making decisions.

One specificity of critical infrastructure is the intricate nature of interdependencies and their consequence on disruption propagation. For example, the power grid and telecommunication are interdependent systems. Power grid functioning requires continuous, real-time data transmission over telecommunications networks to monitor and control the flow of electricity. Likewise, telecommunication networks need electricity to power cell towers, switching, and data centers. Power distribution or telecommunication failure will create disturbances that may negatively impact infrastructure and population. Rinaldi et al. (2001) distinguish four types of sources of interdependencies:

1. **Physical Interdependencies** occur when the operation of one infrastructure is physically dependent on the material output of another infrastructure. For example, water treatment plants and distribution systems require electricity to operate pumps and treatment facilities. Conversely, power plants often need water for cooling and other processes.
2. **Cyber Interdependencies** rely on information and communication technologies to control and operate infrastructure systems. Disruptions in the cyber domain can affect the functionality of multiple infrastructures. For example, financial transactions depend on telecommunications networks for data transfer. A cyberattack on the telecommunications network can disrupt banking operations.
3. **Geographic Interdependencies** arise when infrastructures are close to spatial proximity, so local environmental events can simultaneously affect multiple systems. For example, an earthquake can simultaneously damage power lines, water mains, and communication cables that are co-located or parallel.
4. **Logical Interdependencies** involve dependencies that do not stem from physical connections but from human decisions, policies, or organizational requirements. For example, energy policies that mandate certain production methods can influence the availability and reliability of power. Similarly, financial regulations can impact the operational strategies of banks and financial institutions.

They also propose a set of interdependency characteristics (Rinaldi et al., 2001):

1. **Tight or loose coupling** related to the speed of propagation of disruption from one infrastructure to another,
2. **Disruption effect order** related to the consequence of disruption from an infrastructure to another, ranging from immediate effects to cascading effects that propagate within different layers of the infrastructure,
3. **Temporal characteristics**, including the time it takes for an impact to be felt, the duration of the disruption, and the time needed for recovery,
4. **Infrastructure disruption management** characteristics such as redundancy, robustness, and resilience.

The described interconnections between the studied infrastructure and other infrastructure will support DRUID analysts in characterizing the consequences of disasters within the system and its environment.

The **global environment** is composed of the general forces that influence organizations and their organizational environment. Hatch and Cunliffe (2013) distinguish seven sectors:

1. The **physical sector** concerns natural phenomena such as natural hazards or natural resources.
2. The **social sector** refers to the dynamics linked to class stratification, mobility models, lifestyles, and traditional social institutions (educational systems, religious practices, businesses, and professions).
3. The **cultural sector** represents notions such as history, traditions, behavioral expectations, and values of the society or societies in which the organization operates.
4. The **legal sector** defines the laws and regulations of the countries in which the organization sources, produces, and markets its production.
5. The **political sector** concerns the distribution and concentration of power and the nature of political systems.
6. The **economic sector** consists of the labor market, financial markets, and markets for goods and services.
7. The **technology sector** provides knowledge and information through scientific developments that the organization can acquire and use to implement its products and services.

The described global environment will support DRUID analysts in characterizing prospective trends.

#### 3.3.1.2. Risks of disasters

The second essential dimension of a *DRUID problem* is the **risk of disasters**. As discussed in §1.2.2.1, the **Hazards, Vulnerability, Resilience, and Exposure** concepts support the description of the risk of disasters for a given territory. **Hazard** refers to the phenomenon at the origin of unwanted consequences. **Vulnerability** is the description of physical, social, economic, and environmental factors or processes that increase the susceptibility of a system to be negatively affected by a hazard. **Resilience** is the combination of all the strengths, attributes, and resources susceptible to reducing the level of risk or the effects of a disaster. **Exposure** is related to the possibility of a system to be affected by the hazard. Within the context of the *DRUID method*, hazard agents can be natural, technological, or societal. A scale describes its potential intensity, and representative events illustrate instances of occurrence and associated consequences. **Vulnerability** factors related to the system studied or its environment support the description of properties that will enhance the negative impacts of disaster occurrence. Resilience barriers associated with the system studied or its environment endorse the description of technical, human, and organizational systems that support the prevention, preparation, response, and recovery of systems when a hazard occurs.

The characteristics of the **territory** considered in the study influence the hazards, vulnerability, resilience, and exposure dimensions of disaster risks. A **territory** is a defined geographical area under the jurisdiction or control of a specific government or authority. It can refer to a region, zone, or land not fully integrated into the parent country or managed separately due to its distinct legal or administrative status. Territory characterization requires considering various topics (Mérenne-Schoumaker & Barthelemi, 2014; Tournant et al., 2020). Location factors include spatial information such as coordinates or surface, information about relevant objects for a *DRUID study* located within a territory (infrastructure, spaces, and landmarks), and information about borders and neighboring spaces. The land cover profile indicates the physical land type, such as forest or open water, and the land use profile refers to how people use the land.

### 3.3.1.3. Prospective context

The third essential dimension of a *DRUID problem* is the **prospective context**. The **prospective context** includes three dimensions: **trends, time horizon, and targeted objects**.

The **trend dimension** refers to observable patterns or tendencies that indicate the change in direction in various domains over time. Three trends are considered within the DRUID approach: Megatrends, Global trends, and Local trends. Megatrends are significant drivers of change that will have transformative impacts on individuals, organizations, and societies. Megatrends typically develop over years or decades and occur at the intersection of multiple political, environmental, social, technological, legal, and economic trends (Naughtin et al., 2024). Global trends refer to changes occurring within one of the dimensions of the global environment (physical, social, cultural, legal, political, economic, and technological) of the studied organization and local trends are changes in its local environment (clients, suppliers, subcontractors, financial, unions, or local governments ) (Hatch & Cunliffe, 2013).

The **time horizon** refers to the duration to be considered within the study. It is generally associated with the average planned life of critical infrastructure.

Finally, **targeted objects** refer to the systems affected by the trends. They can be systems or subsystems of critical infrastructure or disaster risks.

### 3.3.2. OntoDRUID scenario definition concepts

The second step of the *DRUID method* is dedicated to elaborating representative prospective scenarios about the evolution of disaster risk and its impact on critical infrastructure performance. It is based on the GMA approach, which was introduced in Chapter 2. *OntoDRUID* must establish a unified vocabulary and conceptual framework related to the different concepts used to describe factors that influence the direction and nature of future developments, critical dimensions of the problem space. Each one is represented by a set of discrete states or conditions, relationships, and interactions between different morphological variables and finally comprehensive narratives constructed from the morphological field, describing coherent and plausible future states. The concepts of *DRUID Morphological Box* and *DRUID Scenario* fulfill this role in *OntoDRUID*.

*DRUID Morphological Box* maps parameters and their values into a multi-dimensional matrix. Each dimension represents a variable, and each cell within the matrix represents a unique combination of states across the variables. This structure allows for the systematic exploration of all possible scenarios. The *DRUID method* considers the different trends (mega, global, and local) used within a *DRUID study* as parameters. Each trend is described by its different potential parameters and values. The identification of representative scenarios begins with identifying possible, feasible, incompatible, and contradictory configurations. This task relies on a logical and empirical consistency analysis process. Then, possible and feasible scenarios are studied to identify representative scenarios.

*DRUID scenarios* are a possible future related to a specific value of trends considered within a *DRUID study*. They are elaborated on, starting with representative scenarios extracted from the *DRUID Morphological box*. A *DRUID scenario* is composed of four contexts. The **trend-driven context** is a narrative description of the situation in which the values of the trends of a representative scenario are presented. The **territory context** is a narrative description of the characteristics of the territory and its evolution trends on the timescale studied. These characteristics include the social, demographic, economic, political, and environmental aspects, among other relevant aspects for the

case study. The **infrastructure context** is a narrative description of the characteristics of the infrastructure and the infrastructure sector, as well as their evolution trends on the timescale studied. These characteristics include regional plans for the infrastructure sector, the prominent technologies available in the market, or current and to-be-implemented policies. The **disaster risk context** is a qualitative, quantitative, or semi-quantitative description of the evolution trends in the timescale studied for the hazards the infrastructure is exposed to, and the infrastructure absorptive capacity per type of possible hazard.

### 3.3.3. OntoDRUID critical infrastructure resilience studies conceptualization

The third step of the *DRUID method* consists of studying the resilience of the critical infrastructure throughout the studied period while considering contexts defined in a *DRUID scenario*. It is based on the Disaster Resilience of Place (DROP) model (Cutter et al., 2008), which was introduced in Chapter 1 (see §1.2.2.2). The third domain of *OntoDRUID* aims to establish a unified vocabulary and conceptual framework related to the different concepts used to describe the evolution of the resilience of the studied critical infrastructure. The concepts of *DRUID Resilience study* fulfill this role in *OntoDRUID*.

The *DRUID Resilience study* relies on a simulation algorithm related to the lifespan of critical infrastructure performance, particularly resilience performance. **Key performance indicators** (KPI) are associated with the performance of the critical infrastructure, and the decision-making profile comprises one or several thresholds and related actions to be performed. The dynamic of the KPI throughout the life of the critical infrastructure represents the "normal" functioning of the infrastructure. The concepts of **hazards, absorptive capacity, shock levels, resilience actions, and decision-making profile** represent the abnormal functioning of the infrastructure. **Hazards** are related to the likelihood of occurrence of unwanted events with a given intensity. The **absorptive capacity** is the level of hazard intensity the infrastructure can support without having damages. The **shock level** refers to the intensity of damage that the infrastructure suffered after the occurrence of a hazard. **Resilience actions** refer to measures performed to restore optional functionality of the infrastructure following a shock, for example, the repair or replacement of damaged technological systems. Finally, the concept of the **decision-making profile** supports the description of the likelihood of the decision-maker to choose between resilience action alternatives.

### 3.3.4. OntoDRUID specific performance conceptualization

The fourth phase of the *DRUID method* compares the specific performance of the studied critical infrastructure with and without considering the evolution of the risk of disasters. This phase translates the simulation results into parameters to be used by a dedicated evaluation module and produces an evaluation of the specific performance. Inputs and Outputs then characterize a particular assessment of the performance module. *Inputs* are the parameters required to perform the review. *Outputs* are the data that composes the evaluation results.

The second step of the ontology design was to conceptualize the different terms to be considered within the ontology. This conceptualization will support the design of the *OntoDRUID* hierarchies of classes.



### 3.4. OntoDRUID hierarchies of classes

The third step in defining *OntoDRUID* is determining the hierarchies of classes related to the essential concepts to be considered within the ontology, previously defined in section 3.3. The associated classes and relationships are formalized following the four steps of the *DRUID method*.

#### 3.4.1. OntoDRUID problem definition and data collection hierarchies of classes

*OntoDRUID*, for supporting the description of a *DRUID problem* must cover the diversity and complexity of critical infrastructure and disaster risks domain, and the prospective context to be used when applying the *DRUID method*.

The "DRUID problem" hierarchy of classes supports the description of a *DRUID problem*. It is composed of six aspects: the critical infrastructure studied, the performance targeted, the geographical location, the risks and the trends considered by the study (see Figure 3. 3).

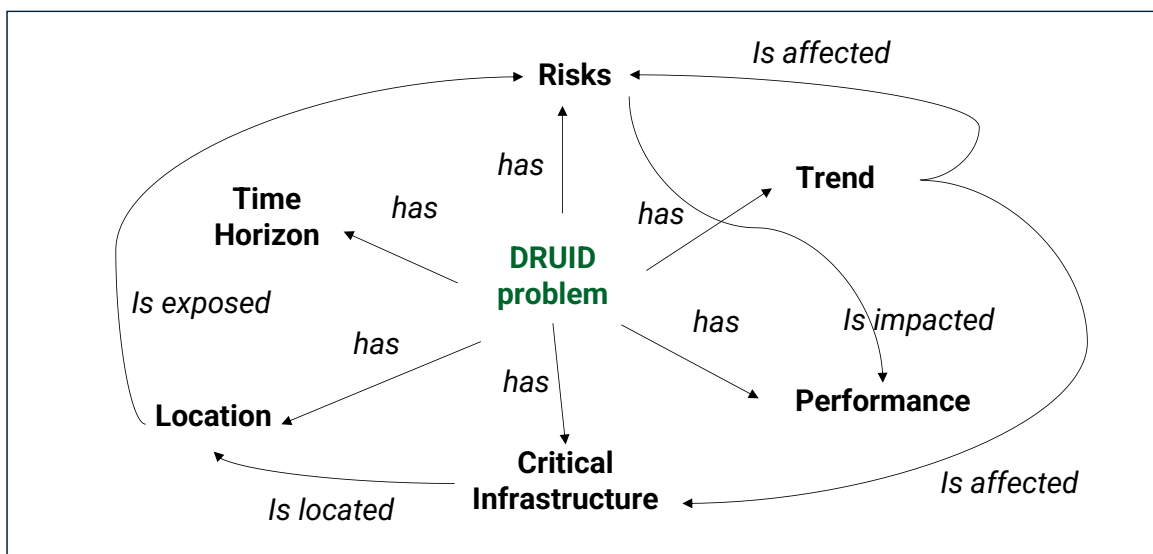


Figure 3. 3. OntoDRUID DRUID Problem classes hierarchy

The "Critical Infrastructure" hierarchy of classes supports the description of the properties of critical infrastructure necessary to achieve a *DRUID study*. It is composed of four aspects. The "Sector" class hierarchy helps characterize the infrastructure sector, subsector, and function such as "Production of electricity based on photovoltaic (PV) solar energy."

The "Organizational" hierarchy is related to both "internal organization," "organizational environment," and "global environment" characteristics. The "internal organization" class has four dimensions (culture, social structure, location, and technology). The "organizational environment" comprises six dimensions (client, supplier, subcontractor, bank, insurance, local government). The "global environment" comprises seven sectors (physical, social, cultural, legal, political, economic, and technological). "Global environment" influences both the "Organizational environment" and the "internal organization, and the "organizational environment" influences the "internal organization".

The "performance indicator" classes allow for defining a set of performance indicators to be used by a *DRUID study*. Finally, the "Coupling relationship" supports formalizing the relationships between infrastructures to represent disaster consequences propagation within infrastructures (see Figure 3. 4).

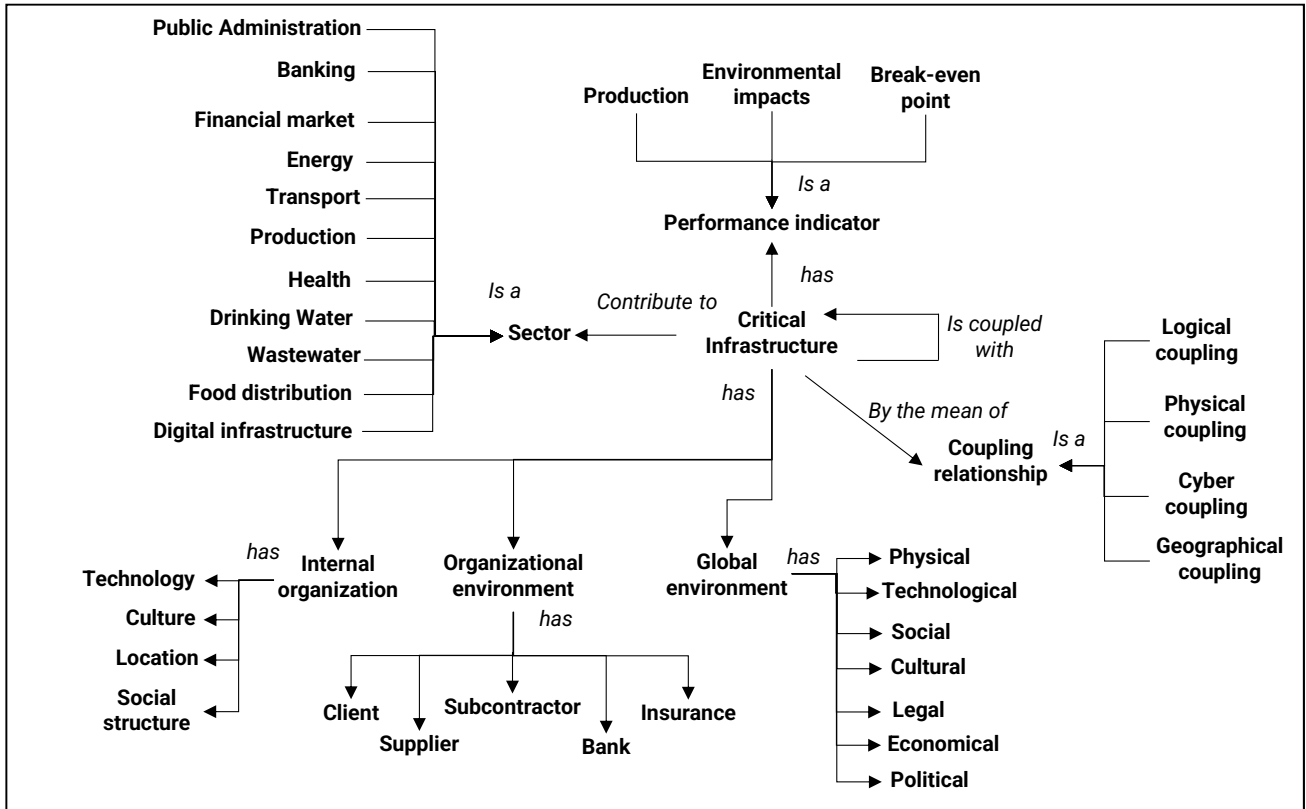


Figure 3. 4. OntoDRUID Infrastructure classes hierarchy

The class “Disaster Risk” hierarchy describes the properties of disaster risks a *DRUID study* considers. A critical infrastructure is defined by the four key dimensions: Hazard, Vulnerability, Resilience, and Coupling (see Figure 3. 5). The Hazard dimension is first characterized by the agent phenomenon that can be natural, technological, or social. Then, a scale will describe the hazards at different intensity levels. Finally, representative events illustrate the nature of the Hazard, complete with the description. The vulnerability dimension is defined as a set of physical, social, economic, or environmental factors that are susceptible to increasing the likelihood and gravity of the consequences of the hazards. The Resilience dimension refers to a set of barriers (prevention, protection, coping, and absorptive) that are susceptible to avoid or minimize the negative effect of the Hazard. Finally, the coupling dimension supports the description of complex hazards due to the interaction of different single hazards with varying coupling relationships.

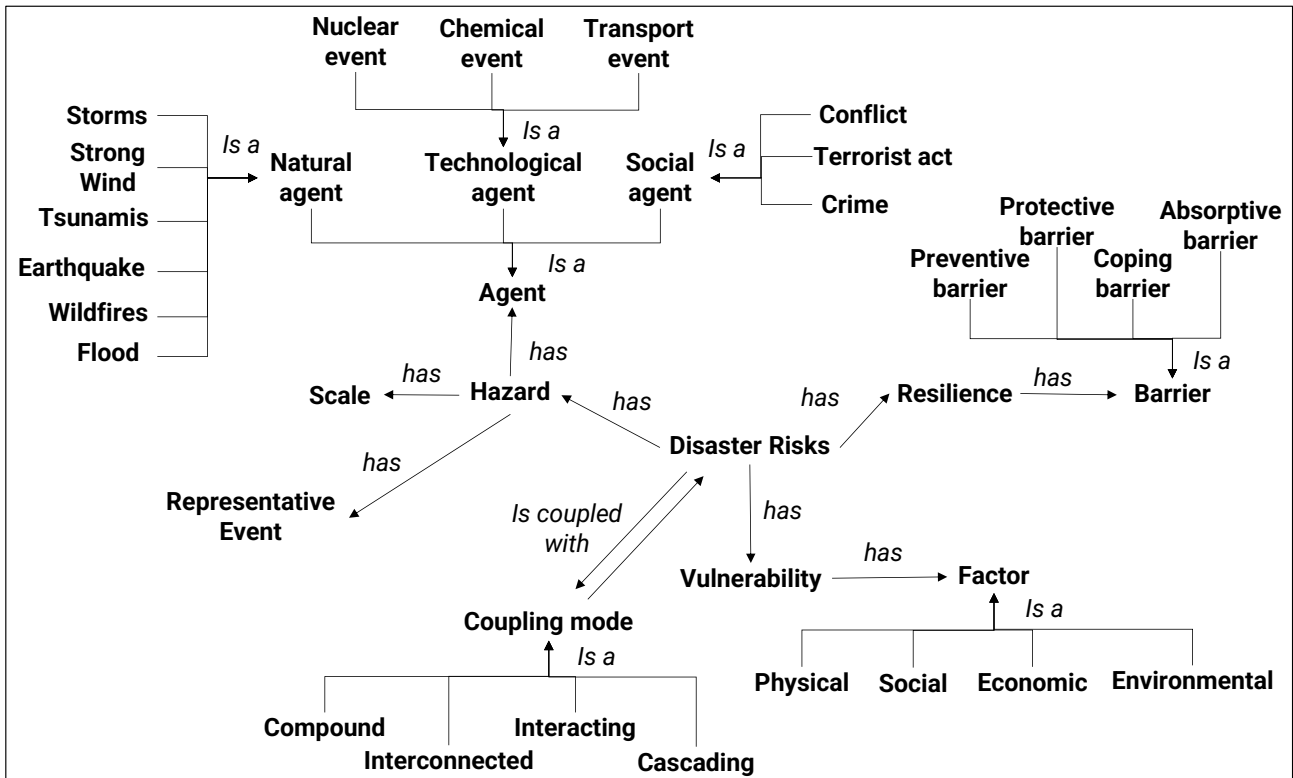


Figure 3. 5. OntoDRUID Disaster risk classes hierarchy

The “Prospective context” class hierarchy describes the prospective context used by a *DRUID* study (see Figure 3. 6). It includes the mega, global, or local trends considered and the spatial and temporal frontiers of the study. The spatial dimension is described by considering the different objects (infrastructure, hazard, or location) possibly impacted by trends and the temporal dimension with the time horizon of the study.

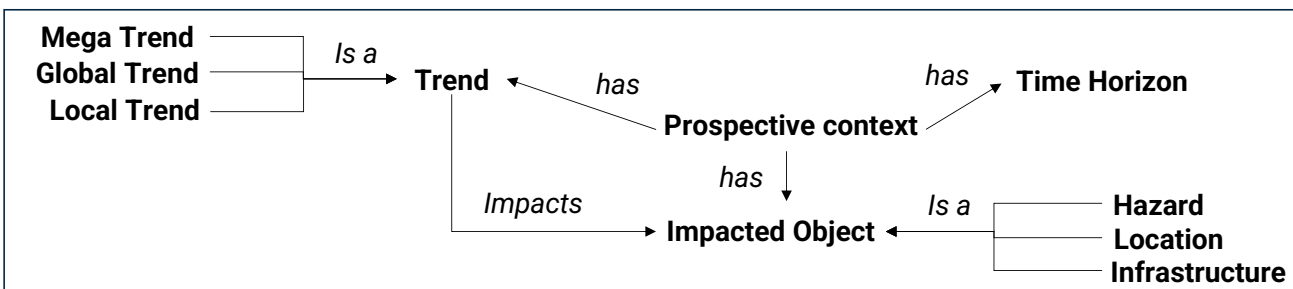


Figure 3. 6. OntoDRUID Disaster Prospective context classes hierarchy

*OntoDRUID* provides the basis to support *DRUID* problem management. Implementing a database and associated graphical user interfaces will allow access to predefined critical infrastructure, risks, and trends to be considered in a *DRUID* study. Then, it will allow data manipulation to characterize a specific *DRUID* study. It also provides concepts and relationships that will support the data collection process. The different variables used to describe the complexity of critical infrastructure, risks of disasters, and trends will help provide information to *DRUID* analysts about which variables have been described and which still need to be described.

### 3.4.2 OntoDRUID scenario definition classes

*OntoDRUID* aims to support the elaboration of prospective scenarios centered on the evolution of disaster risk. The “DRUID morphological box” class hierarchy (see Figure 3. 7), and the “DRUID scenario” class hierarchy (see Figure 3. 8) support this objective.

The “DRUID Morphological Box” class hierarchy supports the description of Morphological Box content by considering the Trends of the *DRUID problem* as parameters of the different configurations analyzed to identify if they are possible, feasible, incompatible, or contradictory, and representative scenarios composed of parameters with specific values.

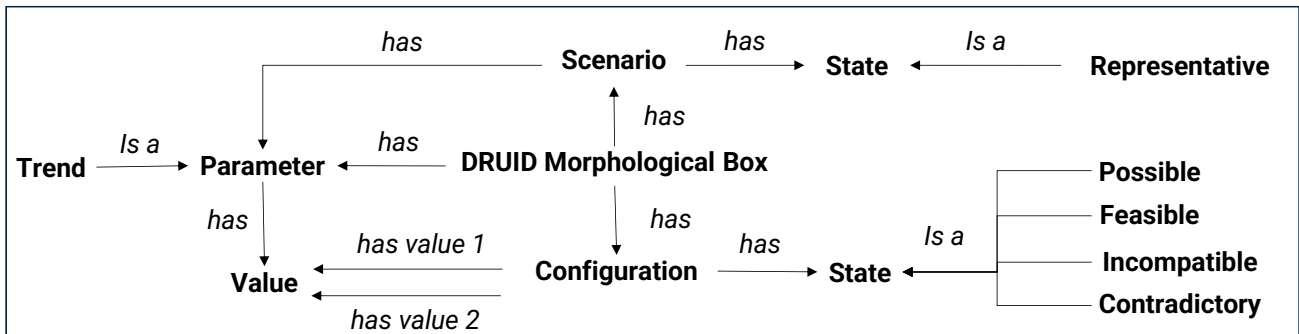


Figure 3. 7. OntoDRUID DRUID Morphological Box classes hierarchy

The “DRUID scenario” class hierarchy supports the description of scenario content by considering the different topics of a *DRUID scenario*. Each variable is characterized by a value associated with a set of temporal periods.

The “Trend context” supports the description of values of the different trends the scenario considers.

The “Territorial context” class hierarchy is related to the description of values of variables associated with the studied territory that will evolve during the scenario duration.

The “Infrastructure context” class hierarchy describes the studied critical infrastructure properties that will evolve during the scenario. Two topics are considered. The first is related to the organizational properties of the critical infrastructure described. The second is related to the evolution of the absorptive capacity to a given risk.

The “Disaster risk context” class hierarchy supports describing the evolution of disaster risks during the scenario. This evolution relies on the description of the hazard dimension and the vulnerability dimension, which depends on the evolution of the territory properties.

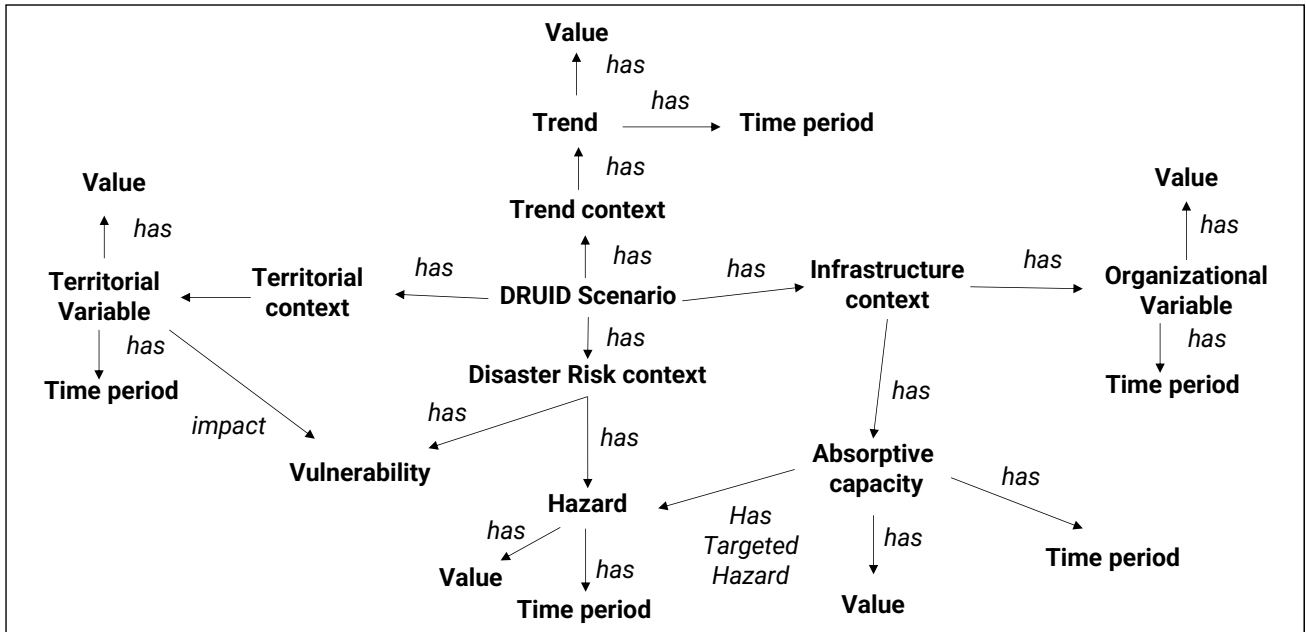


Figure 3. 8. OntoDRUID DRUID Scenario classes hierarchy

OntoDRUID provides the basis for the DRUID scenario design:

1. It supports the selection of the trends used as parameters in the morphological box.
2. It supports the analysis of each configuration to determine whether it is possible, feasible, incompatible, or contradictory.
3. It supports the identification of patterns to define representative scenarios.

It also supports the definition of a representative scenario by guiding the definition of variables describing the evolution of territory, critical infrastructure properties, and disaster risks as a function of the evolution of selected trends. These variables will support the formulation of scenario narratives.

### 3.4.3. OntoDRUID critical infrastructure resilience studies classes

OntoDRUID must support elaborating a simulation algorithm that studies the lifespan resilience of critical infrastructure in a DRUID scenario. The “Resilience study” class hierarchy fulfills this objective by describing the simulation context elaborated within a DRUID study (see Figure 3. 9).

This hierarchy supports describing a DRUID Resilience Study content by first considering a normal context. This context is related to the normal evolution of KPI during the lifespan of the infrastructure. The ontology describes KPIs with value and evolutionary rules and thresholds that will influence decision-making. The abnormal context is related to the hazard considered within the study and the associated absorptive capacity. For both variables, rules describe their evolution through the lifespan of the infrastructure. The Resilience Context describes the shock consequences of the failure of absorptive capacity protecting the infrastructure from hazards and resilience actions that support the recovery of the infrastructure. Finally, the decision-making profile defines the rules that support arbitration between resilience actions.

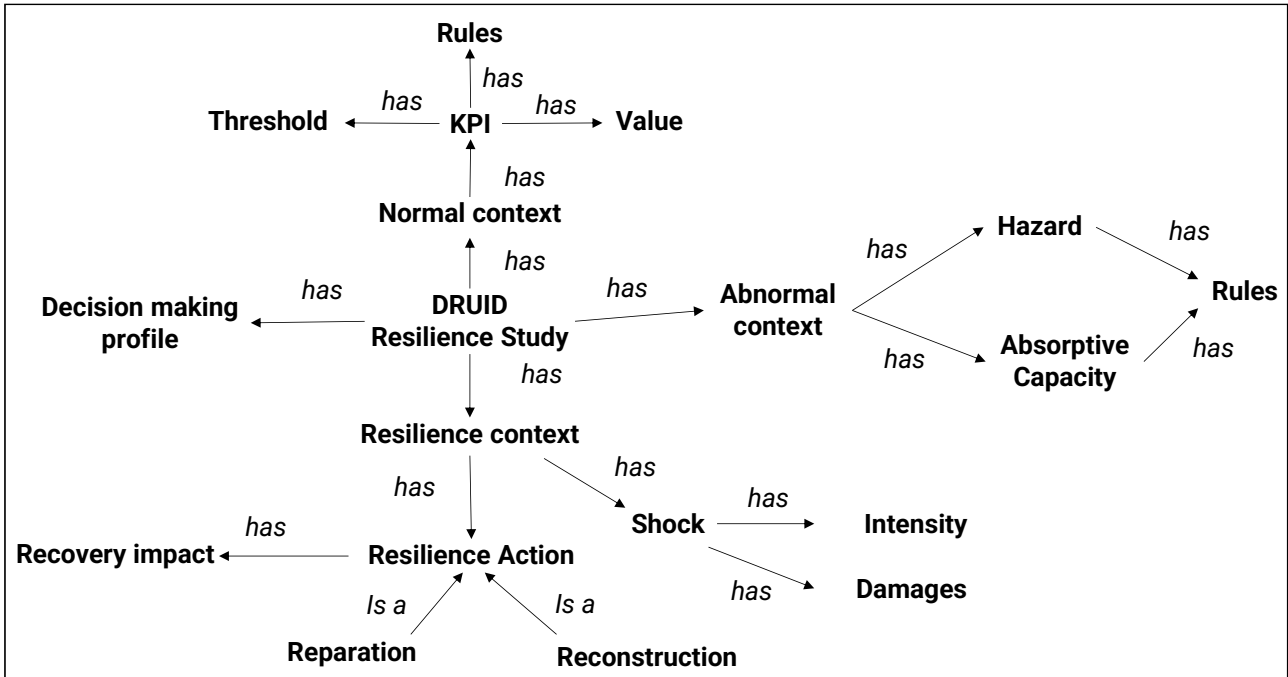


Figure 3. 9. OntoDRUID DRUID Resilience study classes hierarchy

OntoDRUID provides classes and relationships to support the design of the DRUID critical infrastructure resilience simulation algorithm. First, it supports the framing of the temporality of simulations. Then, it will support defining the expected evolution of the critical infrastructure KPIs. Finally, it will allow the definition of the abnormal episodes characterized by the occurrence of events where the hazard intensity is superior to the infrastructure absorptive capacity, provoking damages. Moreover, it will support the profiling of the decision-making about the resilience actions to perform to recover and come back to normal functioning.

### 3.4.4. OntoDRUID specific performance classes

OntoDRUID must support transferring the result of resilience studies to specific performance evaluation modules and analyzing the results of their application to provide results to a DRUID problem (see Figure 3. 10).

The “Specific performance evaluation module” hierarchy of classes supports the description of module characteristics, including inputs and output parameters.

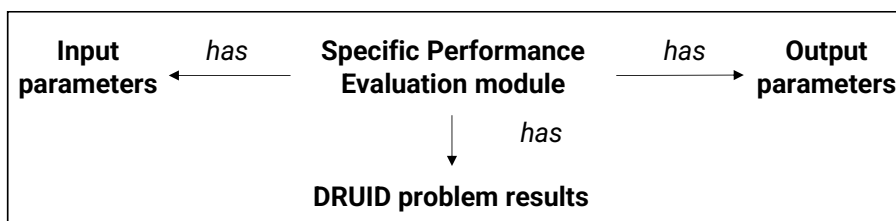


Figure 3. 10. OntoDRUID “Specific performance evaluation module” classes hierarchy

OntoDRUID provides the foundation to support the interaction with specific evaluation modules associated with specific performances considered in the DRUID study. It supports the translation of the simulation results into parameters that constitute the inputs for the evaluation module, as well as the translation of the evaluation module results into the final results of the DRUID study.

The specific performance addressed within the PhD is environmental performance and, more specifically, using Life Cycle Assessment (LCA) to study the life cycle-related environmental impacts of a PV power plant. A specific assessment module is developed to assess the environmental performance of a PV power plant while considering the environmental impacts of reparation and replacement tasks realized to overcome damages initiated by an instance of disaster risk that intensity surpasses the infrastructure absorptive capacity.

The inputs of the PV power plant LCA module are *DRUID simulations*, which result from the resilience study of the PV power plant through its thirty-year lifespan. Each simulation is characterized by the overall electricity production per year, the list of shocks with intensity per year, the list of reparation tasks per year (time interval), and, if any, the year of replacement tasks.

The outputs of the PV power plant LCA module are the environmental evaluation of the PV power plant. The results comprise two dimensions. The first dimension is a baseline scenario without considering the reparation and replacement tasks. The second dimension is the evaluation of each simulation provided.

The output of the PV power plant LCA module supports the narrative answering the initial *DRUID problem*. This narrative is elaborated by comparing the different evaluations considering scenario contexts.

*OntoDRUID* contains an instantiation of the Specific performance evaluation module hierarchy of classes to support the transfer of the *DRUID simulation* results to the PV power plant LCA module (see Figure 3. 11).

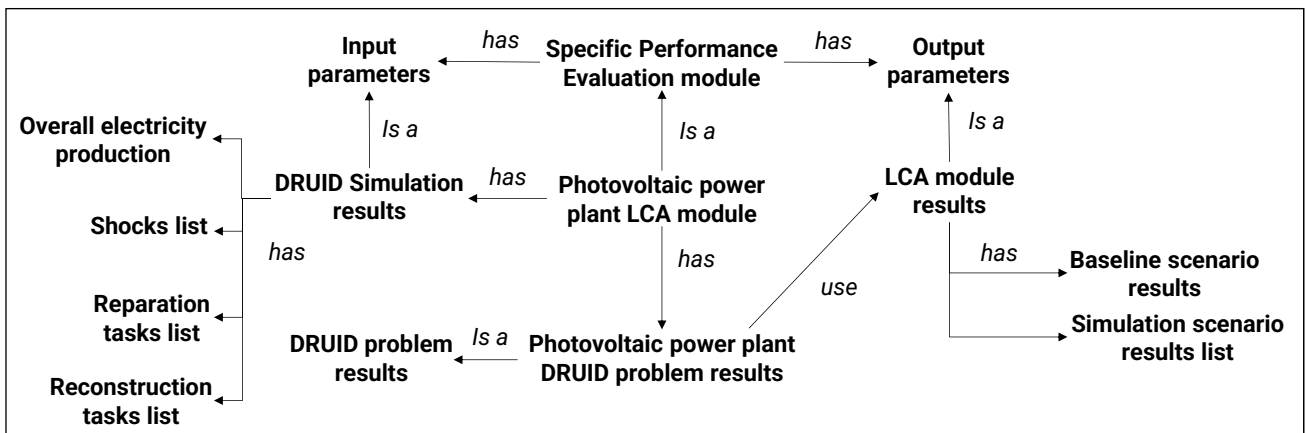


Figure 3. 11. *OntoDRUID* “Photovoltaic power plant LCA module” classes hierarchy

## Conclusion

The *DRUID method* manipulates data about critical infrastructure and disaster risks in order to establish a conceptual framework for various disciplines to address a *DRUID problem*. These data include hazard, vulnerability, and resilience properties. The GMA method uses these data to generate representative prospective scenarios. The simulation algorithm of the lifespan resilience of the critical infrastructure according to representative scenarios provides insights into decision-making results after the occurrence of shocks caused by disaster risks. Finally, it supports the transfer of simulation results to specific evaluation methods, such as LCA in the case of environmental performance evaluation, to use the evaluation results to answer the initial problem formulated.

The development of the *DRUID method* and associated tools raises the challenges of integrating data from different domains, supporting communication between experts and practitioners, and facilitating interoperability between software tools. To address these challenges in the context of the PhD thesis, and thus attempt to answer the first scientific question, the chosen approach was to design and develop an application ontology.

The application ontology *OntoDRUID* provides the fundamental concepts and relationships that support the formalization of the *DRUID method* phases, the design of the associated technological solution, and the communication between *DRUID analysts*, experts, and practitioners. *OntoDRUID* provides essential concepts such as "DRUID problem," "DRUID morphological box," "DRUID scenario," and "DRUID specific performance module" that will shape the DRUID methodology. Hierarchies of classes allow for the description of the diversity and complexity of each concept to support a wide range of applications.

Thus, *OntoDRUID* supports the development of the *DRUID method*. The next chapter presents the guidelines proposed to support the different phases and their illustration, with a case study on the impact of the evolution of disaster risk on the environmental performance of a PV plant.





# Chapter 4. Elaborating the Disaster Risk-gUided scenario Definition (DRUID) Method

## Introduction

It is important to consider the consequences of disaster risks on the Life Cycle Assessment (LCA) of critical infrastructures because they represent non-negligible additional impacts to human and environmental health. Therefore, this PhD thesis proposes a methodological contribution addressing this issue, called the Disaster Risk-gUided scenario Definition (*DRUID*) Method - LCI Module.

The pursuit of the methodological development of the *DRUID method* has been guided by three scientific questions, each one addressed throughout a general task. So far, Chapter 3 has addressed the first task, corresponding to the development of the domain-specific ontology *OntoDRUID*, which established the terminology, concepts, and essential objects that make up the *DRUID method*.

The objective of Chapter 4 is to develop the core methodological structure of the *DRUID method*, thus answering the second scientific question:

*How could representative scenarios of possible evolutions of disaster risks be elaborated? In the context of these scenarios, how could the consequences of disaster events be addressed in the analysis of the performance of the critical infrastructure over its lifespan?*

The *DRUID method* consists of four iterative steps, previously introduced in Chapter 2 and Chapter 3. However, in this chapter, only the first three steps are addressed (see Figure 4. 1). The first step concerns the definition of the problem studied and the recollection of key information. The second step aims to elaborate scenarios that are representative of the possible evolution alternatives of disaster risks in the territory and their effects on the infrastructure. The third step aids the analysis of the scenarios built to identify the potential consequences of disaster risks on the resilience of the critical infrastructure throughout its lifespan given plausible decision-making alternatives.

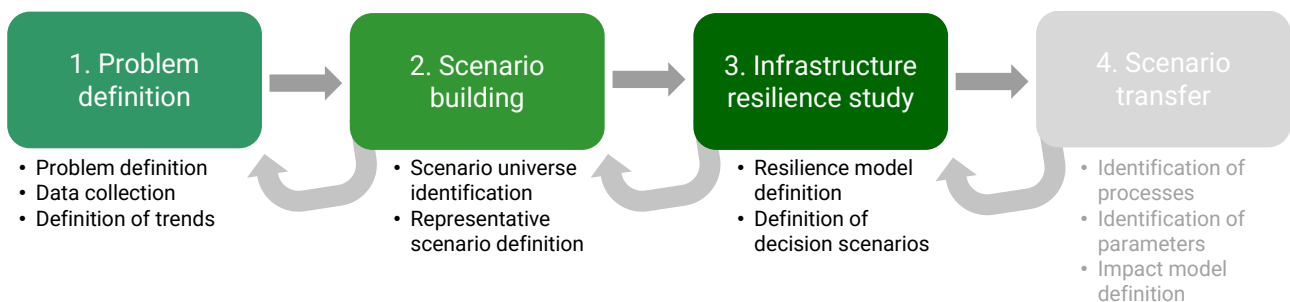


Figure 4. 1. Disaster Risk-gUided scenario Definition (*DRUID*) methodology, focus on steps 1-3

Throughout its three sections, Chapter 4 presents the reasoning behind each step of the method and guiding questions supported by examples of their possible application, which rely on the illustrative case study called *FuturePV*. This case study deals with the identification of the additional environmental impacts, compared with those in the case of a normal operation, caused by the possible evolution of natural disaster risks in a mountainous territory with Mediterranean climate in the south of France on a representative photovoltaic (PV) infrastructure, addressing the present and

future situation. Because of this geographical scope, recommendations for data collection concern almost exclusively French-related sources in the current iteration of the model.

The purpose of the particular case study *FuturePV* is to test and showcase the application of the *DRUID method*, exploring its strengths, limitations, areas of opportunity, etc. Therefore, the numerical results obtained throughout the study are not meant to be conclusive or representative of a specific existing or future PV facility, even if the information gathered to carry out the study comes from real sources with the intention to pose plausible situations.

## 4.1. Step I, Defining the problem

The objective of the problem definition step is to establish the precise problem addressed in the study, and to define and organize the information necessary to build a clear and complete picture of the present and future situation of the studied critical infrastructure.

Therefore, this step concerns two main activities. First, the definition of the canonical problem, which follows a generic problem structure indicating the essential elements to be addressed. It uses the formulation of a *DRUID problem* as a basis, as defined in *OntoDRUID* (see §3.2). The second activity is the collection and organization of the data required to build scenarios that aid in the description of the potential consequences of evolving disaster risks in the studied infrastructure. This data collection process uses the terms and concepts established in the *DRUID problem* to organize the information into coherent and consistent thematic groups, allowing for traceability, reproducibility, and seamless transfer of data to the scenario building step. Data collection results are thus organized, on the one hand, as trends that can have several mutually exclusive values or conditions, and, on the other hand, as descriptions of essential characteristics of each thematic group.

### 4.1.1. DRUID problem definition

The first part of the problem definition step consists in precisizing the essential elements of the *DRUID problem*. These elements are representative of the thematic groups that guide the data collection tasks: the infrastructure, the territory, the risks, and the trends.

Six fundamental questions support the formulation of the studied problem, which are based on the competency questions 1-6 posed in Chapter 3 (see §3.2):

- **Question 1.** What is the critical infrastructure studied?
- **Question 2.** Where is the critical infrastructure located and what are the essential characteristics of this location?
- **Question 3.** Which infrastructure-related performance types are considered within the study (economic, environmental, social, etc.)?
- **Question 4.** What are the types of risks considered within the study (natural, technological, social, political, etc.)?
- **Question 5.** What is the time horizon considered for the study?
- **Question 6.** What are the trends considered within the study (climate change, social, political, technological, norms, etc.)?

The responses to these six questions support the definition of the studied problem by using the DRUID canonical problem model:

Will **<trends>**-driven evolution of the **<risk types>** risks significantly affect the **<performance type>** performance of **<critical infrastructure>** located in **<location>** within **<time horizon>**?

For example, in the *FuturePV* case study, a representative photovoltaic power plant located in a mountainous region with Mediterranean climate in the south of France is studied. The objective is to evaluate how the influence of strong wind risks could change the potential environmental impact results of the critical infrastructure, whilst considering that future evolutions in the territory and its climate may increase the frequency and intensity of climate-related risks and thus render infrastructures in the region more exposed to related risks.

The *FuturePV DRUID problem* studies the impact of the evolution of climate risks and, more specifically, of strong wind on the environmental performance of a photovoltaic plant project. The installed capacity of the PV plant is 1 MWp, with a capacity factor<sup>21</sup> for the overall system of 16%. The PV cell technology consists of multi-crystalline Silicon (multi-Si), and the modules have a 17.5% efficiency, supported by an aluminum frame and a fixed ground-mounted system.

The interest in studying strong wind risks is because they are strongly influenced by changes in the climate, namely storm wind patterns that will likely change through the influence of increasing temperatures. Moreover, they are a major factor to consider when designing a PV plant in structural terms, since wind loads can damage PV modules and their mounting systems, as well as carry debris that can likewise cause damage.

Table 4. 1. Defining the DRUID problem for the *FuturePV* case study

Question	<i>FuturePV</i> case study
What is the critical infrastructure studied?	A photovoltaic (PV) power plant. The installed capacity is 1 MWp, with a capacity factor for the overall system of 16%. The PV cell technology is multi-crystalline Silicon (multi-Si), and the modules will have a 17.5% efficiency, supported by an aluminum frame and a fixed ground-mounted system.
Where is the critical infrastructure located and what are the essential characteristics of this location?	In a mountainous region with Mediterranean climate in the south of France.
Which infrastructure-related performance types are considered within the study (economical, environmental, social, etc.)?	The environmental performance throughout the operational lifespan of the PV system, including upstream-related life-cycle environmental consequences.
What are the types of risks considered within the study (natural, technological, social, political, etc.)?	Strong wind risks
What is the time horizon considered for the study?	The duration of the operational lifespan of the PV infrastructure, which is 30 years and corresponds to a 2050 horizon
What are the trends considered within the study (climate change, social, political, technological, norms, etc.)?	Climate change and territorial evolution related to the energy transition
<b>DRUID problem definition</b>	
Will <b>climate change and territorial</b> -driven evolution of <b>strong wind</b> risks significantly affect the <b>life-cycle environmental</b> performance of a <b>PV power plant</b> located in a <b>mountainous region with Mediterranean climate in the south of France</b> within <b>the next 30 years</b> ?	

<sup>21</sup> **Capacity Factor:** “the ratio of the annual average energy production (kWh) of an energy generation plant divided by the theoretical maximum annual energy production of a plant assuming it operates at its peak rated capacity every hour of the year” (NREL, 2021).

### 4.1.2. Data collection

Having established the problem to be addressed, the second part of the problem definition step addresses the collection of data on the essential concepts of the *DRUID problem* definition: the infrastructure, the territory, the risks, and the trends associated to these elements within the defined temporal horizon.

The objectives of the data collection process are, on the one hand, the collection and organization of information that aids in responding to the question posed by the *DRUID problem* definition, and on the other hand, the identification of the trends that will drive the evolution of the essential elements of the *DRUID problem*.

The data collection process is iterative, and it is organized into four thematic groups: the infrastructure, the territory, the risks and hazards, and the absorptive capacity. Each group is guided by general topics, which indicate the type of information that should be collected. At the end of the data collection for each thematic group, the trends that drive the possible evolutions of certain elements within each group are identified. These trends are related to those posed when defining the *DRUID problem* (see §4.1.1), and it is possible that new trends are identified throughout the data collection process. The corresponding values or conditions that each trend can have should be explicitly stated. For each topic in each thematic group, the trends that influence the change and evolution of said topic should be explicitly stated.

The following paragraphs are dedicated to the methodological process of data gathering for each thematic group followed with examples pertaining to the *FuturePV* case study.

#### 4.1.2.1. Infrastructure-related data collection

The identification of infrastructure-related trends consists in obtaining information on the essential characteristics and the components of the studied infrastructure and the activity sector it is involved in.

The objective is to know with as much detail as possible what the infrastructure is made of to facilitate the identification of the elements/components exposed and vulnerable to certain hazards and what kind of consequences, i.e. damages, can be expected. Moreover, information about the industrial sector itself and its development in the territory is required to understand the opportunities and limitations of possible evolution pathways. The topics and more specific information required for each one is presented in Table 4. 2, as well as proposed questions that could be posed to find this information.

The critical infrastructure is the focus of the study. This critical infrastructure could be already set in place with operations already started or about to start, or it could be at its conception phase. Practitioners must obtain as much information as they can on the critical infrastructure, specifically its current state or the state it is expected to be at the beginning of its operational lifespan. Practitioners are encouraged to use Table 4. 2 and

Table 4. 3 as supports to obtain data relevant to their case.

Defining the trends and characteristics related to the critical infrastructure involves the consideration of the possible evolution pathways of the technologies used, in general and within the context of the studied sector, especially when dealing with fast-changing technologies. For example, in the case of PV cell technologies, laboratory efficiencies have been increasingly improving over the years<sup>22</sup>, which will eventually transform into changes for commercially available technologies. These factors will likely contribute to transforming the future context of the PV sector and the decisions could be influenced by such changes.

Table 4. 2. Infrastructure-related information to be gathered and suggested questions

Topic	Information to be gathered	Possible Questions
<b>Infrastructure characteristics</b>	The specific location of the infrastructure: address, village, or region	Where is the infrastructure located?
	The function that the infrastructure fulfills, meaning the product or service it provides	What is the purpose of the infrastructure?
	Details on how the infrastructure operates.	What are the production objectives of the infrastructure?
		What is the business model of the infrastructure?
	The list of the most important components/systems that make up the infrastructure.	What are the infrastructure technologies?
	The list of the most relevant regulations and norms that the infrastructure must comply with	What regulations and standards must the infrastructure comply with?
	A list providing the description of the factors, elements, conditions, etc. that the infrastructure needs to fulfill its purpose	What are the prerequisites for infrastructure operation?
A list providing the description of the effects of aging on the infrastructure, how does this affect the function it fulfills	What are the effects of aging?	
<b>Development perspectives</b>	A list of factors, elements, or conditions that could improve the performance of the function(s) of the infrastructure	What are the factors that can boost infrastructure performance?
	A list of factors, elements, or conditions that could hinder the performance of the function(s) of the infrastructure	What factors can slow down the operation of the infrastructure?
	A list of trends that can affect the function(s) of the infrastructure during its lifespan, such as: climate change, regional development, crises, etc.	What trends (climate change, regional development, crises, etc.) are likely to impact infrastructure operations?

<sup>22</sup> NREL's Best Research-Cell Efficiency Chart (Last accessed May 2024): <https://www.nrel.gov/pv/cell-efficiency.html>

Table 4. 3. Infrastructure sector-related information to be gathered and suggested questions

Topic	Information to be gathered	Possible Questions
<b>Sector</b>	A description of the technical and technological panorama of the sector	What are the technological alternatives?
	A list of the most important actors in the sector	Who are the actors involved?
	A description of constraining factors that the sector faces or may face	What are the constraints?
<b>Technology</b>	A description on the technical characteristics of the infrastructure	What are the technical specifications?
		What are the production characteristics?
		What are the consequences of aging/degradation?
		Is the technology reliable?
		Which are the risk-related standards?
<b>State of the sector/industry in the territory</b>	A description of the present state of the sector	How developed is the sector in the region?
		Which technologies are most widely used in the region?
		Who are the players in this sector in the region?
		What is the acceptability of the sector in the region?
		What is the accident rate of the sector in the region?
<b>Development perspectives</b>	A description of the envisioned future trajectories of the sector	What are the development objectives of the sector?
		What are the preferred technologies to support the development of the sector in the territory?
		Who are the key players in the development of the sector?
		What factors (subsidies, political will, etc.) are likely to encourage the development of this sector in the region?
		What are the factors (technical, political, legal, economic, geographical, social, etc.) that could hinder the development of the sector in the region?
		What trends (climate change, regional development, crises, etc.) are likely to have an impact on the development of the sector?

The data collection process first involves consulting the preliminary information on the studied infrastructure, which needs to be consulted directly with the solicitors/clients of the study or with relevant specialists. A second level consists of consulting public data (i.e. reports, legal documents, etc.) on the development plans for the sector in the region, which should be available on the websites of regional government agencies.

Interviews with specialists on the technology used in the critical infrastructure on one hand, and the development of the infrastructure-related sector on the other, also fulfill the function of obtaining and validating this information.

Table 4. 4. Data collection sources for the technology-related parameters

Type	Description	Examples – FuturePV Case study
<b>Primary specific information</b>	Internal documents	No access to internal document in the context of the PhD thesis, thus no specific example is provided
<b>Public documentation and databases</b>	Reports on the characteristics of the type of critical infrastructure studied	Recommendations from the PVPS Task 12 documents ( <a href="#">Frischknecht, Stolz, Krebs, et al., 2020</a> )
<b>Specialists – Interview</b>	Obtention and confirmation of primary information Check for data gaps Consult on the changes that could occur in the future period the study addresses: trend scenarios, rupture scenarios	Interview with 2 industrial actors

#### 4.1.2.2. Territory-related data collection

The identification of territory-related trends consists in obtaining information on the characteristics that make up the region where the infrastructure under study is installed. This means collecting data about the geographic location, the land use and land cover occupation, and the relevant changes that affect the territorial characteristics, among others.

This information is important for the study because it aids in determining how the infrastructure and the function it fulfills can affect and be affected by its surrounding environment, in the present and in the future. Additionally, learning about the surroundings and the context the infrastructure is established on is necessary because these affects how the infrastructure interacts with its environment, from an administrative, political, and social perspective. For example, the function of a PV infrastructure is to provide reliable and affordable electricity to the network, therefore it is important to know how the conditions and circumstances of the territory it is situated in may affect its capacity to provide said service.

Moreover, the characteristics of a territory influence the hazards, vulnerability, resilience, and exposure dimensions of disaster risks (see §3.3.1.2). Thus, to better understand what could happen to the infrastructure when potential disaster risks are present in the territory, it is important to gather information on the characteristics of said territory first.

The data collection process is organized into four topics, as presented in Table 4. 5. For each topic, the specific information to obtain is briefly described and coupled with suggested questions to aid in the case of specific inquiries or interviews.

1. The location refers to the geographical position and extension of the territory addressed, as well as important landmarks to retain that characterize the area, such as industrial hubs, natural reserves, archeological sites, airports, (critical) resource extraction zones, etc. Moreover, if the specific location of the critical infrastructure studied is known, it is recommended to specify the distance between the important landmarks and the infrastructure, since it will be important if complex and interconnected risks are addressed.
2. The natural context refers to the land use and land cover profile, the characteristics of the natural environment that describe the territory. Related to the information on key landmarks, this topic also concerns the collection of information on possible restrictions in the area, for example, near natural reserves or agricultural areas, especially concerning the development of a specific critical infrastructure project.



3. Neighboring spaces refer to the physical and administrative borders of the analyzed territory. If the space is spread throughout two or more territories with different administrative jurisdiction, then key information on general territorial aspects and regulations must be consulted for each concerned entity.
4. Dynamic aspects address the territorial characteristics that are susceptible to change, and those that will provide insights on possible trends. This is by far the most challenging information to obtain since changes depend on many unpredictable and uncertain factors.

Table 4. 5. Territory-related information to be gathered and suggested questions

Topic*	Information to be gathered	Possible Questions
<b>Location</b>	Geographical position of the territory	What is the location studied (latitude, longitude, altitude)?
	Surface area or concerned territorial expansion	What is the surface area of the location studied?
	Key infrastructures, spaces, landmarks, etc.	What are the remarkable landmarks located at proximity? At which distance?
<b>Natural context</b>	Land use and land cover profile: <ul style="list-style-type: none"> <li>- Plains, plateaus, mountains</li> <li>- Hydrographic network</li> <li>- Climate zoning</li> <li>- Vegetation zoning</li> <li>- Natural boundaries</li> </ul>	What are the land use and land cover characteristics of the surrounding area?
	Related norms, laws, restrictions, etc. to be aware of	What are the constraints and the opportunities of the land use and land cover characteristics?
<b>Neighboring spaces</b>	Borders, cross-border spaces	What are the borders located nearby? (natural, administrative)
<b>Dynamic aspects</b>	Urbanization Densification Urban sprawl Industrialization / deindustrialization / relocation Migration flows Abandoned land Social changes (impoverishment, etc.) Degradation of the natural environment (deforestation, drainage/irrigation, pollution...)	How has the territory evolved in the past years? (Population, land use and land cover changes, climate changes, etc.)
		How could the territory evolve in the coming years?

\*Topics based on information from ([Mérenne-Schoumaker & Barthelemi, 2014](#); [Tournant et al., 2020](#))

Having established the requirements for the data collection process, the possible sources of information are now addressed.

Because we are dealing with knowledge specific to a region, the most relevant sources of information to consult are public documents, reports, and data provided by the regional authorities and governments. In the French context, relevant public sources are “*Geoportail*” for information on the land use and geographical specifications, the National Institute of Statistics and Economic Studies’ (INSEE in French) website and databases for demographic and economic data, and the government-affiliated official websites of villages, departments, and regions that concern the territory.

A second type of sources pertain to peer-reviewed scientific literature and reports from specialized non-government organizations that cover what was not obtained through public documentation. These sources are useful to recover specialized information about aspects of the territory that are

specific to the study of the critical infrastructure. For example, for the *FuturePV* case study, to estimate the potential electricity production in the region, it is key to know the available solar resource, i.e. the annual global horizontal irradiance profile (kWh/m<sup>2</sup>). This information is produced and made available by specialized institutions such as Solargis through their Global Solar Atlas (Solargis, 2024).

Finally, interviews with experts and specialists on territorial aspects are recommended to complete the possible data gaps, especially for information on the possible evolutions and/or drivers of significant changes of the territory for the relevant period. The experts could also recommend additional sources where to obtain the information required. These specialists can be geographers, demographers, analysts, etc.

Table 4. 6 provides the descriptions of each type of data source recommended as well as examples for the case study context.

Table 4. 6. Data collection sources for the territory-related parameters

Type	Description	Examples – <i>FuturePV</i> Case study
<b>Public documentation, databases, and maps</b>	Reports and documents published and available for the public, emitted by government organizations that have direct jurisdiction on the territory addressed.	INSEE: Data and reports on demography, economy, and related topics <a href="https://www.insee.fr/fr/statistiques">https://www.insee.fr/fr/statistiques</a>
		Geoportail: Maps with information on: land use, administrative limits <a href="https://www.geoportail.gouv.fr/">https://www.geoportail.gouv.fr/</a>
	Reports and documents published and available for the public, emitted by specialized non-government organizations.	CORINE Land Cover: Database for land use information in France, classified by commune, using the CORINE classification <a href="https://www.statistiques.developpement-durable.gouv.fr/corine-land-cover-0">https://www.statistiques.developpement-durable.gouv.fr/corine-land-cover-0</a>
	Data on specific aspects that describe a territory, available as web applications or raw data useful for specialized interpretation.	Global Solar Atlas: Regional statistics of the solar resource availability <a href="https://globalsolaratlas.info/map?c=45.684902,2.636719,6&amp;r=FRA">https://globalsolaratlas.info/map?c=45.684902,2.636719,6&amp;r=FRA</a>
<b>Literature review</b>	Scientific literature to recover missing information or specialized information about aspects of the territorial context that are relevant for the case study	-
<b>Specialists – Interview</b>	To verify the information already obtained. Check for data gaps and possible identification of new information sources. Consult on the changes that could occur in the territory in the future period the study addresses: trend scenarios, rupture scenarios.	Local and regional specialists on geography, urbanism

#### 4.1.2.3. Risk and hazard-related data collection

The identification of risk and hazard-related trends consists in obtaining information on the hazards that are present in the studied territory and that could affect the studied infrastructure. The identification of hazards in this context involves determining the nature, the frequency of occurrence, and the probable evolution pathways.

The objective is to understand what are the hazards that exist in the territory that could eventually affect the infrastructure and its purpose. Naturally, depending on the type of study performed, the hazards to be considered need to be chosen. For example, in the iteration of *FuturePV* here presented, the strong wind hazard is the only one considered.

Additionally, information on the risk management panorama in the territory must also be collected because this information may influence the exposition of the infrastructure versus the hazard. For example, in the case of flood hazards, the existence of dikes, walls, and other physical barriers protect floodable areas, which can be the difference between an infrastructure suffering water damage or not. In the case of strong wind hazards, alarm and preemptive information systems act as the main non-physical barriers. Thanks to these measures, structures and materials can be secured in advance, thus mitigating potential damage to people and infrastructures due to flying debris. In PV installations, this kind of debris is likely the main cause of damage under strong wind conditions (Ceferino et al., 2023).

The data collection process is organized into five topics, as presented in Table 4. 7:

1. **Territorial hazards** refer to the list of hazards that have occurred and may occur in the region, each with their own description of their key characteristics: intensity, frequency of occurrence, etc. If pertinent to the study, it is possible to hierarchize these hazards.
2. **Territorial risk** management addresses the risk management panorama to know which risks are considered or not for prevention, preparedness, and warning systems, and what do these measures imply. Moreover, getting an idea of how these elements could change is also desired.
3. **Hazard characterization** refers to the specific elements used to determine how hazards are considered in regard to their intensity scale, likelihood of occurrence (quantitatively or qualitatively), as well as the trends that might change this probability of occurrence and how this might change.
4. **Complex risks** refer to the possible existence of compound, interacting, interconnected, and/or cascading risks in the territory.
5. **Emerging risks** refer to new risks that are likely to appear in the territory because of the influence of major trends, for example climate change, territorial densification, social or political crises, land use and land cover change, etc.

Table 4. 7. Risk-related information to be gathered and suggested questions

Topic	Information to be gathered	Possible Questions
<b>Territorial hazards</b>	The list of natural hazards and their descriptions. Possible hierarchization.	What are the main natural hazards in [territory]? Which are the most important ones to be considered?
	The list of technological hazards and their descriptions. Possible hierarchization.	What are the main technological risks in [territory]? Which are the most important ones to be considered?
	The list of the most important disasters and their descriptions	Which have been the disasters with the most severe consequences in the [region]?
<b>Territorial risk management</b>	The risk management/culture panorama	Which risks are covered by prevention, preparedness, and warning systems?
		Which risks are not covered by prevention, preparedness, and warning systems?

		What are the scenarios for the evolution of disaster prevention and preparedness practices?
		What risk management practices (barriers, insurance, etc.) are in place in the territory and in the infrastructures?
		What trends (climate change, territorial evolution, crises, etc.) could have an impact on risk management?
<b>Hazard characterization</b>	For each hazard considered, a scale of intensity	Is the scale proposed to characterize the probability of hazard occurrence relevant? If not, what might be a suitable alternative for this scale?
	For each hazard, its probability of occurrence in the region, which can be expressed as: its probability density function, its return rate in a certain period.	In your opinion, what is the current probability of occurrence (distribution) of the hazard? Where could this information be obtained?
	For each hazard, a description of the possible future changes, and if possible, changes in their frequency/probability of occurrence/return rate	What are the trends (climate change, territorial evolution, crises, etc.) that may impact the probability distribution of hazards? How do you think the probability of hazard occurrence will change in the short, medium, and long term?
<b>Complex risks</b>	The list of possible complex risks of four different natures: Interacting risk, Compound risk, Interconnected risk (NATECH), Cascading risk	Have complex events, such as NATECH, already occurred in the region?
	For each risk, if possible, a description of the future changes they could have.	How do you see complex risks evolving?
<b>Emerging risks</b>	The list of possible risks can emerge because of possible future changes, with a description of the trends that could have influenced their emergence.	What trends (climate change, territorial evolution, crises, etc.) could lead to the emergence of new risks?

The sources that can be considered to obtain information on the hazards that can affect a territory are of two general natures (see Table 4. 8).

Public data provided by concerned government organizations present the most reliable sources of information. For example, in France the “*Document d’information communal sur les risques majeurs (DICRIM)*” provides, for a given city, a list of hazards and preventive measures organisms and the population must follow to avoid major consequences to their wellbeing. Another alternative is the consultation of “*Georisques*”<sup>23</sup>, which provides information about natural and technological hazards that concern a given postal address.

In the case hazard hierarchization is deemed relevant for the study, one alternative is to rank the hazards according to their frequency of occurrence. For a case in France, this number can be estimated for disasters from the number of “*Arrêté de reconnaissances de l’état de catastrophe naturelle*” on a given city, provided by the Gaspard public database ([Ministère de la Transition écologique, 2024](#)). A resource that includes the risks related to a given zone with the support of an

<sup>23</sup> Georisques website (Last accessed: May 2024): <https://www.georisques.gouv.fr/>

online map is “Aux Alentours” (MAIF, 2023), gathering information from “georisques” found in the Gaspard database.

The data collected through public sources should be complemented with information obtained through interviews with specialists on hazards, and if possible, familiarized with the hazards that can occur in the studied territory. Moreover, this interview process also serves as a way corroborate and validate public data and obtain insight on future-oriented aspects.

Finally, if there has been a Risk Assessment performed for the related infrastructure project, the practitioner should recover information related to Risk Identification and Risk Analysis.

Table 4. 8. Data collection sources for the risk and hazard-related parameters

Type	Description	Examples – FuturePV Case study
<b>Public documentation and databases</b>	Reports and documents published and available for the public, emitted by government organizations that have direct jurisdiction on the territory addressed.	DICRIM: Document containing the concerned hazards for a ‘commune’ DDRM: Document containing the concerned hazards for a region, e.g. for the Alpes-Maritimes <sup>24</sup>
	Data on specific aspects that describe the hazards present in a territory. Available as raw data useful for more specialized interpretation.	Geoportail: Maps with information on: land use, administrative limits <a href="https://www.geoportail.gouv.fr/">https://www.geoportail.gouv.fr/</a> Copernicus Climate Change Service: Datasets on historical climate (wind speed, temperature, etc.) and prospective models (projections, reanalysis) <a href="https://climate.copernicus.eu/">https://climate.copernicus.eu/</a>
<b>Specialists – Interview</b>	To verify the information already obtained. Check for data gaps and possible identification of new information sources. Consult on the changes that could occur in the territory in the future period the study addresses: trend scenarios, rupture scenarios.	Local and regional specialists on geography and risks

In cases when raw data need to be collected from databases, it will likely require specific treatment and analysis, especially when looking into historical and prospective information on hazard sources and their intensities. Thus, the practitioners or someone in their team ought to be familiar with software tools that can assist them in this task.

#### 4.1.2.4. Absorptive capacity-related data collection

The identification of the trends related to the absorptive capacity of the infrastructure consists in investigating the hazards and risks that the infrastructure is exposed to throughout the studied period as well as the measures that are and may be in place in the future to face them and mitigate their potential effects. In other words, information on the absorptive capacity helps to describe the evolution of the capacity of the infrastructure to resist hazards and avoid damage.

<sup>24</sup> Document on major risks in the Alpes-Maritimes (Last accessed: June 2024): <https://www.alpes-maritimes.gouv.fr/content/download/40374/302208/file/DDRM06%20Version%202021.pdf>

The objective is to identify and characterize the elements that make up the capacity of the critical infrastructure to cope with the impacts of different types of hazards, and if possible, estimate how they could change throughout the operational lifespan of the infrastructure.

The data collection process is organized into three topics, as presented in Table 4. 9:

1. **Hazard exposure** concerns the hazards the infrastructure is likely to face throughout its lifespan, and thus pose a risk to it. This includes natural, technological, and complex hazards/ risks.
2. **Safety and management** refer to the physical and structural barriers and measures that are in place to prevent, mitigate, and recover from the potential effects of incoming hazards and risks. Barriers can be deliberately placed because of specific hazards or conform physical and mechanical characteristics of infrastructure components that are made to resist certain types of hazards under certain standards, for example, mechanical strength of structures to resist damage or destruction under certain mechanical loads. For these physical and mechanical characteristics, it is recommended to obtain information on the components' fragility models related to potential structural failures, if available. Among recovery measures, it is recommended to include insurance schemes because the financial resources available for recovery after damage to the infrastructure are likely to represent a key limiting factor.
3. **Post-damage decision making** concerns the criteria, arguments, or factors that could guide possible decisions on the topics of repairing or refurbishing certain components after damages, versus seizing the opportunity to change damaged or destroyed equipment with newer and better technology. For example, in energy production systems, the refurbishing option can go from the refurbishing of a minor part of the plant to the extreme of choosing to replace the entire infrastructure with newly manufactured systems, which is known as repowering (Herceg et al., 2022).

Table 4. 9. Infrastructure absorptive capacity-related information to be gathered and suggested questions

Topic	Information to be gathered	Possible Questions
<b>Hazard exposure</b>	The list of hazards and risks the infrastructure is exposed to.	What are the hazards/risks to which the infrastructure is exposed?
<b>Safety and management</b>	A description of the prevention and protection measures that are and could be in place to face each risk.	What prevention and protection measures are planned?
	A description of the mechanical and physical resistance of the infrastructure when faced with each type of hazard considered for the study. If possible, obtain the fragility models for the relevant components / structures.	What are the resistance thresholds of the infrastructure?
	A description of the effects of aging and possible future changes in the infrastructure affect its capacity to resist the effects of hazards and risks (for each type of hazard, if possible).	How does the aging of the infrastructure influence its resistance to hazards/risks?
	A description of the insurance scheme, if possible, for each hazard	How are risks insured?
	A description of the strategies that are followed after a damage or failure occurs in the infrastructure following a given hazard, including an estimation of the time taken to perform these actions.	What are the maintenance strategies?

<b>Post-damage decision making</b>	A description of the criteria that relevant decision makers would/could consider when facing a decision whether to repair or replace certain components of the damaged infrastructure.	What are the criteria for deciding whether to repair or replace equipment that suffered from accident damage?
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For the data collection process (see Table 4. 10), the first source to consult is the documentation from the infrastructure project plus the people working on said project, specifically for the data on hazard exposure, safety and management (i.e. the safety manager or knowledgeable people working in that department). Moreover, interviewing specialists in the field as well as people involved in the infrastructure project is key to elucidating the decision-making criteria that may or may not exist, as well as the potential evolution of the absorptive capacity.

If the study is of a general nature and there is no specific documentation that can be consulted, possible sources of information are public, industrial, or institutional reports addressing resilience, failures, possible damages, etc. on similar infrastructures. For example, the reports done by the International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS) Task 13 on Reliability and Performance of Photovoltaic Systems <sup>25</sup> provide information on failure and performance-related issued in PV systems.

In the case of public data of infrastructure resilience, prevention measures, or fragility curves is scarce or inexistant, scientific literature could provide information through specific studies. Because of the experimental and specialized nature of these studies, the practitioner extracting this information needs to be explicit on the hypotheses and assumptions that are made to use said information for the critical infrastructure case study.

For example, in the case of PV systems faced with strong wind hazards, from what could be found in English language scientific literature sources, there only exist one thesis (Goodman, 2015) plus a study based on results from said thesis (Ceferino et al., 2023) that have created fragility curves for rooftop and ground-mounted PV systems located in the United States and the Caribbean.

Table 4. 10. Data collection sources for the absorptive capacity-related parameters

<b>Type</b>	<b>Description</b>	<b>Examples – FuturePV Case study</b>
<b>Primary specific information</b>	Documents available from the (specific) infrastructure project	-
<b>Specialists – Interview</b>	Obtention of primary information on the characteristics of the infrastructure project Check for data gaps Consult on the changes that could occur in the future period the study addresses: trend scenarios, rupture scenarios	Interview with 2 industrial actors on: risks PV is exposed to, actions taken before and after the components get damaged
<b>Public documentation</b>	Reports and documents available online for similar infrastructure projects.	PVPS reports on risks, stresses, and damages on PV installations and its components (Herz et al., 2021; Köntges et al., 2017).

<sup>25</sup> IEA PVPS Task 13 website (Last accessed: May 2024): <https://iea-pvps.org/research-tasks/performance-operation-and-reliability-of-photovoltaic-systems/>

<b>Scientific literature</b>	Journal articles and scientific publications for specific information.	Study on PV fragility curves versus strong wind (Ceferino et al., 2023; Goodman, 2015).
<b>Specific documentation – Norms</b>	If accessible, official norms the infrastructure technology must fulfill	IEC 61215-1 (2021): Test requirements for PV modules for terrestrial applications, containing information on tests for mechanical loads. IEC 61730-2 (2023): Test requirements for PV installations

### 4.1.3. Case study application

For the version of the *FuturePV* case study presented throughout this document, the data collection process is based on the elements determined in the *DRUID problem* definition: the PV power plant, a French Mediterranean mountainous region, strong wind risks, and climate change and territorial-driven trends within a 30-year horizon.

#### 4.1.3.1. PV infrastructure and sector-related data

Regarding the PV infrastructure, as stated in the problem definition, the installed capacity is 1 MWp, with a capacity factor for the overall system of 16%. The PV cell technology is multi-crystalline Silicon (multi-Si), and the modules will have a 17.5% efficiency, supported by an aluminum frame and a fixed ground-mounted system (Frischknecht, Stolz, Krebs, et al., 2020).

To envision the technologies that could have a significant impact in the future PV market, NREL's best research-cell efficiency chart<sup>26</sup> gives an idea of experimental PV developments that might become commercially viable. However, commercially speaking, crystalline silicon technologies seem to be the most predominant ones and they are expected to continue being so in the coming decades.

On the PV sector side, looking at the RTE "*Futures Énergétiques*" report (RTE, 2021), six different energy production mix scenarios are proposed, and PV plays an important part in all of them, between 13-36% which represent around 70 to 208 GW of the installed capacity of the generation mix in 2050.

Considering the 35% increase in electricity consumption that has been predicted for 2050 in France (~1% average annual increase) (RTE, 2021), regions will also need to adapt to the changing demand by rising their electricity production capacity taking into account the expected contributions of PV. On this front, regional objectives have been established. For example, in the Provence-Alpes-Côte d'Azur (PACA) region in the south-east of France, the goals on PV development are 11,730 MWp of PV installed power by 2030 (where 2,850 MWp are ground installations) and 46,852 MWp by 2050 (where 12,778 MWp are ground installations) (DREAL Provence-Alpes-Côte d'Azur, 2019). At the end of the first trimester of 2024, there were 679 MWp of installed PV according to data from ENEDIS<sup>27</sup>, which is far from its 2023 objective of 8,316 MWp. Thus, more pressure is needed to fulfill the regional objectives, and how each department from the PACA region will react depends on many factors, but the attitudes and decisions made on the matter will significantly shift the course of PV development.

<sup>26</sup> NREL's Best Research-Cell Efficiency chart (Last accessed: May 2024): <https://www.nrel.gov/pv/assets/pdfs/best-research-cell-efficiencies.pdf>

<sup>27</sup> ENEDIS Répartition départementale des projets (Last accessed: June 2024): <https://data.enedis.fr/pages/projets-installations-production/>



The trends to ensure progress towards the territorial PV development objectives will impact the infrastructure sector. These trends are related to the RTE scenarios (described in §4.1.3.2) as well as the influence of climate change. However, although the RCPs do provide important insights regarding future climate, considering global and regional attitudes is just as important to estimate future trajectories for the infrastructure sector. These attitudes have been studied in Shared Socioeconomic Pathways (SSPs) coupled with the RCPs, as presented in Chapter 1 (§1.2.3.1). Therefore, 3 SSP-RCPs are considered as a driving trend, namely SSP-RCP 2.6, SSP-RCP 4.5, and SSP-RCP 8.5.

#### 4.1.3.2. Territory-related data

It is established that the photovoltaic plant project would be in a mountainous region with Mediterranean climate in the south of France.

According to Météo France, zones with Mediterranean climate are characterized by mild winters, hot summers, and frequent strong winds. Rainfall is scarce in winter and more abundant during spring and autumn, usually as storms (Météo-France, 2023). In the case of the solar resource in the region, the annual Global Horizontal Irradiation can be between 1300 and 1550 kWh/m<sup>2</sup> (Solargis, 2024). The mountainous zones in the French Mediterranean region contain forested areas that may be affected, in the future, by dry seasons due to higher regional temperatures, which could lead to unwanted desertification influenced by forest fires, meaning significant potential changes to land cover (GREC-SUD, 2016). To protect forests and their biodiversity, objectives towards reforestation and forest management have been set by the regional authorities (Région Sud PACA, 2024).

Considering that the subject of the study is a critical infrastructure whose main purpose is to produce electricity, it is relevant to have an idea of how electricity demand is expected to change in the studied period. In France, the electricity transmission network operator, RTE has explored three consumption trajectories for 2050 with the following hypotheses (RTE, 2021):

- **Reference trajectory:** There is a progressive electrification aiming to replace fossil fuels and a strong ambition to increase energy efficiency. Continuous economic and demographic growth is assumed, as well as a good degree of efficiency in public policies and plans. The manufacturing industry grows, and its share of GDP stops declining. The renovation of buildings is considered, as well as the associated rebound effect.
- **Sobriety/Sufficiency:** Lifestyle habits evolve towards greater sobriety in terms of use and consumption, resulting in a general reduction in energy requirements, including electricity.
- **Deep reindustrialization:** The share of GDP related to manufacturing will fall sharply to 12-13% by 2050. The scenario considers investment in cutting-edge, strategic technology sectors, as well as the relocation of high-emission production abroad, expecting a reduction in the carbon footprint of French consumption.

From the territory-related data gathered, the RTE scenarios (RTE, 2021) and the land use and land cover (LULC) change are taken as the most representative territorial trends. LULC can evolve in three general directions: maintaining the current LULC (no change), towards desertification, or towards reforestation and ecosystem restoration.

#### 4.1.3.3. Risk and hazard-related data

To obtain data that illustrate the data collection process for risks and hazards, two French communes with Mediterranean climate and mountainous regions were selected: Caille and Andon in the Alpes-Maritimes department (see Figure 4. 2). According to the information available in Géorisques (2024b),

the concerned hazards are floods, earthquakes, ground movement, clay swelling, forest fires, radon, and soil pollution. Moreover, the region is also exposed to climate hazards such as storms, strong winds, hail, heat strokes, and cold spells, as indicated in the document on major risks (DDRM) in the Alpes-Maritimes (Préfet des Alpes-Maritimes, 2021, p. 26).



Figure 4. 2. Map on the reference region between Cailles and Andon (Géorisques, 2024a)

Because the case study is meant to illustrate the basic features of the proposed methodology in a limited time frame, only one natural hazard was selected for evaluation, namely strong wind, even though it is well established that the chosen region is exposed to several kinds of hazards. Wind was chosen because it is a common factor among the climate hazards present in the region, data on wind speed is available in public databases, and because of the potential structural damage wind loads can cause in PV infrastructures, which is discussed in later paragraphs in this section.

According to Météo France, strong wind consists in damaging winds that exceed averages of 88 km/h or 24.44 m/s, corresponding to a level 10 in the Beaufort scale (see §1.2.1.2) (Météo-France, 2024b). When consulting the register on natural disasters in the Gaspard database (Ministère de la Transition écologique, 2024) for the reference geographical location, only one catastrophic event related to strong wind occurred in the region between Cailles and Andon in 1982. Moreover, in the DDRM there are 31 registered events for storms and 11 for strong winds from 2001 to 2020 (Préfet des Alpes-Maritimes, 2021, p. 35).

To complement the study of the influence of strong wind in the region, one historical dataset, ERA5<sup>28</sup>, based on reanalysis, and three prospective datasets<sup>29</sup> were collected from the Copernicus Climate Change Service, extracting information on wind speed and gust (the maximum 3-second wind) at a 10-meter height for the selected region (see Annex I. for details). Historical data on wind speed and gust was used to study the past incidence of strong wind events. Prospective data on wind speed was used to elucidate the evolution of average wind intensity for the considered timeframe in the study, that is, from 2020 to 2050.

Reanalysis data from 1940 to 2020 indicates that the wind speed and gust profile has had similar behavior throughout the years, which is close to a Weibull distribution, with a mean wind speed of 1.97 m/s, a mean gust speed of 6.53 m/s, (see Figure 4. 3) and more than 90% of the annual events

<sup>28</sup> ERA5 reanalysis (Last accessed: June 2024):

<https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview>

<sup>29</sup> Wind speed data from climate models (Last accessed: June 2024):

<https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-energy-derived-projections?tab=overview>

lying below 15 m/s for gust (see Figure 4. 4. a). Moreover, the data on wind gust above the 95<sup>th</sup> percentile suggests that there has been little to no change on the behavior of maximum wind gusts from the past to the present (see Figure 4. 4. b).

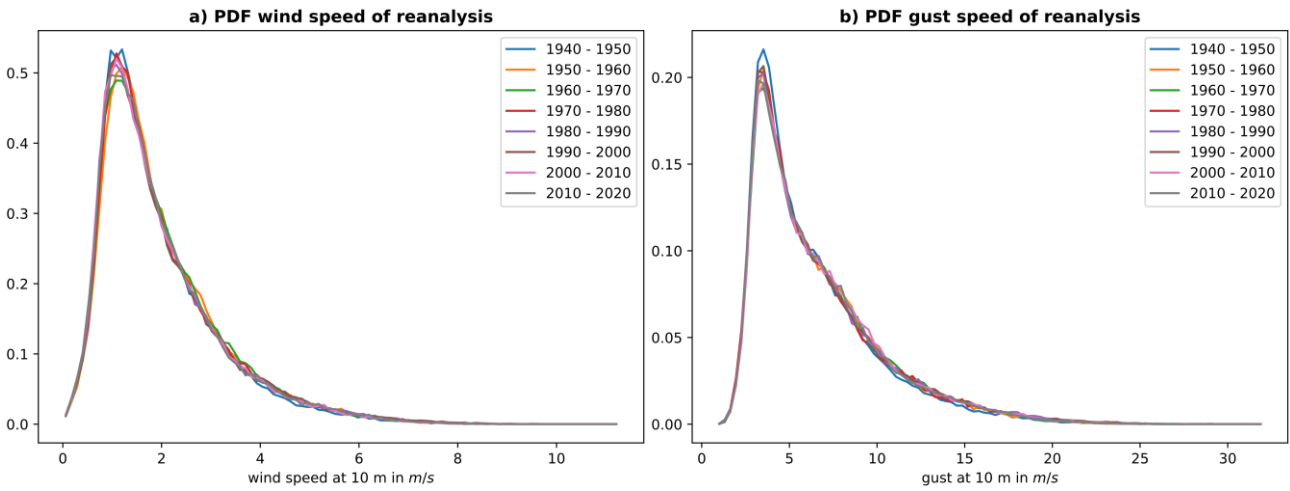


Figure 4. 3. Probability Density Functions at 10 meters for different decades of a) wind speed and b) wind gust

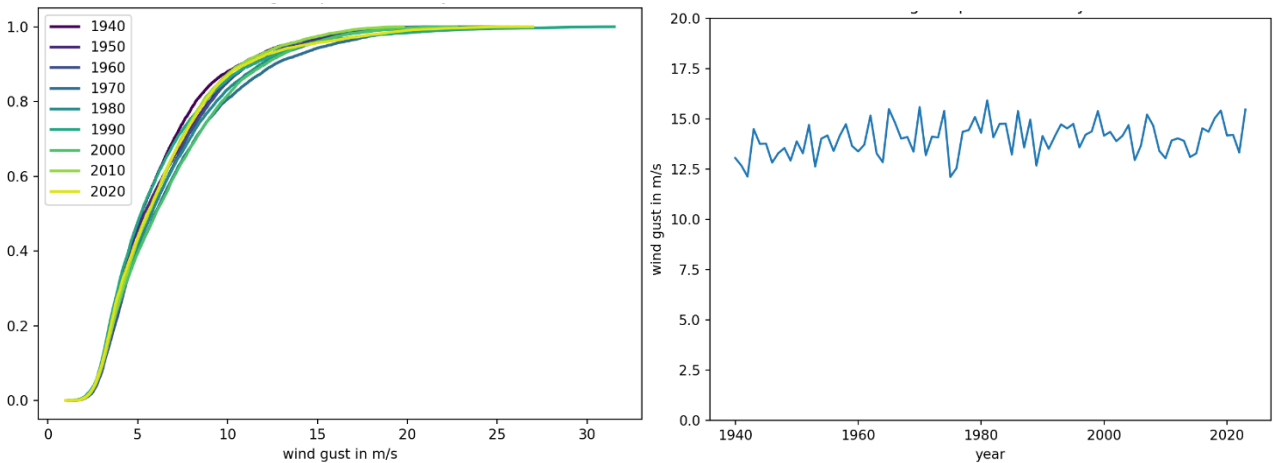


Figure 4. 4. a) Cumulative Density Functions at 10 meters for different decades of wind gust and b) 95-percentile of historical wind speed values

For the prospective datasets, data on average wind speed at 10 meters above the ground for the RCP scenarios 2.6, 4.5, and 8.5 were taken from two different models: ALADIN63 for RCP 2.6 and 8.5, and WRF381P for RCP 4.5. Despite the different premises behind the models, the CDF of the wind speed intensities does not seem to vary significantly, with more than 90% of the data points below a 5 m/s average wind speed (see Figure 4. 5). This is an indication that according to the models, the wind speed profile does not change from one RCP scenario to another.

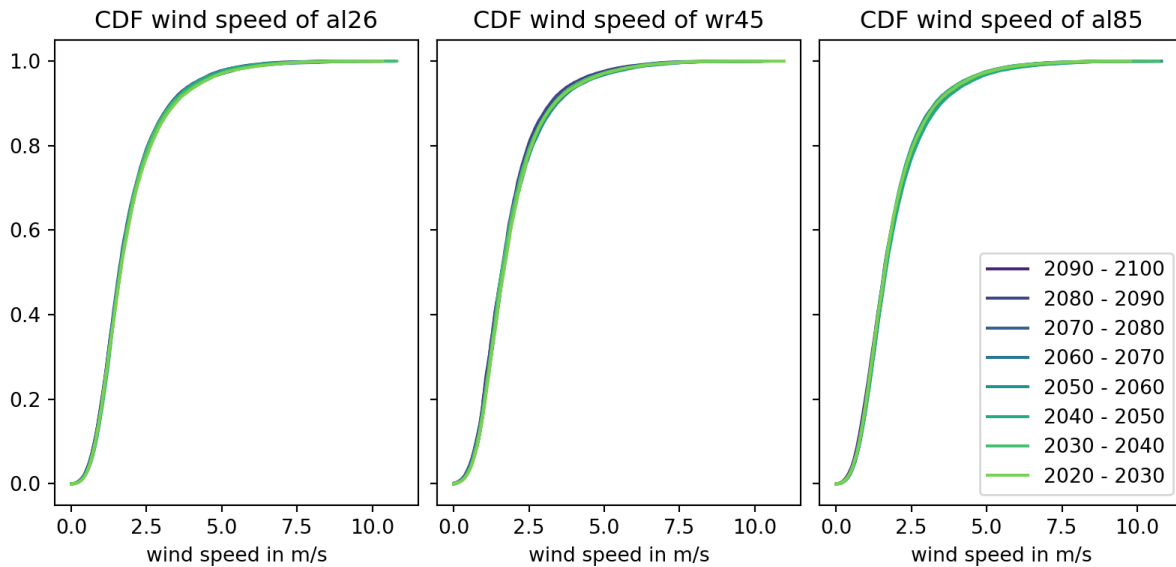


Figure 4. 5. Cumulative distribution functions of wind speeds at 10 meters for RCP scenarios 2.6, 4.5, and 8.5, respectively

All in all, it can be observed that disastrous strong wind events are extremely unlikely for all the considered RCP scenarios, and that wind speeds do not seem to change significantly in the future for the studied region. However, complementing this information based on data from the literature and discussions with PV-related specialists, the wind speed and gust measurements from the meteorological station will likely not accurately reflect the wind speed and gust that the PV plant will be subjected to because of local orographic effects related to fluid dynamics influenced by local topography, the spatial configuration of PV modules, local factors such as temperature and pressure changes, and the fact that wind gust measurements vary depending on the characteristics of the instruments used, i.e. anemometers (Azorin-Molina et al., 2023). Therefore, both the location and by extension the PV infrastructure could be subjected to very strong winds. Additionally, strong winds have direct and indirect effects on the PV infrastructure that could result in damage. Direct effects are the wind loads exerted on the structural components, i.e. the PV modules and their mounting structures, and indirect effects relate to impact damage due to flying debris, which could happen even at moderate wind speeds.

Despite the RCP scenarios having seemingly little to no influence in the future wind speed profile, the changes in temperature coupled with the land use and land cover change are likely to influence the exposure of the territory and the studied infrastructure to strong wind hazards. For example, dense forests represent obstacles for strong winds, lowering the perceived wind speed of an area depending on the direction of the wind (Camus et al., 2019). However, local groups of specialists such as GREC-SUD have studied the possible evolutions of climate in the French Mediterranean region Provence-Alpes-Côte d'Azur and they have estimated that increases in average temperatures will influence a decrease in yearly precipitation, leading to dry periods that will impact forested areas and the general population, increasing the risk of wildfires and potential deforestation (GREC-SUD, 2016). Therefore, the RCPs are considered as a driving trend, specifically coupled with the SSPs (see §4.1.3.1).

#### 4.1.3.4. Absorptive capacity-related data

This is likely the most challenging information to obtain because of the specificity required from the component side and the hazard side, meaning that not all parts of the infrastructure have the same absorptive capacity when facing a certain hazard.

Information from the interview conducted with two PV industrial actors in France revealed that the external factors that may cause damage to PV infrastructures and disrupt their operations, either related to strong winds or other phenomena, are:

- Cables exposed to the sun deteriorate due to prolonged heating periods.
- Heavy soiling may occur due to the proximity to an environment with many floating particles and particle-related pollution, such as wineries, cement plants, roads and rail networks.
- PV cell shading creating hotspots.
- Poorly installed connectors, which is the precursor to insulation defects and corrosion.
- Rodents that bite and eat cables.
- Poor module installation on the mounting system.
- High humidity causes faster degradation of the inverter. The inverter is the easiest component to degrade in the transformation chain because of all its electronic components.
- Glass breakage due to moisture intrusion on the cells. This is more common in very humid environments.
- Vegetation in contact with the panel.
- People walking on the panels during installation or maintenance operations.
- Flooding that problems for the covers of the cables because they lose their insulation. Cables are resistant to water, but they are affected after several years of prolonged exposure to water.
- Hail may cause severe damage to PV module glass, but it is more dangerous for the cells inside.
- Storms cause damage to tracking systems, but more common damage happens in the form of hotspots in modules and similar intermittency problems.
- Fires may cause the destruction of several important components, such as PV modules, cables, inverters
- Lightning strikes, although these are less common than the previously mentioned phenomena.

In particular, for the case study that focuses on the absorptive capacity of the PV infrastructure vs strong winds, information was obtained on the potential structural failures of the ground mounted PV modules, since these are the most important components in the PV infrastructure. A structural failure is considered as the structural states or threshold conditions beyond which the performance requirements of the infrastructure are no longer satisfied (Goodman, 2015).

The fragility function of a system, structure, or component gives an indication of the probability of failure or damage given an extreme mechanical load, which, in this case, is a wind load. From the literature research of fragility functions versus wind loads for ground mounted PV modules, only two documents were identified: one PhD thesis (Goodman, 2015) plus a study based on results from said thesis (Ceferino et al., 2023). The latter study focuses on the creation of fragility functions for rooftop and ground-mounted PV systems located in the United States by updating Goodman's fragility function with Bayesian methods.

Fragility models for structural damage due to mechanical loads are typically represented by a lognormal shape, represented by the following equation:

$$q(w; v, \beta) = \Phi\left(\frac{\ln(w) - \ln(v)}{\beta}\right)$$

(Equation 4. 1)

Where  $q$  is the probability of panel failure due to a wind gust  $w$ ,  $u$  is the wind gust with a failure probability of 50%,  $\beta$  is a normalizing factor<sup>30</sup>, and  $\Phi$  is the cumulative standard normal distribution function (Ceferino et al., 2023). In the study, the values found suggest that ground mounted PV systems have a higher reliability than rooftop mounted systems versus high wind loads, which the authors estimate as a 0.2% probability of annual PV panel failure.

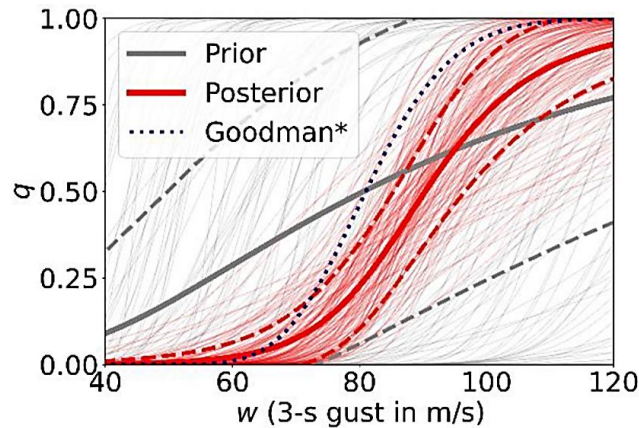


Figure 4. 6. Fragility curve from random samples  $u$  and  $\beta$  for ground mounted PV modules, recovered from Ceferino et al. (2023)

There are limitations of considering failure for a PV system using this fragility curve that was refined using data from sites on hurricane zones. However, the information used to generate this curve is valuable to estimate the fragility curve for *FuturePV*.

In contrast, more accurate information could be obtained on the fragility and absorptive capacity of PV infrastructures through wind tunnel tests to know how the wind behaves under particular conditions (Wittwer et al., 2022) and have a better idea of how, how much of, and how often does a PV infrastructure suffer damage at certain wind profiles. Nevertheless, it would still be challenging to estimate the probability of failure with different failure definitions versus different wind gusts.

Based on this information, the evolution of the absorptive capacity at the infrastructure level depends on the evolution of strong winds in the region, meaning they also depend on the SSP-RCP trend. Those in charge of the infrastructure are likely to react to changes in the environment to protect their investment, that is, the infrastructure that fulfills a critical role in the community, in this case the production of electricity. Making sure the infrastructure is resilient and reliable is necessary from an economic and social responsibility point of view.

## 4.2. Step II, Building the scenarios

The objective of the scenario building step is to conceive a group of scenarios that represent the possible future situation and evolution pathways of disaster risks in the territory to estimate their potential effects on the critical infrastructure studied. This scenario building process is based on the General Morphological Analysis (GMA) morphological box method (see §2.2.1.3), and in accordance with what has been established in the *DRUID morphological box* and *DRUID scenario* (see §3.3.2).

<sup>30</sup> " $\beta$  defines the width of the transition range between winds with low and high failure probability, and it is a measure of aleatory uncertainty in the vulnerability analysis. In the limit, when  $\beta \rightarrow 0$ , [(Equation 4. 1)] becomes equivalent to a deterministic assessment, where the panel would fail after a fixed wind threshold" (Ceferino et al., 2023).

A scenario, as defined in Chapter 2, is a description of a possible future situation based on a specific set of assumptions, including the narrative or sequence of events that describe that path from the present to the future (Godet, 2007c; Weidema et al., 2004).

There are two general tasks to carry out in this step. First, all the scenario universe is defined by establishing all possible combinations of the identified trends. This is done through a process that is inspired by GMA to obtain the solution space containing an ensemble of scenarios related to the critical infrastructure, which are separated into scenario classes. Then, from this solution space, representative scenarios are chosen to be later studied in function of the resilience of the critical infrastructure, which consists in the exploration of what could happen to the performance of the critical infrastructure when faced with a specific context described by the conditions of the scenario.

Throughout this process, it is recommended to organize workshops or consultation sessions with relevant specialists and experts in the field, to verify and validate the defined scenario classes as well as the representative scenarios chosen.

The following sub-sections elaborate on the proposed approach to each task alongside the illustration with the case study.

#### 4.2.1. Identifying the scenario universe

Identifying the scenario universe starts with the *DRUID morphological box* definition. It is built upon the driving trends and their respective values, as defined in the Problem Definition step (§4.1).

As an example, the morphological box for *FuturePV* is shown in Table 4. 11. It consists of the driving trends identified for the PV infrastructure and sector (SSP-RCP, RTE scenarios), the territory (RTE scenarios, LULC change), the risks and hazards (SSP-RCP), and the absorptive capacity (SSP-RCP).

Table 4. 11. *FuturePV* case study morphological box

SSP-RCPs	RTE scenarios	LULC change
Sustainability	Reference	No change
Middle of the road	Sobriety	Desertification
Fossil-fueled development	Deep reindustrialization	Reforestation

This problem space consists of a total number of 27 scenarios ( $T_{SC}$ ) represented by its 3 trends: the SSP-RCPs with 3 values, the RTE scenarios with 3 values, and the LULC change with 3 values.

$$T_{SC} = \prod_{j=1}^n v_j = 3 * 3 * 3 = 27$$

Reducing the number of scenarios is done with the help of the Cross Consistency Assessment (CCA), whose objective is to evaluate the consistency between the values of each parameter, thus leaving only the alternatives that result in non-contradictory and possible scenarios.

In the following paragraphs some recommendations to carry out a CCA for a DRUID morphological box are shared. These recommendations are based on the development of the *FuturePV* case study.

#### 4.2.1.1. CCA recommendations

The CCA involves the evaluation of the logical and empirical consistency for all the established trends and their values. In some special cases, normative consistency checks are also possible, requiring more careful justification since they pertain to constraints based on social norms, ethics, laws, and standards, among others (Ritchey, 2011b).

Logical consistency between the values of the trends involves verifying whether the hypotheses and the assumptions each value is based on are compatible amongst themselves or not. For example, the value of a trend that relies on the accelerated growth of a regional population is not compatible with another value of a trend that supposes an important reduction of resource consumption in the same region. To carry out the logical consistency check, it is recommended to distinctly and explicitly state the hypotheses and assumptions of each value of each trend in the morphological box.

In the case of empirical contradictions, these are related to specific conditions of the case study that are extremely implausible or impossible to happen at once. Factors that may play a role in these assessments could be related to specific regional restrictions, political biases or the development of the infrastructure-related sector in the studied territory.

For *FuturePV*, the cross-consistency matrix consists of three blocks and 27 cells that indicate the number of pair-wise relationships between parameter values that exist in the morphological field. The CCA is done by first focusing on the SSP-RCP trends (Riahi et al., 2017) versus the RTE scenarios (RTE, 2021) and the LULC change, followed by the RTE scenarios versus the LULC change.

Given the global scale of SSP-RCP trends, in addition to the myriads of hypotheses that are involved for their creation, it is difficult to contrast them to other trends at more specific scales. Thus, justifying mutual incompatibilities and impossible situations between trends is complicated because of their difference in scale, especially when the high variability and uncertainty associated to the effects that SSP-RCP trends might have on different regions of the world. Potentially, all SSP-RCP trends are compatible with all other trends and scenarios. Therefore, comparisons for the CCA between global trends and other trends of different scales ought to be made in normative terms, stating clearly the reasons for restricting certain scenarios. This is under the clear understanding that established normative inconsistencies do not mean that the scenarios are impossible or implausible.

The statements that aid in the completion of the cross-consistency matrix, as shown in Table 4. 12 are as follows:

- The hypotheses of SSP-RCP sustainability are based on sustainable development principles. These necessitate the contribution of behaviors and actions that reduce the carbon footprint to reach “net-zero carbon” objective by the year 2100. Thus, disappearance of forested areas due to desertification should be incompatible with this pathway. Ideally, after 2040, forest areas ought to increase as natural carbon capture sources (Riahi et al., 2017). Therefore, scenarios including this option are restricted in normative terms.
- SSP-RCP middle of the road describes a pathway where society, economics, and technology follow similar trends to those found historically. France, being a developed country, will have an advantage progressing towards its sustainable development goals, albeit slowly. Additionally, income inequalities and social tensions between socioeconomic groups within the country will likely create difficulties that impede progress towards energetic sobriety. Therefore, the RTE scenario of sobriety is deemed incompatible in normative terms.



- SSP-RCP fossil-fueled development describes an extreme case where rapid technological progress and the development of human capital take center stage as the means to achieve sustainable development. This implies higher energy requirements and consumption of resources, which is incompatible with the lofty goals of energetic sobriety and plans to reduce the intensity of energy use throughout sectors. Therefore, the RTE reference scenario and the sobriety scenario are deemed normatively incompatible.
- RTE scenarios versus LULC values did not have any logical inconsistencies between each other. However, the principles behind the reference and the sobriety scenario push for preserving biodiversity, therefore the desertification condition is incompatible. This conservation principle concerns all RTE scenarios (RTE, 2022), but depending on the pressures exerted on the region, the LULC may still change towards desertification if firm measures are not taken.

Table 4. 12. CCA for the FuturePV case study, where “x” indicates the values of certain parameters are deemed as incompatible

		SSP-RCPs			RTE scenarios		
		2.6	4.5	8.5	Reference	Sobriety	Reindustrialization
RTE scenarios	Reference			x			
	Sobriety		x	x			
	Reindustrialization						
LULC change	No change			x			
	Desertification	x			x	x	
	Reforestation			x			

From the eliminated alternatives in the CCA, 12 scenarios are left, shown in Table 4. 13.

Table 4. 13. FuturePV solution space

SSP-RCP scenario	LULC change	RTE scenario
2.6	No-change	Reference
2.6	No-change	Sobriety
2.6	No-change	Reindustrialization
2.6	Reforestation	Reference
2.6	Reforestation	Sobriety
2.6	Reforestation	Reindustrialization
4.5	No-change	Reference
4.5	No-change	Reindustrialization
4.5	Desertification	Reindustrialization
4.5	Reforestation	Reference
4.5	Reforestation	Reindustrialization
8.5	Desertification	Reindustrialization

As a final remark that can be made on the FuturePV case study is that because there are only three morphological parameters and the number of scenarios and the pair-wise relationships are the same,

it is possible to check the consistency of each scenario individually. However, comparing one value of a driving trend against another value of trend is in theory simpler than comparing three or more values at the same time.

#### 4.2.1.2. Defining scenario classes

The definition of scenario classes lies on the premise that the scenarios presented in the solution space share fundamental characteristics that makes it possible to group them.

The recommended approach to establish these scenario classes is to select one driving trend from the morphological box to guide the scenario classification. The recommended selection criterion is based on the magnitude of influence of the trend, meaning that the most important trend is likely the one with the broadest influence. However, depending on the objectives of the case study addressed, it could be more appropriate to choose a specific trend to guide the scenario classification. In the end, for each scenario class, the representative characteristics should be described. This description also acts as a justification of why these scenarios are grouped together.

For example, in the *FuturePV* case study, the SSP-RCP pathways represent global changes on average temperatures and societal attitudes, while the RTE scenarios only concern the French territories and, in a way, they react to more widespread changes that influence France. Thus, in this case, the scenario classes are defined based on the SSP-RCP scenarios (see the different color shadings in Table 4. 13). The representative characteristics for each group are:

- **SSP1-RCP 2.6, Sustainability:** These scenarios describe situations focused on strong actions towards sustainable development, where the management of global resources improves, and low resource consumption and more efficient energy consumption and production are prioritized. Therefore, territorial efforts focus on reducing their carbon footprint whilst taking care of human and environmental health, which involve conservation and reforestation efforts.
- **SSP2-RCP 4.5, Middle of the road:** These scenarios describe intermediate scenarios where global trends follow their historical patterns. Efforts are made towards sustainable development, but they are not so strong because of shifting economic and social situations. The energy consumption trajectories aim towards more efficient use of energy and pushing industrial activities forward.
- **SSP5-RCP 8.5, Fossil-fueled development:** In this group only one scenario exists, and it describes a situation where the worst case for the climate change pathways has come to pass, thus LULC change is strongly driven towards desertification. Thus, to reduce their carbon footprint, the French territories prioritize sending their most carbon-intensive production abroad.

#### 4.2.2. Defining the representative scenarios

The definition of the representative scenarios involves selecting one or more scenarios from each scenario class for which the evolution of territorial, risk, the infrastructure sector, and the absorptive capacity context will be explored. The purpose of defining representative scenarios is to prioritize the number of scenarios to be analyzed, since it is likely that practitioners would have limited time and resources to perform the analyses.

A way to approach this selection is through the identification of extremely different scenarios. For example, practitioners could use the most optimistic scenario, the most pessimistic scenario, an intermediate scenario, and the most likely scenarios for their study. To determine the latter, having a consultation or a workshop session with relevant experts in the field is recommended. It is worth

noting that because all scenarios selected start from the same *DRUID problem*, they share the same characteristics at the beginning of the operational lifespan of the PV infrastructure,  $T_0$ .

For each representative scenario chosen, the essential characteristics that constitute the scenario given their related trends are described. These pertain to the specific infrastructure-related, territory-related, risk-related, and absorptive capacity-related characteristics.

To know which values of each characteristic are related to a given scenario, we need to go back to the data collection for each thematic group and their topics. During this process, the trends that directly influenced each topic were explicitly stated, thus facilitating the traceability of the causal chains, so to speak.

The structure of a representative scenario description, as established in Chapter 3 (see §3.3.2) is composed of four contexts:

1. **The trend-driven or scenario context:** A narrative description of the situation that the trends present, which makes up the general context of the representative scenario. It is based on the general description of the scenario class and addresses the particularities related to the scenario.
2. **The infrastructure context:** A narrative description of the characteristics of the infrastructure and the infrastructure-related sector, and the evolution trends on the studied timescale. These characteristics include regional plans for the infrastructure sector, the prominent technologies available in the market, current and to be implemented policies, etc.
3. **The territory context:** A narrative description of the characteristics of the territory and its evolution trends on the studied timescale. These characteristics include the social, demographic, economic, political, and environmental aspects, among other relevant aspects for the case study.
4. **The disaster risk context:** A qualitative and quantitative/semi-quantitative description of the evolution trends in the timescale studied for the following risk-related characteristics:
  - a. The hazards the infrastructure is exposed to, including their nature, the likelihood of occurrence per intensity level, and causal chains if relevant.
  - b. The absorptive capacity per type of possible hazard or damage. It is possible to distinguish the absorptive capacity for different system components, if that information is available.

As in the data collection process, the evolution of each characteristic included should be described in the time steps defined.

For example, in the *FuturePV* case study, only one representative scenario is selected, and it is described in Table 4. 14.

Table 4. 14. SSP2-RCP 4.5-based representative scenario for FuturePV

Reference scenario: Middle of the road   No LULC change   RTE reference
<b>Trend-driven or scenario context</b>
<p>This scenario describes an intermediate scenario where global trends follow their historical patterns. The economic and social situations are shifting. Therefore, it is difficult to make strong efforts towards the sustainable development goals in the region. The efforts that are being made and those planned for the next few decades will likely enable to maintain the LULC in the region as it is, meaning there will not be further deforestation in this period.</p> <p>The approximate change in regional temperatures is presented relative to the reference values between 1976 and 2005 are (GREC-SUD, 2016):</p> <ul style="list-style-type: none"> <li>• 2025-2035: from 0.5 to <math>1.0 \pm 0.4</math> °C</li> </ul>

- 2035-2045: from 1.0 to  $1.3 \pm 0.4$  °C
- 2045-2055: from 1.3 to  $1.5 \pm 0.5$  °C

In terms of the electricity sector in France, there is a progressive electrification aiming to replace fossil fuels alongside ambitions to increase energy efficiency on the demand side. Continuous economic and demographic growth as well as the growing manufacturing industry contribute to an increasing energy demand.

#### Infrastructure context

##### Sector

There is a relatively stable market in PV technologies and given the slow progress towards the regional objectives to increase the installed capacity in the territory, investments are dedicated towards more reliable and efficient crystalline Si technologies. Moreover, regional and national efforts towards PV recuperation strategies are being reinforced. These strategies are related to establishing efficient operations on recuperation, testing and recycling or reutilization of removed PV modules and installations, especially focusing on crystalline Si technologies. This is reinforced with the increased prices in the PV market expected due to the depletion of essential metal and mineral resources.

##### Technology

Mono-crystalline technologies cover the majority of the market share, while multi-crystalline cells are slowly disappearing from the global market (Masson et al., 2023), but are still available for lower prices than mono-Si cells. The expected efficiencies of each technology are the following<sup>31</sup>:

Period	Mono-Si %	Multi-Si %
2025-2035	21	20
2035-2045	24	22
2045-2055	27	24.5

China is expected to continue being the main producer of these technologies (Masson et al., 2023).

#### Territory context

The French Mediterranean region continues to be a popular destination for tourists around the world. The number of people present in the region varies from season to season, and this makes it challenging for local authorities to stay in line with their sustainable development objectives, which include energy and electricity supply challenges. Nevertheless, preservation efforts are sufficient to maintain a balance between the natural environment and the urban zones.

The seasonal variability affects the demand for electricity, but it does not directly affect the location where the PV infrastructure is at, since low tourism is expected in mountainous regions compared to the littoral.

#### Disaster risk context

##### Hazard

Strong winds are assessed in terms of the maximum wind gust per year. Because of the changing climate, dry spells followed by very intense storms have become increasingly common occurrences, which are accompanied by strong winds. However, despite these changes, the expected intensity of wind gust in the region does not change significantly throughout the years. The probability distribution depicting the occurrence of strong wind in the region throughout the studied period is shown in Figure 4. 7.

##### Absorptive capacity

In the interest of providing reliable energy services and keep fulfilling the objectives towards the renewable energy transition, regional authorities as well as the PV infrastructure managers make efforts to maintain their absorptive capacity measures throughout the period. Insurance payouts and the lack thereof due to inaccurate measurements of wind gust strongly influence the decisions made by the infrastructure managers.

The absorptive capacity parameter is therefore quantitatively represented for all the period, through the fragility curve shown in Figure 4. 8. This curve represents the probability of PV panel failure under given wind gusts.

<sup>31</sup> Values estimated from PVPS recommendations and Premise estimations (Last accessed: June 2024): <https://premise.readthedocs.io/en/latest/transform.html>

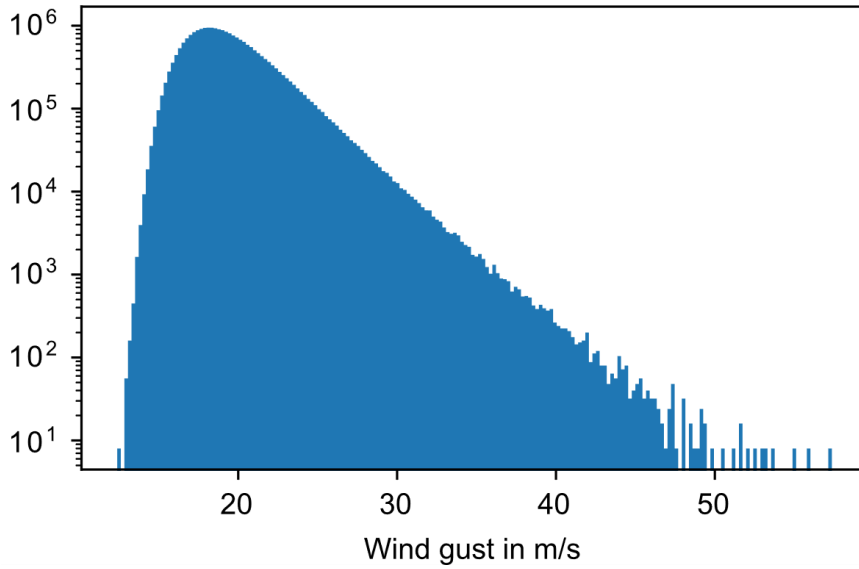


Figure 4. 7. Histogram of wind gust in logarithmic scale estimated through RCP 4.5

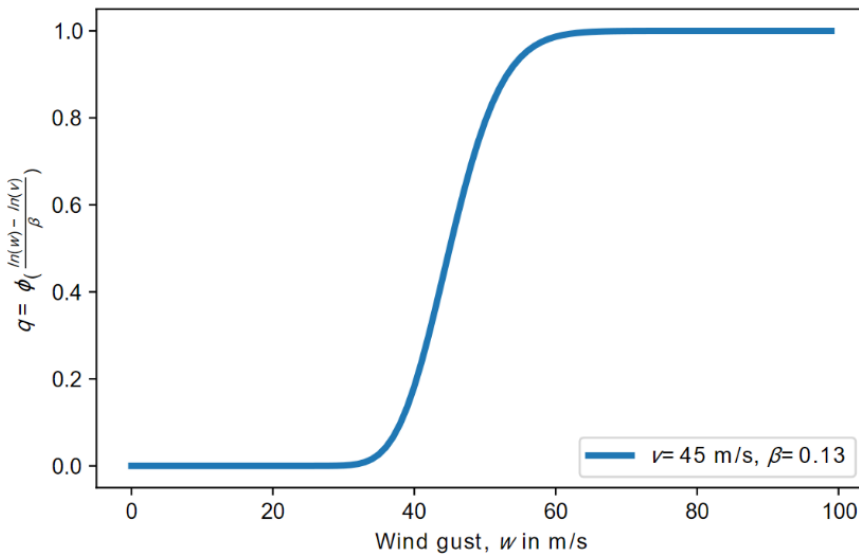


Figure 4. 8. Fragility curve with  $v = 45 \text{ m/s}$  and  $\beta = 0.13$

Some specific assumptions have been made on the strong wind hazards and the absorptive capacity in order to test the capabilities of the *DRUID method* through the illustrative case study, *FuturePV*.

#### 4.2.2.1. Assumptions on the strong wind hazard

In the case of strong wind hazard, the wind gust values used for the representative scenario are modeled using the relationship between the historical wind speed and wind gust in the region as a reference. This is because wind gust data is not calculated in the prospective RCP-based models and therefore is not available for us to use directly.

The first assumption is that PV modules are set at approximately 2 meters above ground level and most of the wind data available is related to a 10-meter height, so the wind that affects them ought to be adjusted using a correction factor, as shown in the following equation (Xu et al., 2024):

$$v_{2m} = 0.748v_{10m}$$

(Equation 4. 2)

Where  $v_{2m}$  and  $v_{10m}$  are the wind speed values at 2 meters and 10 meters respectively.

The second assumption is that the wind gust values used for the chosen representative scenario are modeled using the relationship between the historical wind speed and wind gust in mountainous regions near the reference location. This is because wind gust data is not calculated in the prospective RCP-based models and therefore is not available for direct use.

To obtain this information, a dataset of daily wind speed measurements from 79 ground stations from the Météo France network<sup>32</sup> were downloaded for three conterminous departments in the south-east of France: Alpes-Maritimes (06), Alpes des Hautes Provence (04) and Var (83). From these wind measurements, the following parameters were considered:

- **FFM**: daily mean of average 10-min wind speed at 10 m, and
- **FXI3S**: daily maximum of 3-s wind gust at 10 m.

Measuring stations located in mountainous regions were identified and chosen based on their altitude, which ranged from 600 meters to 1400 meters. Moreover, only those with joint availability of FFM and FXI3S were selected, meaning 13 stations in total.

The measurements for FFM and FXI3S from these stations are shown in Figure 4. 9.

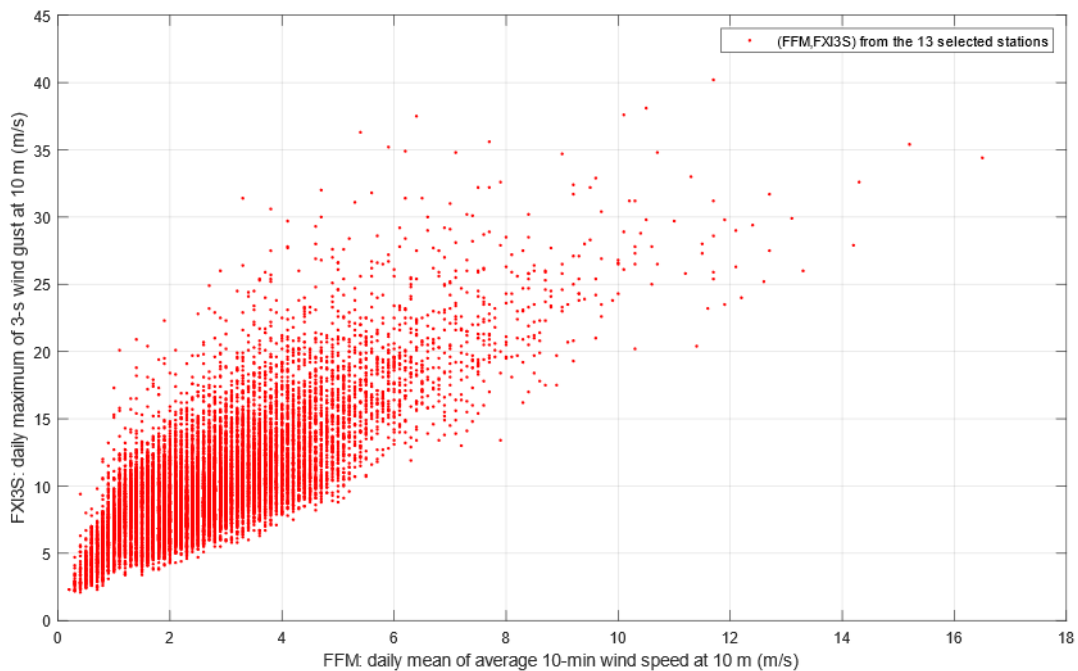


Figure 4. 9. FFM and FXI3S measurements

To build a model that can be used to estimate future wind gust from these data, a stochastic model was constructed relating the FFM to the FXI3S using the following elements:

- A non-parametric regression function to approximate the conditional expectancy,  $E(FXI3S|FFM)$ , and

<sup>32</sup> Météo-France, Données climatologiques de base – quotidiennes (Last accessed: July 2024): <https://meteo.data.gouv.fr/datasets/6569b51ae64326786e4e8e1a>

- A set of non-parametric probability density functions of the residual  $FXI3S - E(FXI3S|FFM)$ , using the type-I generalized extreme value distribution, (Guthrie, 2020) as shown in (Equation 4. 3), for 10 ranges<sup>33</sup> of FFM wind speed.

$$f(x) = \frac{1}{\sigma} e^{\frac{x-\mu}{\sigma}} \exp\left[-e^{\frac{x-\mu}{\sigma}}\right], \quad -\infty < x < \infty, \sigma > 0$$

(Equation 4. 3)

Where  $\mu$  is the location parameter, and  $\sigma$  is the scale parameter.

Comparing the results obtained with this model versus the measured values form the 13 stations, as shown in Figure 4. 10, it seems that the model represents well the measured data.

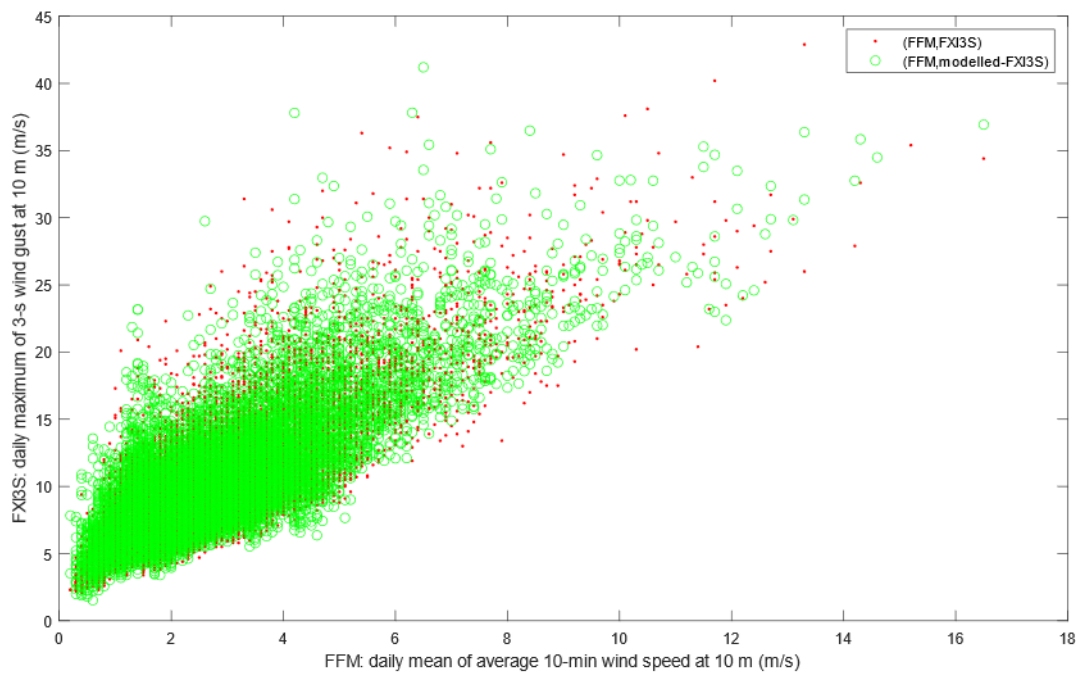


Figure 4. 10. Comparison between the model and the measured data for FFM vs. FXI3S

Thus, the model was used to estimate the future wind gust per year for the representative scenario.

#### 4.2.2.2. Assumptions on the absorptive capacity

Ceferino et al. (2023) presented a fragility curve that was refined using data from PV systems exposed to strong winds that were caused by hurricanes in the Caribbean, therefore those PV systems were built knowing that those kinds of extreme events could happen in that region. However, in *FuturePV* the zone selected for the illustrative study is not exposed to winds of such magnitudes. Therefore, for *FuturePV* the fragility curve has been modified by changing the parameters  $\nu$  and  $\beta$  of (Equation 4. 1) to approximate what we estimate is a more conservative value that also lets us test the *DRUID method*. The  $\nu$  parameter helps determine at which gust speed do 50% of damages to the PV system occur (displace the fragility curve horizontally), and the  $\beta$  parameter determines the size

<sup>33</sup> Ranges of FEM wind speed considered: 0.2 to 1.2, 1.2 to 1.7, 1.7 to 2.1, 2.1 to 2.4, 2.4 to 2.7, 2.7 to 3.0, 3.0 to 3.4, 3.4 to 4.2, and 4.2 to 16.5.

of the transition range between winds with low and high failure probability (changes the slope of the curve). The tested values are  $v = 45 \text{ m/s}$  and  $\beta = 0.13$  (see Figure 4. 8).

### 4.3. Step III, Studying the infrastructure resilience

The objective of the infrastructure resilience study is to evaluate the potential effects of disaster risks on the performance of the critical infrastructure for each chosen representative scenario. It is based on a resilience model that tests the operational performance of the critical infrastructure versus possible disaster events given the specific scenario context.

The proposed resilience model considers that the critical infrastructure fulfills a certain purpose, providing a product or a service. When the infrastructure is producing or providing the service below a certain performance threshold, it generally means that it is doing so at a loss, which is likely unsustainable and unprofitable. Therefore, if its performance goes below the given threshold, then the model considers the hypothesis that actors responsible for making the decisions on the future of the critical infrastructure are faced with a choice. This choice pertains to whether they take this loss in performance as an opportunity to increase the production capacity of the critical infrastructure and its profitability by updating it with better performing technology, or if only the damaged components are repaired, and operations continue as usual with the reestablished production capacity.

In the following paragraphs the structure of the resilience model is presented, followed by the application to the case study with exploratory results. The practical implementation of the model was done in Python.

#### 4.3.1. Infrastructure resilience model

For each representative scenario, the resilience model consists of using the described elements and parameters to estimate: i) the hazards that could affect the critical infrastructure in the studied period, ii) whether the infrastructure is adversely affected by the hazards, iii) the likely magnitude of damage the infrastructure suffers, and iv) the decision-making consequences on the infrastructure after a shock of a certain magnitude.

Thus, the key elements of proposed resilience model are:

1. **The hazards**, which are described by their intensity and probability of occurrence over a certain period. Case-specific considerations with causal chains might need to be made when compound hazards and complex risks are involved.
2. **The absorptive capacity**, which can be divided into classes or levels that represent different thresholds of likely failure or damage conditions of the infrastructure versus different hazard intensities. These are described by the fragility curves, e.g. in Figure 4. 6. In the case of complex risks, special attention should be focused on the intensity of the hazard at the end of the causal chain that may disrupt the operations of the critical infrastructure. For certain hazards, such as floods, it is possible that the fragility curve describes a Boolean failure condition when it goes over the threshold (Di Maio et al., 2022), meaning that below said threshold no failure happens and above it the infrastructure always fails. In such a Boolean case, there is only one absorptive capacity class.
3. **The shock levels**, which describe the intensity of damage that the infrastructure has suffered after comparing the probability of occurrence of the hazard with the absorptive capacity of the critical infrastructure when facing said hazard. This damage description most likely depends on the failure condition established by the fragility curve. For example, in *FuturePV*, the shocks on the PV



infrastructure are related to the percentage of the damaged components, which can be expressed in terms of the installed capacity in kWp, from 0% to 100%. In other words, this represents the fraction of all components of the critical infrastructure that have suffered damage with respect to the whole infrastructure.

4. **The event type**, which establishes the type of event that occurred. An event type can be:
  - **No event:** The shock level was zero, therefore no changes occurred.
  - **Repair-type event:** The production capacity of the critical infrastructure is reestablished to its original level for the next iteration. In the current model, one iteration equals a year of operation.
    - For *FuturePV*, repairing means replacing the damaged components with new components of the same technology, characteristics and producing capabilities.
  - **Replacement-type event:** The production capacity of the critical infrastructure is upgraded for the next iteration.
    - For *FuturePV*, replacing is repowering, meaning that all the components of the PV infrastructure (the PV modules, the mounting system, the inverters, and the electrical installation) are changed and replaced by new and better performing technologies, increasing the installed capacity whilst using the same surface area that was prepared for the original infrastructure.
5. **The performance thresholds**, which establish limits related to the performance of the critical infrastructure. An upper and a lower limit are established, which later serve to determine whether the infrastructure should be repaired or repowered after a shock. Thus, if the performance of the critical infrastructure is above the upper threshold, a repair-type event occurs. If the performance value is between the two thresholds, then decision makers ought to choose whether to repair the damage done to the infrastructure or replace the whole infrastructure with better performing components and technology. Otherwise, going below the lower threshold automatically triggers a replacement-type event. The principle behind establishing this lower threshold is that it could be economically and technically problematic if the damage to the performance of the critical infrastructure reached a certain level, which may put the decision makers in a position of contemplating this situation as an opportunity to upgrade the infrastructure for long-term benefits. Likewise, the principle behind the upper threshold is that the performance worsens but not by much, so it is more convenient to directly repair the damage.
6. **The decision-maker profile**, which describes the likelihood that an actor decides either to repair only the damage done or to replace the entire infrastructure, when faced with a situation that is between the repair and replacement thresholds.

The proposed resilience model is an iterative process which has  $n$  iterations in a period of evaluation. It begins by evaluating the exposition to risk of the critical infrastructure by comparing the maximum intensity of the hazard experienced per iteration with the absorptive capacity. If the intensity of the hazard is within the range of a given absorptive capacity level, then a second evaluation takes place that depends on the definition of the failure condition, and the result is the shock level associated to this yearly event. The shock level has a direct impact on the production capacity of the critical infrastructure. Thus, the production capacity of the current iteration is compared to the performance thresholds and the type of event is established with its corresponding effects on the production capacity of the critical infrastructure. Afterwards, a new iteration begins unless it is the last iteration.

At the end of the iterative process, the model stores data on the number and level of shocks, the amount and the type of events that occurred, and when the replacement-type event took place. These represent the decision scenarios for a given representative context scenario.

In *FuturePV*, the period of evaluation corresponds to the 30-year operational lifespan of the PV infrastructure. Each iteration of the model corresponds to a year of operations.

Each element of the resilience study must be described with the corresponding specificities, and existing conditions that are specific to the study must also be described and justified. In *FuturePV* the resilience model has two special conditions:

- Only one replacement-type event is allowed per period of evaluation because the financial resources that would be available to build a second PV plant are limited. Therefore, whenever a non-zero shock occurs after a replacement event, the model will always establish a repair-type event that sets the production capacity of the critical infrastructure to the new post-replacement level for the next year
- No replacement-type events can happen before the 10<sup>th</sup> year of operation because it is assumed that making such a change relatively early in the operational lifespan is something that stakeholders would not agree to.

### 4.3.2. Application to study the resilience of *FuturePV*

#### 4.3.2.1. Hypotheses and key elements

In the representative intermediate scenario of *FuturePV*, the performance of the 1 MWp PV installation throughout its 30-year lifespan is the focus of the resilience study. The function of a PV installation is to produce electrical energy, therefore the performance-related parameter is the electricity produced by the PV system ( $E_{lifetime}$ ) throughout its lifespan, represented by the following equation:

$$E_{lifetime} = \sum_{n=1}^{lifetime} E_{PV}(n)$$

$$E_{PV}(n) = P_{OutputAnnual}(1 - d)^n$$

(Equation 4. 4)

Where:

- $E_{PV}(t)$  is the overall electricity produced in a certain year, expressed in kWh per year,
- $n$  is the “nth” year when the PV system is operating,
- $d$  is the annual degradation rate of the PV modules, an indication of the loss of efficiency which represents a degradation of their output production throughout their lifespan.
  - For the case study, it has a base value of 0.7% = 0.007, for mature PV technologies (Frischknecht, Stolz, Health, et al., 2020)
- $P_{OutputAnnual}$  is the electricity production output in kWh per year, represented by the Specific Yield  $SY$ , which is the ratio of the average electricity production in a year per kilo-Watt peak installed in a certain region. This ratio is used to estimate the electricity production performance of the PV installation in a given location, representing in a simplified way the ensemble of factors that aid in the estimation of the electricity produced in a year (i.e. the performance ratio, module efficiency, module orientation and spacing, shadowing effects, AC/DC conversion losses, etc.). Therefore:

$$P_{OutputAnnual} = P_x SY$$

(Equation 4. 5)

Where  $P_x$  is the installed capacity in kWp of PV system  $x$ .

For *FuturePV* case study:

- The specific yield,  $SY$ , is 1400 kWh/kWp, typical of a southern France location
- The installed capacity for the base system,  $P_1$ , is 1,000 kWp
- The installed capacity for the repowered system is:

$$P_2 = \eta_2 \frac{P_1}{\eta_1}$$

(Equation 4. 6)

Where  $\eta_1$  and  $\eta_2$  are the PV module efficiencies for the base and the repowered installation, respectively.

As previously explained, two thresholds need to be defined to determine the type of action after a shock. These performance thresholds are estimated with respect to the electricity production of the installation as follows.

The upper limit or **repair performance threshold** is established based on the expected annual electricity production in kWh at the 30<sup>th</sup> year of operation ( $E_{30}$ ) of the undamaged baseline PV infrastructure, equal to 1,133 MWh, described by the following equation:

$$E_{30} = 1000 [kWp] * 1400 \left[ \frac{kWh}{kWp} \right] * (1 - 0.007)^{30} = 1,133,980 [kWh]$$

The lower limit or **repowering performance threshold** is fixed with respect to the repair threshold based on a ratio chosen by the practitioners. Thus, in this specific case, the repowering ratio was originally fixed to 50% of the repair threshold value ( $0.5 * E_{30}$ ), equal to 567 MWh. Additionally, another repowering threshold of 75% is tested to observe the influence of this repowering threshold on the repowering-related results.

In this scenario, the **replacement-type event** considers that the entire PV infrastructure is replaced with a newly manufactured system that has more efficient multi-Si modules<sup>34</sup> with an efficiency that depends on the on the moment of the operation lifespan when the system is replaced (see Table 4. 14). As previously mentioned, this concept is known as repowering, which has become quite common in the PV sector as the efficiencies of PV technologies have been rapidly increasing year by year ([Herceg et al., 2022](#); [NREL, 2024](#)).

The **decision-maker profile** is quantitatively represented by a probability of occurrence (%). It is an element of the resilience model that is not exclusively defined by the representative scenario evaluated. This means that it is recommended to vary this parameter to observe how different

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<sup>34</sup> Despite establishing that the future market being more inclined towards the mono-Si technology in this scenario, multi-Si one has been chosen because later when estimating the environmental impacts of the system, the model that has used as basis ([Besseau et al., 2023](#)) is adapted for multi-Si PV cell technologies.

decision-making profiles affect the results of the resilience study. For *FuturePV*, four profiles are tested:

1. *0% repowering*: Decision-makers that would always choose to repair when they can.
2. *10% repowering*: Decision-makers that would mostly opt to repair of the time so there is only a 10% probability of deciding to repower.
3. *50% repowering*: Decision-makers with a more leveraged perspective who would choose to repair 50% of the time.
4. *100% repowering*: Decision-makers that will always choose to improve the production capacity, therefore will never choose to repair.

The only **hazard** the PV infrastructure is exposed to is strong wind, represented by the probability of occurrence of wind gust throughout three distinct decades. Per iteration representing a year, the resilience model uses the hazard dataset to choose a wind gust value and compares it to the absorptive capacity of the critical infrastructure.

The **absorptive capacity** and the **shock levels** are both described by the fragility curve determined for *FuturePV* (see §4.2.2.2), which represents the probability of PV panel failure under given wind gusts. To estimate the potential damage that the PV infrastructure could be subject to per year, the following considerations are made.

(Equation 4. 1) represents the fragility curve for each PV panel in the whole 1 MWp PV system in the baseline infrastructure. This installed power is equivalent to approximately 3530 panels, each having a corresponding probability of failure or damage which are assumed independent from each other. With this, it can be established that a binomial distribution ( $B$ ) describes the probability of a certain number of PV panels ( $N_{PV}$ ) break with a probability given by the fragility curve ( $q$ ). Thus, the binomial distribution  $B(N_{PV}, q)$  has the following characteristics:

- Expected value, or mean:  $E(B) = N_{PV}q$
- Variance:  $V(B) = N_{PV}q(1 - q)$

Because the sample size of panels is large this binomial distribution can be approximated by a normal distribution, according to the De Moivre-Laplace theorem:  $B(N_{PV}, q) \sim N(N_{PV}q, N_{PV}q(1 - q))$ , where:

- The expected value of the normal distribution is equal to the expected value of the binomial distribution:  $E(N) = E(B) = N_{PV}q$
- The standard deviation of the normal distribution  $\sigma(B)$  is equal to the square root of the variance of the binomial distribution:  $\sigma(N) = \sqrt{V(B)} = \sqrt{N_{PV}q(1 - q)}$

Moreover, we can assume that damage to the PV system is proportional to the damage to all PV panels,  $D = \frac{B}{N_{PV}}$ . Therefore, the damage function can also be approximated by a normal distribution with the following characteristics:

- Expected value:  $E(D) = q$
- Standard distribution:  $\sigma(D) = \frac{\sqrt{q(1-q)}}{\sqrt{N_{PV}}}$

For Future PV, the infrastructure resilience model has been developed as a code based on Python 3. Two files were created: **druid\_resilience.py**, and **druid\_resilience\_main.py**<sup>35</sup>. These are related to the functions of the code and the main code itself, respectively. To test the model, 100,000 Monte Carlo simulations were performed for each decision maker profile and the two variations of the repowering threshold, amounting to a total of 800,000 Monte Carlo simulations across 8 different studies. As an output, the resilience model generates a *pickle* file that can be used in other Python codes. It contains the following information per simulation:

- A list with the annual electricity production for the 30-year period,
- A list with the annual intensity of damages for the 30-year period,
- A list with the annual wind gust intensity for the 30-year period,
- A list with the type of event that may happen per year for the 30-year period,
- A variable that stores the year the repowering event may happen. If no potential repowering event is registered, then the value is set at -1 because it is out of the range of the possible repowering years.

#### 4.3.2.2. Results and discussion

Figure 4. 11 represents the electricity production performance for the case when no shocks affect the infrastructure in the course of 30 years, thus it is possible to visualize how the electricity produced each year decreases due to the effects of module degradation. In contrast, Figure 4. 12 shows a potential case where two different repair-type events occur throughout the lifespan and another case with some repair events and a repowering event where the yearly electricity production increases in the later years.

Because the current version of the model iterates on an annual basis, it only provides information on the overall effects of repair or repowering-type events in the year. This means that the model assumes that only one shock may impact the infrastructure per year, which ignores the possibility of multiple events throughout different seasons of the year. This is meant to be compatible with risk estimations that set annual probabilities.

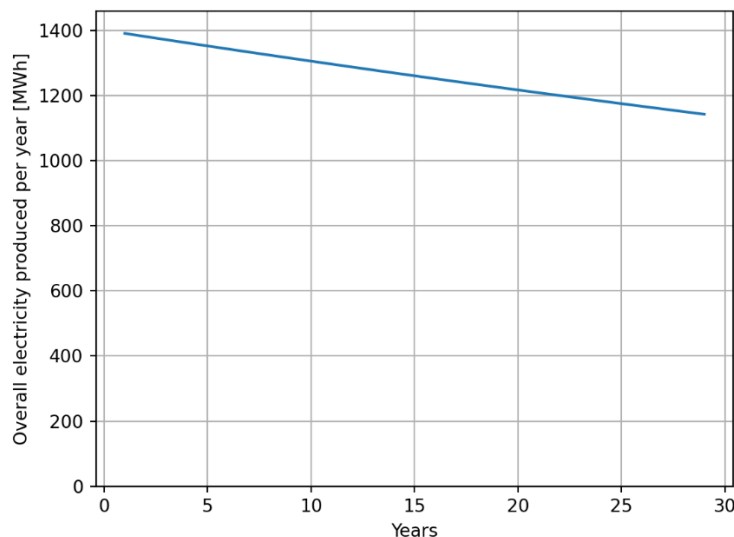


Figure 4. 11. PV infrastructure electricity production performance with no shocks

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<sup>35</sup> The code will be made available after the PhD thesis defense.

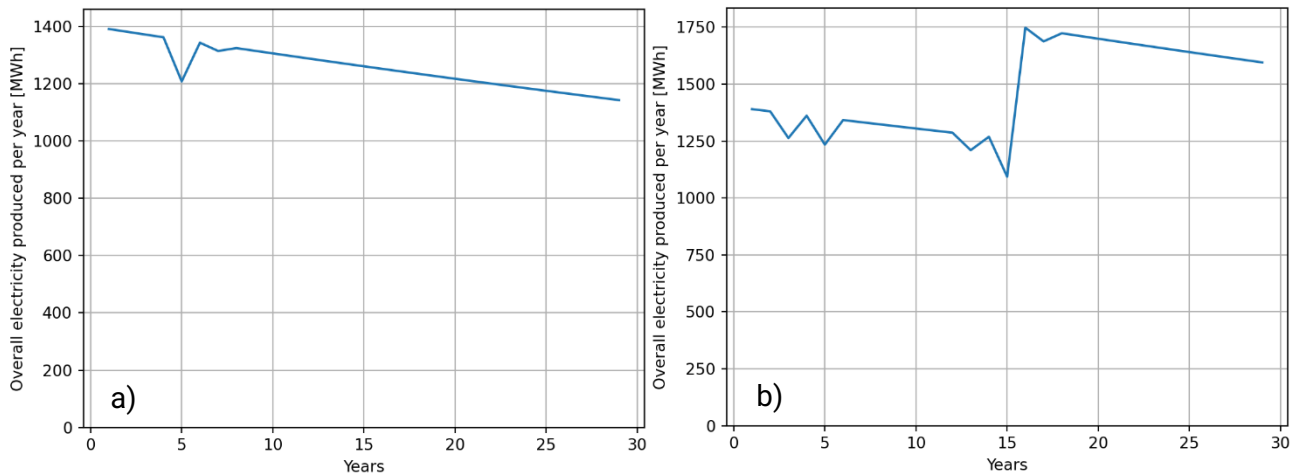


Figure 4. 12. Examples of PV infrastructure electricity production performance with a) 2 shocks, and b) several shocks with repowering

Repair-type events as expressed in the resilience model reset the production capacity of the PV infrastructure to what it should be for the next year, including the respective reduction due to the degradation rate. A more complex version of the model should represent that there was a slight increase of the production capacity that is proportional to the percentage of the repaired PV modules. At present, storing this information would make the model computationally heavier and not as efficient to run thousands of Monte Carlo simulations in a couple of minutes. Tests would need to be done to see if these additional details would change the results significantly and therefore check if a more complex model would be more valuable despite its expected extended run-time.

Figure 4. 13 depicts distribution of damages modeled throughout the 800,000 Monte Carlo simulations. As expected, it is observed that in an overwhelming majority of years the PV infrastructure suffers no damage and thus continues to operate as usual. Most instances of damage occur between 0.028% and 1% of the PV infrastructure, which for the baseline system represents damage to components related to a range of 0.28 kWp to 10 kWp of installed power. For the baseline PV system with a total of approximately 3530 modules, this loss is equivalent to having between 1 and 35 potentially damaged PV modules.

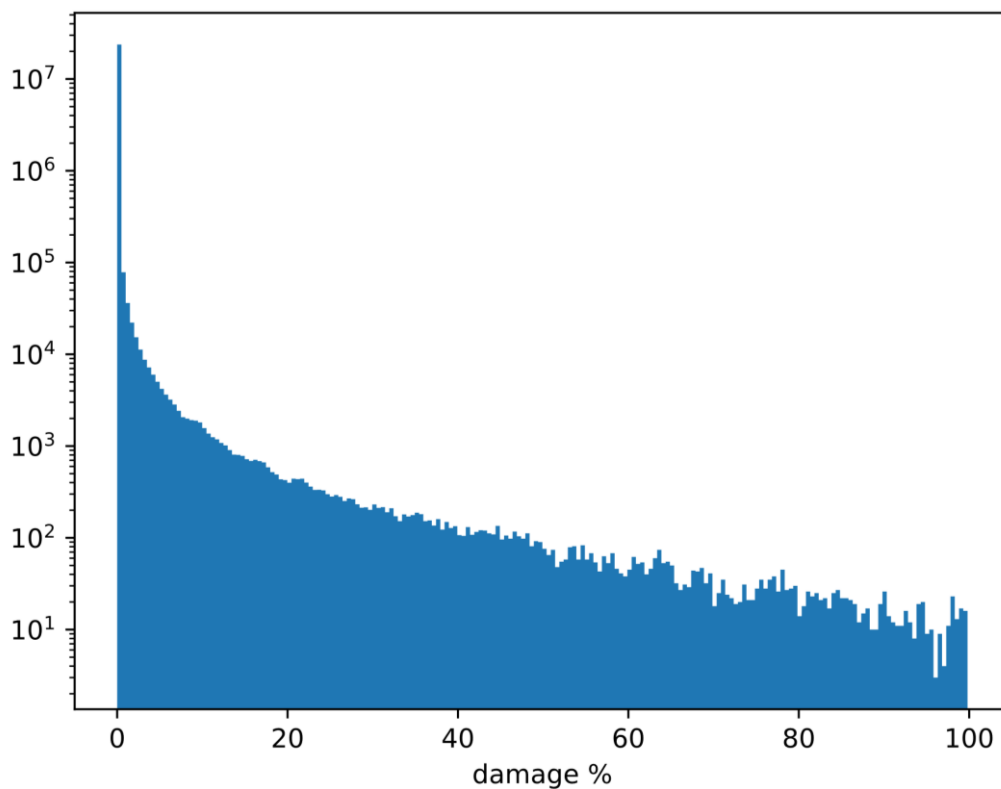


Figure 4.13. Distribution of shock intensity on the PV infrastructure, including all tested decision profiles, logarithmic scale

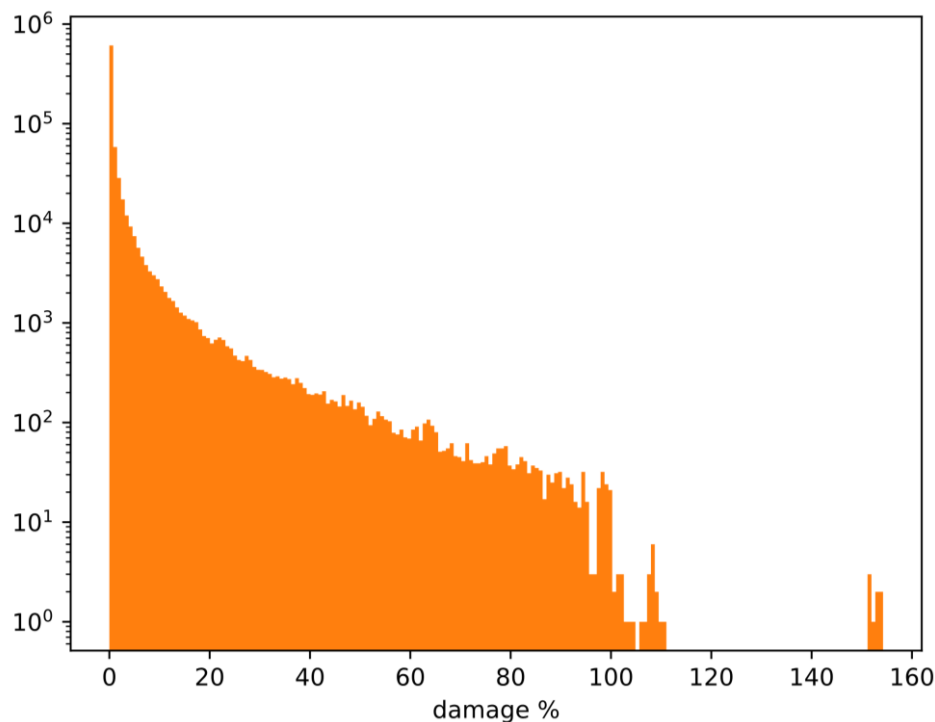


Figure 4.14. Distribution of accumulated damage to PV plant throughout the 30 years, logarithmic scale

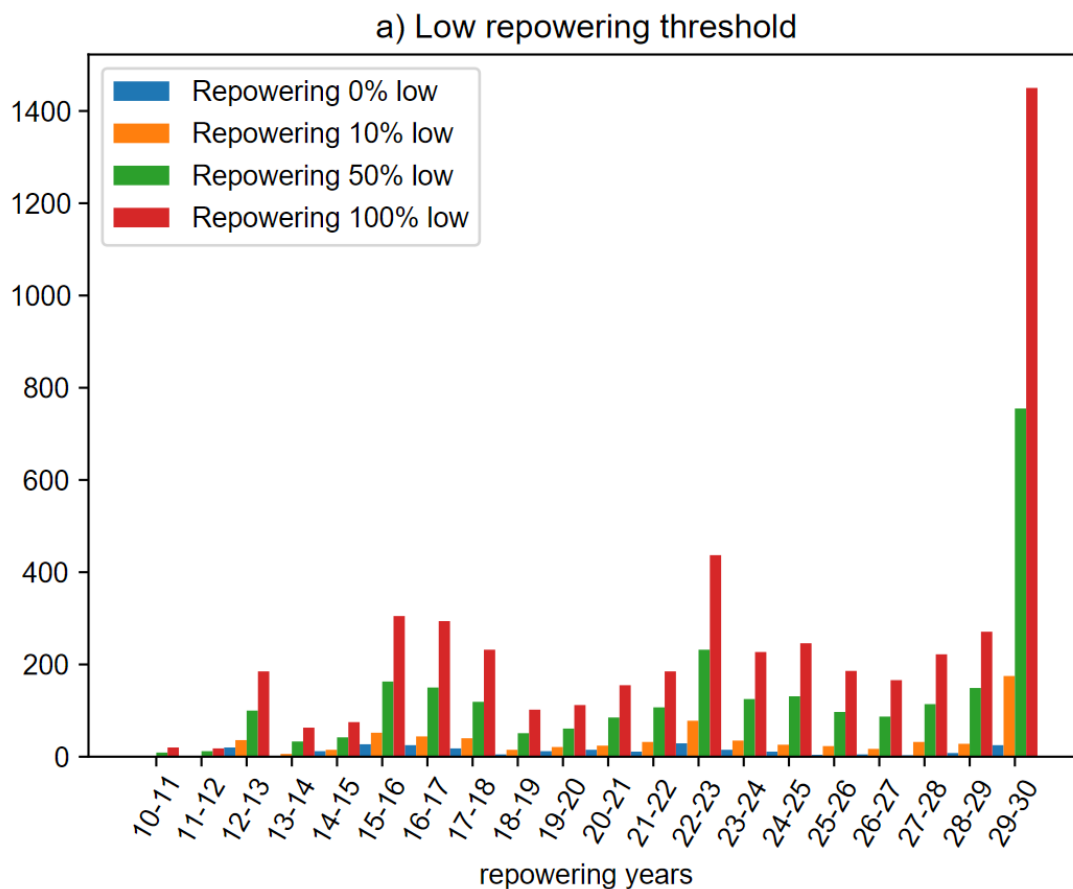
The average number of shocks that cause damage to the PV infrastructure throughout the studied 30-year period is 1.13, meaning that at least one event could happen during the expected operational lifespan of the PV infrastructure. In Figure 4.14, it can be observed that the infrastructure may suffer a cumulated damage that also tends to the minimum 1% of its total components, with a mean of

1.75% damage. Additionally, in 31.5% of cases the PV infrastructure does not suffer from any damage at all throughout its operational lifespan.

Figure 4. 15 shows the frequency of the repowering events throughout the years for the four decision profiles and the two repowering thresholds. It starts on the 10<sup>th</sup> year because, in the model, it is assumed that decision-makers will not contemplate the alternative of repowering before the 10<sup>th</sup> year of operation.

In both histograms, some 'spikes' in repowering events are observed between years 12-13, 15-18, and 22-29, especially in the 50% and 100% repowering decision profiles. When comparing Figure 4. 15 with the box plots depicting wind gust values throughout the 30-year period (see Figure 4. 16), the 'spikes' correspond to years when a relatively higher number of wind gust data outliers reached a value above 40 m/s, which has an associated probability of PV failure of 18% (see Figure 4. 8). The fragility function is very sensitive to different wind gust values, for example, 38 m/s wind gust has a 9% probability of failure while 45 m/s and 50 m/s have a 50% and 79% probability of failure, respectively.

The peak at the 29-30 year mark is explained by the repair threshold, which is estimated based on the annual electricity production at the 30<sup>th</sup> year for the undamaged baseline PV system. So, the repair threshold is expectedly breached with the slightest damage to the PV infrastructure, which for a 100% repowering decision profile means to instantly decide to repower. Finally, it is worth noting that a decision to repower at the end of the PV system's lifespan is akin to deciding to renew the project with new infrastructure that will operate for another 30-35 years.





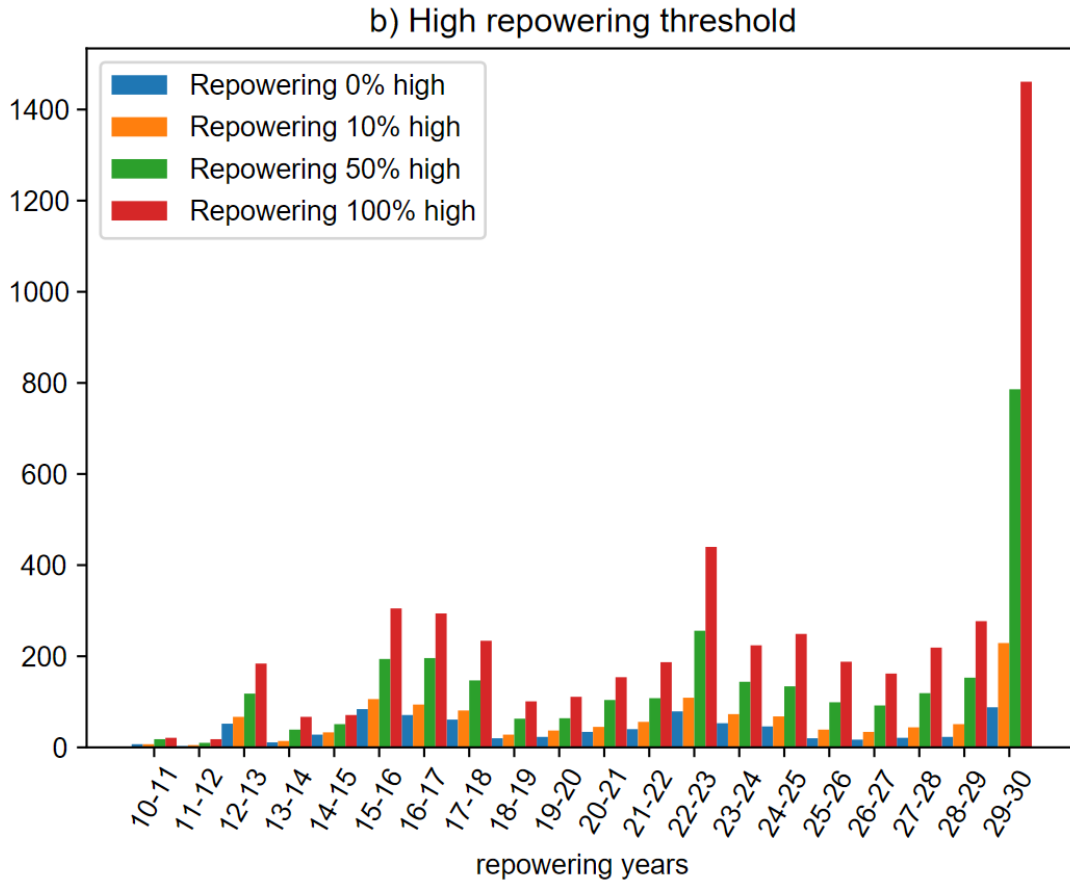


Figure 4. 15. Frequency of repowering events per year for a) the lower and b) the higher repowering threshold

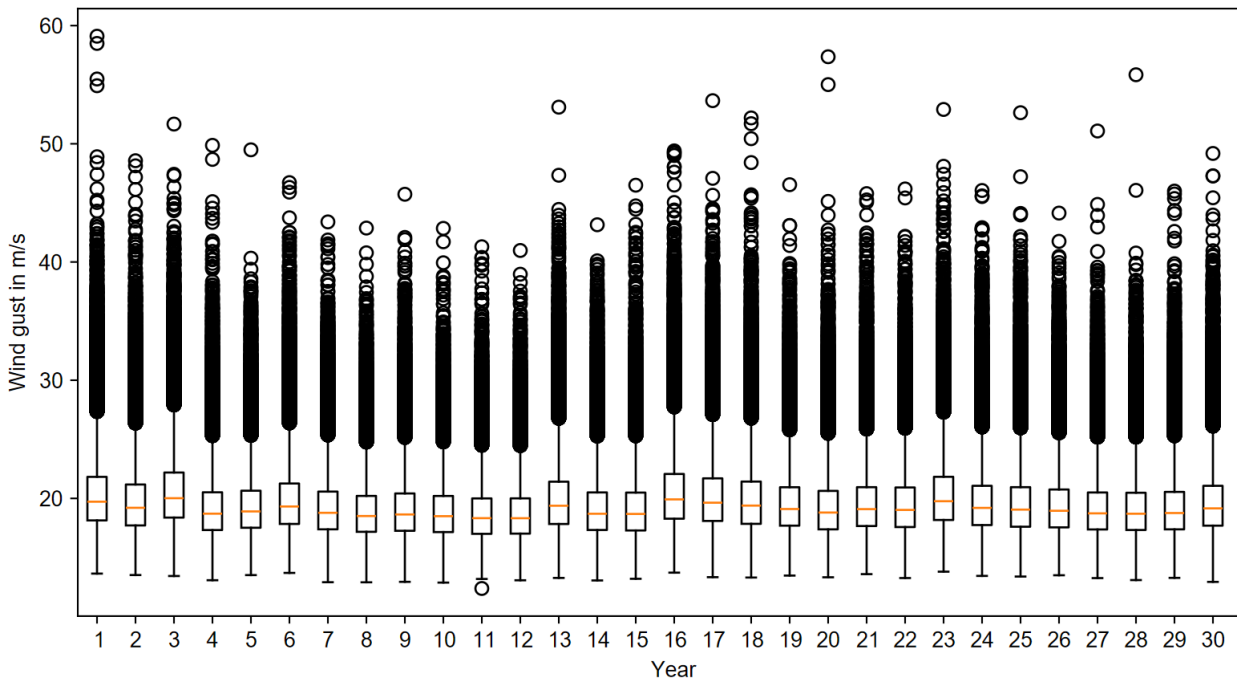


Figure 4. 16. Box plot of wind gust values over the years

For both repowering thresholds, the 100% repowering profile has the same behavior, with 4.3% of the Monte Carlo simulations having a repowering event. This similar behavior is expected given that the only way a repair event would occur is if a shock does not push the performance beyond the repair

threshold. In contrast, the 0% repowering profile only depicts the cases when the shocks push the performance beyond the repowering threshold, which amount to 0.22% of the total events (repair plus repowering) for the lower repowering threshold, as shown in Table 4. 15.

As expected, repowering events happen more frequently when establishing a higher repowering threshold. However, from the obtained results, it appears that as the likelihood that a decision-maker chooses repowering over repair increases, the importance of the value of the repowering threshold decreases.

Table 4. 15. Comparison of different performance threshold hypotheses for the repowering events

Decision maker profile	Repowering events			
	Threshold = 0.75*1,134 MWh		Threshold = 0.5*1,134 MWh	
	Occurrences	% of total events	Occurrences	% of total events
0% likelihood to repower	781	0.69%	248	0.22%
10% likelihood to repower	1220	1.08%	701	0.62%
50% likelihood to repower	2895	2.55%	2622	2.31%
100% likelihood to repower	4967	4.38%	4951	4.37%

0

A specific observation to make on the case study is that there are many hypotheses made to try to represent risks and their consequences in a quantitative way. These hypotheses pose situations for which there is not enough data and could be difficult to obtain in a more exhaustive version of the case study. However, for other types of risks this information might be easier to obtain. For example, in the case of flooding hazards, the fragility curves associated to the absorptive capacity measures of PV installations assume either no failure below a 1-meter threshold or complete failure above said threshold (Di Maio et al., 2022). Therefore, the probability of failure or damage depends on the probability that the flooding level breaches the failure threshold.

Moreover, the resilience model has yet to include the influence of complex disaster risks, which requires a good understanding of the causal relationships that these events imply. This will be a difficult task, therefore it could be addressed in future research.

Overall, it has been observed that the resilience model provides an estimation of the expected damages for a representative scenario and allows for comparisons between different decision maker profiles.

## Conclusion

Throughout this chapter the first three steps of the iterative *DRUID method* have been presented, which aid in the study of the potential consequences of disaster risk on the performance of a critical infrastructure, including potential damages and the post-damage decisions made by different types of decision-makers. This development has been motivated by the second scientific question of this PhD thesis.

The illustrative case study, *FuturePV*, has been used to show the capabilities of the *DRUID method*, from the definition of the problem to the data collection for the study, the building of the scenarios,

the description and the identification of a representative scenario, and the study of the resilience of the critical infrastructure under the chosen scenario.

The development of the *DRUID method* is supported by the concepts presented in Chapter 3, and the method itself proposes an approach to reach its objectives without prohibiting a practitioner from using different tools than those recommended, such as the software used for the resilience study. The latter aspect is very important because the model does not impose structures to, for example, store the collected data or perform the resilience study. The goal is to provide guidance on how this kind of study could be done and complement the abstract methodological aspects with a concrete example. The *FuturePV* case study, although relatively simple, showcases the fundamental aspects of what the *DRUID method* contributes to the study of the consequences of disaster risks on the performance of a critical infrastructure. Of course, there are still some capabilities of the *DRUID method* that ought to be tested in a future version of the case study, namely carrying out the resilience study with the effects of complex risks.

The results produced throughout steps I, II, and III of the *DRUID method* are used to contextualize and establish the key aspects to be evaluated in the fourth step of the *DRUID method*, namely the scenario transfer in the context of the Life Cycle Inventory. Its purpose is to coherently link the consequences of damages to the infrastructure caused by disaster risks to its related environmental impacts, aiming to analyze the changes in the environmental performance of the critical infrastructure between a situation without shocks and scenarios with shocks. This is the subject of Chapter 5.

## Chapter 5. Performing a Disaster Risk-guided Life Cycle Assessment with DRUID LCI

### Introduction

Life Cycle Assessment (LCA) is probably the most common method to evaluate the potential environmental impacts of products and systems all over the world. As addressed in Chapter 1, LCA is usually applied to model systems according to their average operation conditions, meaning that situations that may induce deviations are not considered in the inventory analysis phase. Unfortunately, these assumptions could present unrealistic situations to decision-makers, especially in critical infrastructures such as energy production systems, where deviations from average conditions are bound to happen in their lifespan.

Throughout this project, evolving disaster risks have been identified as important sources of possible deviations and damages to critical infrastructures that should be considered in LCA. Not doing so means that the potential environmental impacts of critical infrastructures are being underestimated, which could have significant and unwanted consequences on the decisions made from these analyses. To facilitate the consideration of the effects of disaster risks on the life cycle inventory (LCI) and resulting environmental impacts of a critical infrastructure, this PhD thesis proposes the Disaster Risk-guided scenario Definition (DRUID) Method – LCI Module. DRUID LCI is a four-step iterative method meant to define scenarios supporting the description of potential consequences of evolving disaster risks in the environmental performance of a critical infrastructure. Chapter 4 addressed the first three steps of the method, namely i) problem definition, ii) scenario building and iii) infrastructure resilience study, providing details on the approach and an illustrative example through the case study called *FuturePV*.

The objectives of Chapter 5 are to illustrate the application of DRUID LCI to an LCA study using *FuturePV*, and to present the approach taken to develop the fourth step of DRUID LCI, which is the scenario transfer to LCI. Furthermore, LCA results with and without using DRUID LCI are compared to highlight the contributions of the method and discuss its areas of opportunity. The example follows the same representative scenario illustrated in Chapter 4. All of this is done to answer the third scientific question:

*How could the results from the disaster risk-guided scenarios be included at the Life Cycle Inventory level so that they represent relevant decision-support elements? How can LCA results produced using these scenarios be presented so that they are useful and relevant to decision makers?*

The structure of this chapter follows the typical four phases of LCA defined in ISO 14040 (ISO 14040, 2006) specifically for the *FuturePV* case study, as shown in Figure 5. 1. First, the goal and scope definition phase is addressed. Then, the LCI and LCIA for the baseline scenario and DRUID scenarios are presented, including a detailed explanation of the DRUID scenario transfer approach. Finally, the LCIA results are discussed.

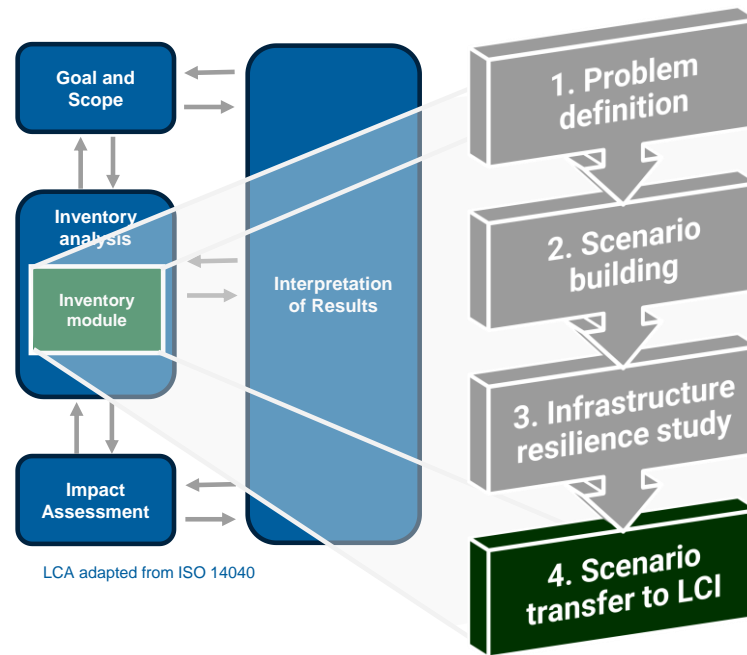


Figure 5. 1. Focus on the LCA application of the DRUID method - LCI module and the scenario transfer step

## 5.1. Goal and Scope Definition

### 5.1.1. Purpose of the study

The **purpose of the study** is, for an illustrative case study on a PV infrastructure project, to investigate how and why the environmental impact results change between scenarios that consider the disturbances on the product system operations caused by evolving disaster risks, compared to standard scenarios without disturbances. The specific objective is to test DRUID LCI in an illustrative case study and compare the results obtained throughout the phases of LCA with the application of DRUID LCI versus a conventional LCA of the baseline scenario.

The illustrative case study is *FuturePV*, which has been posed in Chapter 4 to describe a representative DRUID scenario with its alternatives derived from the resilience study. The baseline scenario shares the same technical characteristics of the PV system as the DRUID scenarios. However, the baseline scenario does not use DRUID LCI, meaning that disaster risk-guided scenarios and their potential effects on the environmental impact results are not considered.

### 5.1.2. Functional unit

The **functional unit** for the evaluated system is defined following the recommendation of the International Energy Agency PVPS Task 12, thus it is related to the “AC electricity delivered to the grid quantified in kWh” (Frischknecht, Stolz, Health, et al., 2020). Specifically, the functional unit for *FuturePV* is **the production of 1 kWh of electricity by a photovoltaic (PV) installation, considering an operational lifetime of 30 years in the South-East of France**. The 30-year period is based on the life expectancy of most components in an actual PV infrastructure. The case study considers that components of the PV infrastructure may be damaged during disaster risk events. If they are indeed damaged, they would need to be replaced with new components. In practice, these replaced components could still work after the 30-year period because they would have only operated for a portion of their expected lifespan. Therefore, to permit a fairer comparison between the baseline scenario and the scenarios defined using DRUID LCI, it has been decided to keep the 30 years as the period of evaluation for the potential environmental impacts of the PV infrastructure.

### 5.1.3. Impact categories

The **life cycle impact assessment (LCIA) categories** considered for the assessment are the Ecological Footprint (EF) version 3.0 midpoint impact categories based on their no long-term (no LT) indicators, meaning that it excludes emissions beyond 100 years (Fazio et al., 2018). The specific impact categories to test are shown in Table 5. 1.

Table 5. 1. LCIA categories from EF 3.0 no LT (Fazio et al., 2018)

Impact category	Indicator	Unit	Recommended default LCIA method
<b>Climate change</b>	Radiative forcing as Global Warming Potential (GWP100)	kg CO <sub>2</sub> eq	Baseline model of 100 years of the IPCC (IPCC, 2013)
<b>Ozone depletion</b>	Ozone Depletion Potential (ODP)	kg CFC-11eq	Steady-state ODPs as in (WMO, 1998)
<b>Human toxicity, cancer effects</b>	Comparative Toxic Unit for humans (CTU <sub>h</sub> )	CTU <sub>h</sub>	USEtox 2.1. model (Rosenbaum et al., 2008)
<b>Human toxicity, non-cancer effects</b>	Comparative Toxic Unit for humans (CTU <sub>h</sub> )	CTU <sub>h</sub>	USEtox 2.1. model (Rosenbaum et al., 2008)
<b>Particulate matter/Respiratory inorganics</b>	Human health effects associated with exposure to PM <sub>2.5</sub>	Disease incidences	PM method recommended by UNEP (UNEP, 2016)
<b>Ionizing radiation, human health</b>	Human exposure efficiency relative to U <sup>235</sup>	kBq U <sup>235</sup>	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al., 2000)
<b>Photochemical ozone formation</b>	Tropospheric ozone concentration increase	kg NMVOC eq	LOTOS-EUROS (van Zelm et al., 2008) as applied in ReCiPe 2008
<b>Acidification</b>	Accumulated Exceedance (AE)	mol H <sup>+</sup> eq	Accumulated Exceedance (Posch et al., 2008; Seppälä et al., 2006)
<b>Eutrophication, terrestrial</b>	Accumulated Exceedance (AE)	mol N eq	Accumulated Exceedance (Posch et al., 2008; Seppälä et al., 2006)
<b>Eutrophication, aquatic freshwater</b>	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq	EUTREND model (Goedkoop et al., 2009) as implemented in ReCiPe
<b>Eutrophication, aquatic marine</b>	Fraction of nutrients reaching marine end compartment (N)	kg N eq	EUTREND model (Goedkoop et al., 2009) as implemented in ReCiPe
<b>Ecotoxicity freshwater</b>	Comparative Toxic Unit for ecosystems (CTU <sub>e</sub> )	CTU <sub>e</sub>	USEtox 2.1. (Rosenbaum et al., 2008)
<b>Land use</b>	Soil quality index (Biotic production, Erosion resistance, Mechanical filtration and Groundwater replenishment)	Dimensionless, aggregated index of: kg biotic production/ (m <sup>2</sup> *a) kg soil/ (m <sup>2</sup> *a) m <sup>3</sup> water/ (m <sup>2</sup> *a) m <sup>3</sup> g.water/ (m <sup>2</sup> *a)	Soil quality index based on LANCA (Bos et al., 2016)
<b>Water use</b>	User deprivation potential (deprivation-weighted water consumption)	kg world eq. deprived	Available WATER REMaining (AWARE) (UNEP, 2016)
<b>Resource use, minerals and metals</b>	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq	CML (Guinée & Lindeijer, 2002)
<b>Resource use, energy carriers</b>	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ	CML (Guinée & Lindeijer, 2002)

#### 5.1.4. Background and foreground processes

Regarding the elements that will be included in the life cycle inventory (LCI), the **background** processes are modeled using the Ecoinvent reference database, version 3.9.0<sup>36</sup> cut-off<sup>37</sup>, which contains information on the supply chain for thousands of flows and processes. For the **foreground** processes, the assumptions from the IEA PVPS Task 12 (Frischknecht, Stolz, Krebs, et al., 2020) are used to model the PV system, with the inventory updates proposed by Besseau et al. (2023) for multi-crystalline silicon-based (multi-Si) PV installations. Specifically, the study considers a fixed ground mounted system located on the mountainous regions with Mediterranean climate in the south-east of France, whose PV multi-Si modules with a 17.5% efficiency were manufactured in China. The installed capacity of the PV system is 1 MWp, which would occupy a surface area of approximately 1 hectare.

#### 5.1.5. Modeling approach

The applied **modeling approach** consists in an attributional process-based LCA with a parametrized life cycle inventory model built from the PARASOL\_LCA model (Besseau et al., 2023). PARASOL\_LCA relies on the parametrization of existing LCI data, like that from Ecoinvent, to make case-specific inventories for PV systems whose parameters can be changed for evaluation. It is based on *Brightway2* (Mutel, 2017), which is an open-source Python library used as framework for LCA, and on *lca\_algebraic* (Jolivet et al., 2021), a *Brightway2*-based library that uses symbolic calculus to facilitate the parametrization of life cycle inventories and sensitivity analyses. The model presented in this PhD thesis is an adapted version of PARASOL\_LCA which mainly introduces new parameters related to DRUID scenarios and includes said parameters to the flows of the affected life cycle processes.

The development of a parametrized model permits the consideration of the effects of DRUID scenarios on the product system in an explicit way. As mentioned in the previous paragraph, the idea is to include new parameters with respect to those of PARASOL\_LCA that are linked to the processes of the product system representing the changes that happen because of disaster risks affecting the infrastructure. This way, a practitioner can, on the one hand, observe the changes happening on the LCA model through the parameters related to DRUID scenarios, and, on the other, have the possibility to test different parameter values and study specific changes on the LCA results.

It must be mentioned that the method developed in this PhD refers to decision making contexts addressing the consequences of changes that happen in the product system because of marginal changes. For this reason, a consequential modeling approach might be a more appropriate LCA approach objective-wise. However, because the focus of the PhD thesis is the development of the DRUID LCI method it was decided to build the LCA model from the parametrized model and PV inventory that had already been established by PARASOL\_LCA, keeping its base hypotheses and assumptions which are related to attributional LCA. Another reason that justifies the choice of using attributional LCA is because the case study addresses a single PV infrastructure, which is a case that an attributional LCA model is better adapted for.

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<sup>36</sup> Ecoinvent 3.9 webpage (Last accessed: June 2024): <https://support.ecoinvent.org/ecoinvent-version-3.9>

<sup>37</sup> Polluter-pays principle, where wastes are the producer's responsibility, and using recyclable products is incentivized. Information from: [https://support.ecoinvent.org/system-models#Allocation\\_classification](https://support.ecoinvent.org/system-models#Allocation_classification)

### 5.1.6. System boundaries

The **system boundaries**, which are the general processes that are considered in the LCA study, are as seen in Figure 5. 2. The processes considered are the manufacturing for the multi-Si modules, the mounting system, the electric installation, and the inverter; the transportation from the manufacturing country to the installation site; the installation; the operation of the PV system; and the recycling of some materials. The consideration of the end-of-life process of recycling is done in accordance with the cut-off approach (Ecoinvent, 2024).

Because the product system is built on PARASOL\_LCA, the process related to recycling of materials only includes glass, aluminum, and copper. However, more detailed end-of-life processes are otherwise not considered in the current iteration of the project. In the future, this aspect should be reinforced because of the potential influence of the end-of-life processes when evaluating the product system with DRUID scenarios.

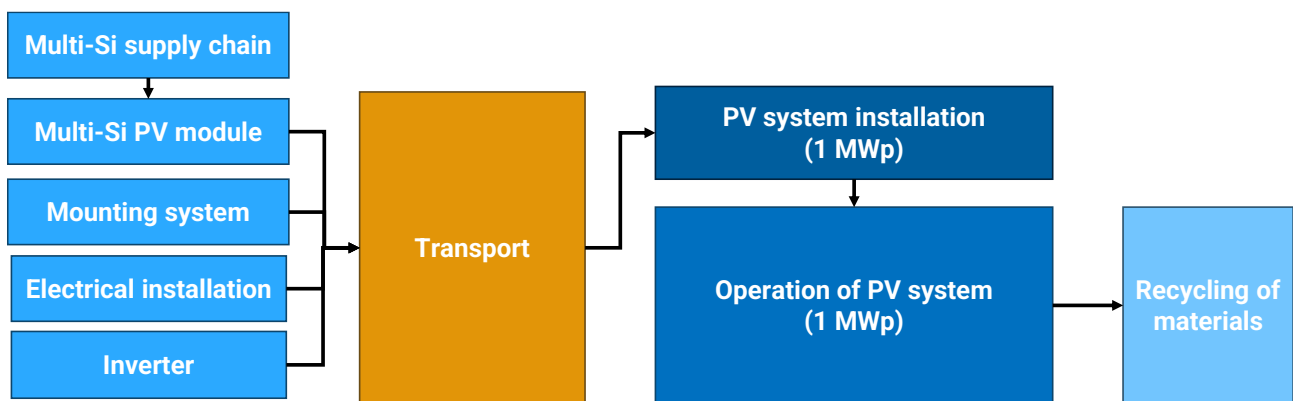


Figure 5. 2. System boundaries of the PV infrastructure

## 5.2. Model Development - Inventory Analysis and Impact Assessment

This section is dedicated to the LCI and LCIA steps for *FuturePV*. In subsection 5.2.1, a conventional LCA modeling approach is described, including the LCI model used for the baseline scenario, followed by the impact model. These represent the reference from which the DRUID LCI model will be based on. Subsection 5.2.2 describes the application of DRUID LCI, explaining in detail the fourth step of the method, the scenario transfer, followed by its application to *FuturePV*.

### 5.2.1. Reference model using conventional parametrized LCI

A parametrized model is used to perform the Life Cycle Inventory (LCI) analysis, therefore it is necessary to first define the reference model (Perez-Lopez et al., 2020). In this case, PARASOL\_LCA is the reference model, consisting of 35 five parameters described throughout five major processes: manufacturing, transport, installation, operation, and recycling (see Figure 5. 3). PARASOL\_LCA was developed to enable the consideration of improvements in the PV industry that are not represented in the Ecoinvent database, and to permit the exploration of “the prospective environmental performance of PV systems with a multicriteria perspective by varying the large set of parameters defined, which can be of interest to PV stakeholders in an eco-design perspective” (Besseau et al., 2023).



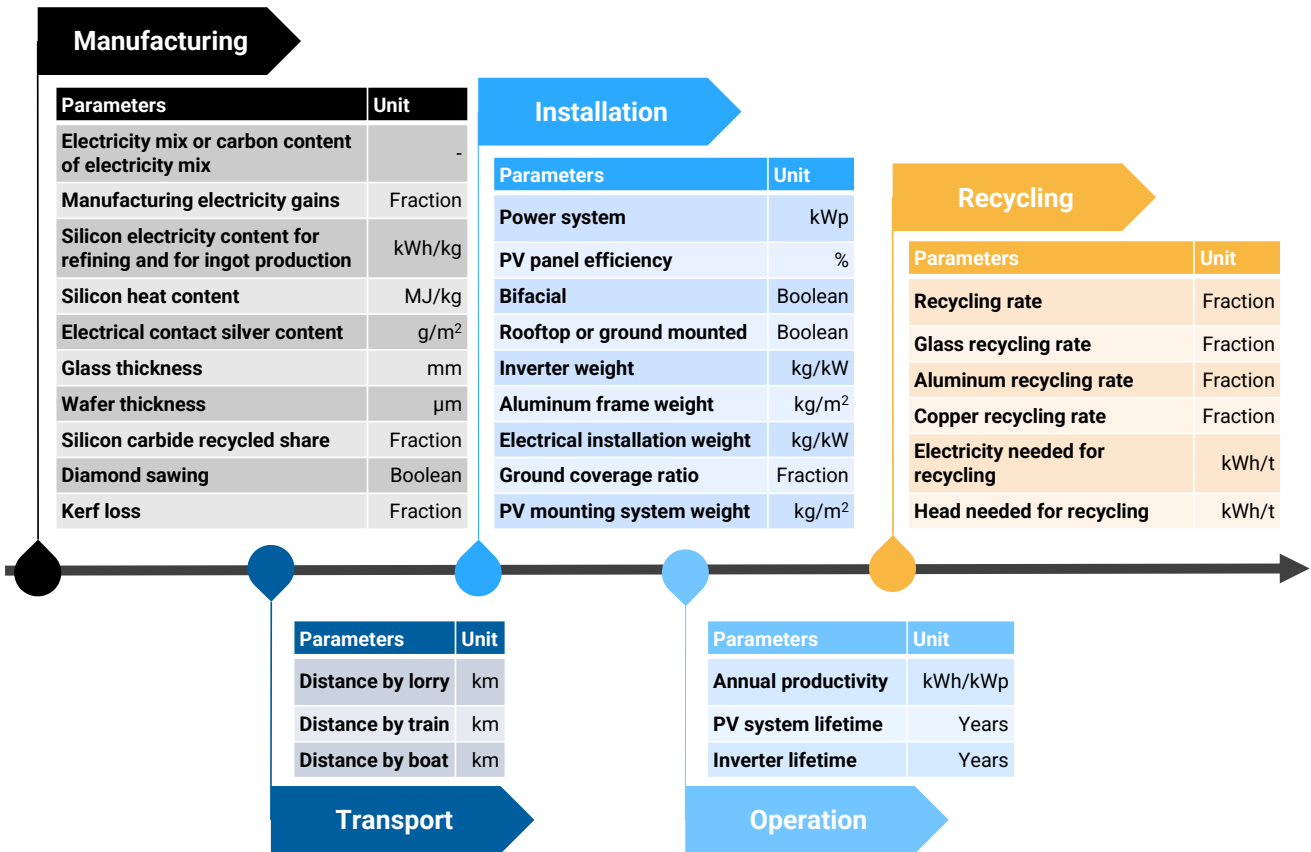


Figure 5. 3. Graphical representation of PARASOL\_LCA parameters, from (Besseau et al., 2023)

For the baseline PV model of *FuturePV*, PARASOL\_LCA is used to describe the PV infrastructure project. The values considered for PV systems in the LCI model are those suggested in PARASOL\_LCA’s publication (Besseau et al., 2023) and in the inventory recommendations from PVPS Task 12 (Frischknecht, Stolz, Krebs, et al., 2020). The specific values established for the system parameters in *FuturePV* are described in Annex II.

For the environmental impact assessment, the impact model is based on the environmental impacts of each life cycle process (see Figure 5. 3) expressed per functional unit, meaning 1 kWh of electricity produced by the PV system. These are evaluated per impact category considered, as stated in section 5.1.3. The LCIA is performed using the open-source Python libraries *Brightway2* (Mutel, 2017) and *lca\_algebraic* (Jolivet et al., 2021).

### 5.2.2. Application of DRUID LCI

To define the PV model including the elements that DRUID scenarios introduce, the four iterative steps that make up DRUID LCI are applied (see Figure 5. 4). The information from the LCA goal and scope definition phase provides the first clues and information to start applying the method. The DRUID LCI module steps and results presented throughout Chapter 4 are directly linked to the *FuturePV* LCA study in this chapter, therefore the results of the resilience study for the representative scenario ‘SSP-RCP 4.5 | No land use change | RTE reference’ (see §4.3.2) are used as inputs to define the DRUID LCI model through the scenario transfer step.

This subsection focuses on the description and application of the **fourth step of the DRUID LCI method, the scenario transfer to LCI**. The scenario transfer step involves three activities: i) the

identification of life cycle processes, ii) the identification of flows and parameters, and iii) the definition of the impact model.

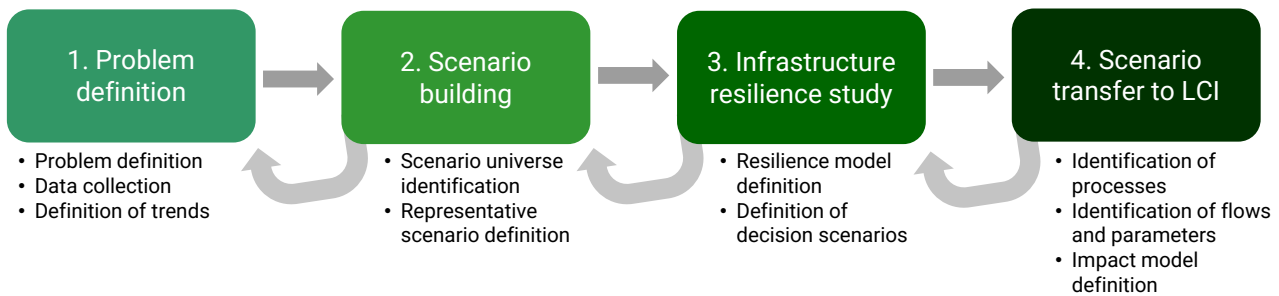


Figure 5. 4. Disaster Risk-guided scenario Definition (DRUID) Method – LCI Module steps

The objective of the scenario transfer step is to define a life cycle inventory model to study the consequences of disaster risks on the environmental performance of the studied critical infrastructure. Specifically, the purpose is to transform the outputs of the infrastructure resilience study into compatible flows and processes that form part of the LCI model of the critical infrastructure. These flows will be quantified and cohesively interpreted in the posterior impact assessment.

Ideally, the defined DRUID LCI model ought to be compatible with and adaptable to the different representative scenarios that could be assessed in the resilience study. Therefore, the said model should share the same characteristics across scenarios, be easily editable, and consistently provide the outputs in the same format. Alternatively, the model could have an adjustable parameter for each scenario characteristic that can be different. With this in mind, LCA models that could fulfill this purpose were looked into.

Parametrized LCA models have the capacity to consider temporal, spatial, and technological variability of product systems, using input parameters to describe selected flows (Besseau, 2019; Tannous et al., 2019). Because of the desired characteristics for the DRUID LCI model mentioned in the previous paragraph, a parametrized LCA model was chosen as basis.

Thus, the DRUID scenario transfer step consists of defining parameters and processes that represent the results from the resilience study, and cohesively integrating them with the reference parametrized LCA model to develop the parametrized DRUID LCI model of the critical infrastructure.

The DRUID scenario transfer step consists of three general tasks. **First**, the life cycle flows and processes that are affected by repair and replacement-type events need to be identified. For each type of event, supplementary processes that will change the original system boundaries are included. It is expected that replacement-type events will cause the inclusion of a second version of the product system, and repair-type events introduce supplementary maintenance activities. For example, a 10% damage to the PV modules trigger repair events that must change the damaged modules for equivalent components. Thus, in this case, the maintenance process is linked to the upstream processes of manufacturing these new PV modules. **Second**, the flows that are specifically affected by the events are revisited to determine which ones can be parameterized. Clear relationships between the information from the resilience study and the parameters must be established when defining these parameters. **Third**, the algebraic equation representing the impact model that relates the impacts from all the processes to the functional unit is established considering the modifications made because of the new processes, flows, and parameters.

The DRUID LCI-related parameters that should be defined are linked to the failures of and disturbances to the life cycle flows and processes of the infrastructure because of disaster risks and their consequences. In general, two major types of parameters can be identified, which are those related to the repair-type events and the replacement-type events.

From the data collection on the absorptive capacity, the practitioner already has an idea of how infrastructure failures are defined, which usually are directly related to infrastructure damages (see §4.1.2.4 and §4.1.3.4). Furthermore, in the description of the elements of the resilience model, the nature of the effects of disaster risks on the infrastructure are described for each shock level, as well as the meaning of each repair or replacement-type event for the studied infrastructure (see §4.3.1). Using this information as support, it is possible to determine what processes and flows should be changed and/or added to the LCI of the product system in order to represent the failures and disturbances induced by disaster events.

#### 5.2.2.1. Identification of processes

The *FuturePV* resilience study was performed for the representative scenario, exploring four different decision maker profiles (see §4.3.2), ranging from the most conservative that favors repairing as much as possible, to the most performance-oriented that favors replacement. In total, 100,000 Monte Carlo simulations were performed per profile, and the following information was obtained for each one:

- The overall electricity production per year,
- A list with the intensity of shocks per year,
- A list of events per year, and
- The year a replacement-type event took place.

As explained in Chapter 4, two types of events are possible depending on how the effect of the corresponding disaster event on the infrastructure is addressed.

**Replacement-type events** represent situations where the infrastructure is repowered, meaning that all the components of the critical infrastructure are changed for new and better performing technologies without the reuse of parts (Herceg et al., 2022) regardless of the level of damage they suffered. The purpose is to increase the annual electricity production (kWh per year) by increasing the installed capacity whilst using the same surface area that was occupied by the original infrastructure (kWp/m<sup>2</sup>). Considering this definition, the representation of repowering in the LCI requires the consideration of a second product system with different technologies that operates for a certain period of the 30-year operational lifespan considered for the study. This secondary product system for the repowered PV infrastructure uses the same life cycle processes as the first product system for the base PV infrastructure. This is a pessimistic case in which PV components built in the future would have no gains in terms of manufacturing efficiency, and therefore have the same material and energy consumption and pollutant emissions.

**Repair-type events** represent situations where the electricity production capacity of the critical infrastructure is reestablished to its original level by changing the damaged components for new components with the same characteristics. This means that the damaged components per event must be accounted for, as well as all the life cycle processes required to get the system back to regular operations. The components considered in the product system are the PV modules, the

mounting system, the electrical installation, and the inverter. Naturally, these events are also related to the repowered PV infrastructure.

With these established links, the system boundaries of the product system are updated as shown in Figure 5. 5. The new system boundaries are separated into two distinct systems.

The first system is the baseline PV system (see Figure 5. 5. a), and the processes considered are the manufacturing of the multi-Si modules, the mounting system, the electric installation, and the inverter; the transportation of all those components from the manufacturing country to the installation site; the installation; the operation of the PV system, and the maintenance. The latter concerns the repairing activities of damaged components. The second system is the repowered PV system (see Figure 5. 5. b), and the flows and processes considered are the same as those in the baseline PV infrastructure.

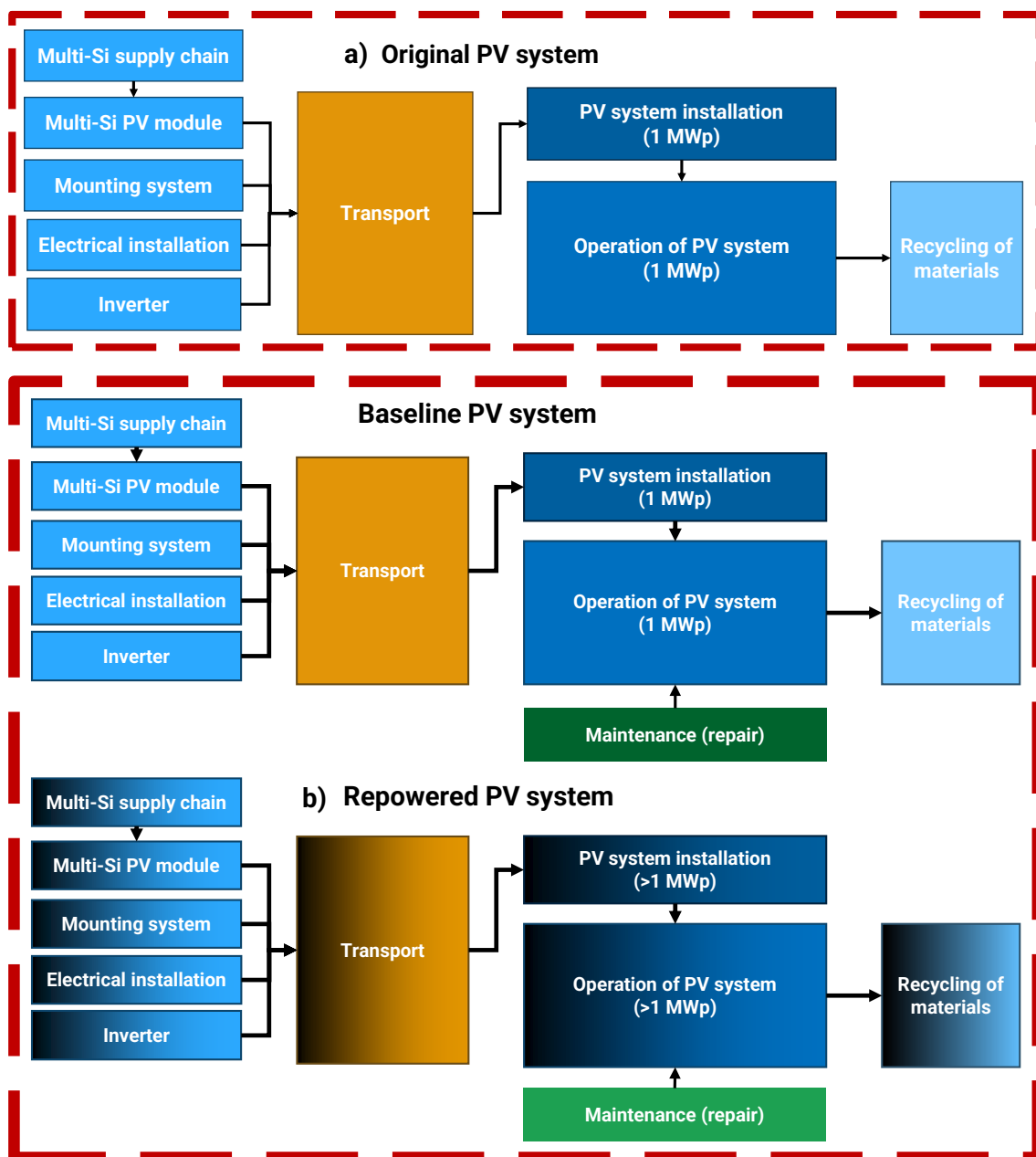


Figure 5. 5. Comparison of a) the original system boundaries for the PV system with an average lifespan of 30 years, and b) the updated system boundaries that include the baseline PV system, and the repowered PV system

The updated system boundaries facilitate the task of identifying the flows that can be parametrized. In this case, the maintenance processes and the repowered PV system contain all the elements that intervene after the infrastructure experiences a repair or a repowering event.

#### 5.2.2.2. Identification of flows and parameter definition

For the **repowered PV system**, the corresponding reference flows of each process involved in the life cycle of the PV system are used to represent the new infrastructure.

In this project, repowering implies that the original surface area used by the baseline PV installation will be used in its entirety to increase the installed capacity thanks to higher efficiency of the PV modules, that permit the production of more electricity per year with the same surface. Since PV module efficiency can be turned into density of installed capacity expressed in kWp/m<sup>2</sup>, which is an input parameter of the parameterized LCA model, the installed capacity of the repowered PV infrastructure is estimated with the following equation:

$$P_2 = \eta_2 \frac{P_1}{\eta_1}$$

(Equation 5. 1)

Where:

- $P_2$  is the installed capacity of the repowered PV installation in kWp,
- $\eta_2$  is the efficiency of the repowered modules,
- $P_1$  is the installed capacity of the original PV installation in Wp, and
- $\eta_1$  is the efficiency of the original modules in.

The two new repowering parameters,  $P_2$  and  $\eta_2$ , are thus considered in the model, as shown in Table 5. 2, alongside a module degradation rate parameter.

The representative scenario modeled considers that repowering will use PV modules based on the same PV technology but with increased efficiency, therefore the same life cycle processes for both systems are considered. This is also why the degradation rate for the repowered system is the same as the one for the baseline system. Additionally, the model contemplates the changes in module efficiency throughout the period, as described in the representative scenario (see §4.2.2.), with module efficiencies for the repowered system of 22% after the first decade and 24.5% after the second decade.

Moreover, because the system will be repowered in the future, it is possible that some of the manufacturing processes of the PV module could have improved in terms of energy efficiency and material use, although this was not tested in *FuturePV*. PARASOL\_LCA allows to do these changes. However, PARASOL\_LCA was not equipped to declare the baseline PV system and the repowered PV system in the same inventory model. To obtain LCA results on both systems, it would have been necessary to run two separate instances of the parametrized model and the subsequent impact assessment, which was not ideal for our study. Therefore, some changes have been made to the original PARASOL\_LCA code for the DRUID LCI model to allow a modular definition of new processes and product systems with different characteristics.

Regarding the modeling of the **maintenance processes**, the information required is linked to the quantity of components that were damaged throughout the operational lifespan of both the baseline

and repowered system. A way to express how much of each of these components was damaged is by translating the shocks to a fraction of their reference flows. In PARASOL\_LCA, the reference flows of the PV module and the mounting system processes are expressed in surface area (reference flow in  $m^2$ ), while the electrical installation and the inverter processes are expressed in weight (reference flow in kg). The values for all these processes depend on the size of the installation, meaning the installed capacity (kWp).

Thus, the first parameters that are defined are the repair rates for each component considered, distinguishing between components in the base and the repowered PV system. This makes a total of 8 repair rate parameters, as shown in Table 5. 2.

The resilience study provides event-specific information for each lifespan iteration tested, including the year each event happened, the shock intensity, and it was a repair event on the base infrastructure, a repowering event, or a repair event on the repowered infrastructure. Repair rates are estimated from the corresponding shock level for the corresponding PV infrastructure. Since the failure description in the absorptive capacity only describes overall damage to the infrastructure, an overall repair rate is considered, and that same value is assigned to the repair rate of each component. For example, a shock level 1 represents 20% damage to the infrastructure, thus the repair rate for the PV modules, the mounting system, the electrical installation, and the inverter are all given the same value of 0.2.

However, because the parametrized LCA model does not consider the events per year as the resilience study does, the repair rate represents the sum of all the repair rates that happened throughout all the events in the corresponding period. For example, if two shocks occurred in 30 years without repowering, one causing 10% damage and the other 25% damage, then the total repair rate for all components in the base PV system is equal to 35%.

Table 5. 2 shows the parameters defined for the DRUID LCI model, and all but the temporal-type parameters have been explained so far. These parameters serve the purpose of linking the new parameters and their related flows and processes to the functional unit (FU), which is the reference value the environmental impact results will be based on.

Table 5. 2. Parameters added for the DRUID LCI model

Parameter type	Parameter name	Description	Range	Unit
<b>Replacement / Repowering</b>	PV module efficiency, repowering	Efficiency of the PV module technology used in the repowered system	0.22 OR 0.24	-
	PV installation capacity, repowering	Installed capacity of the repowered PV installation	$P_2$	kWp
	Degradation rate, repowering	Degradation rate of PV module technology used in the repowered system	0.7	Percent
<b>Repair</b>	PV module repair rate, base	Fraction of the PV modules that were repaired for the base installation	0.0 – 2.0	Fraction
	PV module repair rate, repowering	Fraction of the PV modules that were repaired for the repowered installation	0.0 – 2.0	Fraction

	Mounting system repair rate, base	Fraction of the mounting system supports that were repaired for the base installation	0.0 – 2.0	Fraction
	Mounting system repair rate, repowering	Fraction of the mounting system supports that were repaired for the repowered installation	0.0 – 2.0	Fraction
	Inverter repair rate, base	Fraction of the inverters that were repaired for the base installation	0.0 – 2.0	Fraction
	Inverter repair rate, repowering	Fraction of the inverters that were repaired for the repowered installation	0.0 – 2.0	Fraction
	Electric installation repair rate, base	Fraction of the electric installation (cables, connections, etc.) that was repaired for the base installation	0.0 – 2.0	Fraction
	Electric installation repair rate, repowering	Fraction of the electric installation (cables, connections, etc.) that was repaired for the repowered installation	0.0 – 2.0	Fraction
<b>Temporal</b>	Repowering year	Year when the repowering happens	1 - 30	Year
	Repowering period	Time required to dismantle the base PV installation and start operating the repowered PV installation	0.5 – 2.0	Fraction of a year
	Energy loss ratio, base	The estimated years of electricity production lost due to repair events in the base installation	0.0 – 30.0	Fraction of a year
	Energy loss ratio, repowering	The estimated years of electricity production lost due to repair events in the repowered installation	0.0 – 30.0	Fraction of a year

The FU of the product system is 1 kWh of electricity produced by the system. To estimate the environmental impacts per kWh, the total production of electricity throughout the 30-year period is needed. Under normal circumstances, the base PV system produces a certain amount of electricity per year represented by:

$$E_{t,x} = P_x SY_x (1 - d_x)^t$$

(Equation 5. 2)

Where:

- $E_{t,x}$  is the electricity produced during a certain year  $t$  by the PV system  $x$ ,
- $P_x$  is the installed capacity of the PV system in kWp,
- $SY_x$  is the specific yield of the PV system in kWh/kWp per year, and
- $d_x$  is the module annual degradation rate of the PV system, which is typically equal to 0.007.

The resilience study showed that repair and repowering events disrupt the electricity production operations, which can be explained as periods when a certain amount of the installed capacity of the PV system is not producing electricity. These interruptions must be included in the model to quantitatively show the consequences disaster risks have on the studied infrastructure. Therefore, these periods of time are considered as parameters for the repair and the repowering cases.

For the **repowering case**, it is necessary to consider two elements. First, the year when the repowering happens ( $t_{ry}$ ), because the electricity produced by the base system and the repowered system depend on their respective periods of operation. With this consideration, the total electricity produced ( $E_T$ ) is expressed as:

$$E_T(d_1, d_2) = \begin{cases} P_1SY_1(1 - d_1)^{t_{ry}} + P_2SY_2(1 - d_2)^{30-t_{ry}}, & 0 < d_1, d_2 < 1 \\ P_1SY_1t_{ry} + P_2SY_2(30 - t_{ry}), & d_1, d_2 = 0 \end{cases}$$

(Equation 5. 3)

The second element to consider is the time it takes to dismantle the base PV system and install the repowered system, since this is a period within the 30 years of evaluation considered by the study when no electricity is being produced. It is important to consider this parameter in order to make a fair comparison between all the scenarios.

In *FuturePV*, this repowering period ( $t_{rp}$ ) is considered as 6 months. Including this value in the total electricity production when the degradation rate is zero only requires the subtraction of 0.5 years from the repowered operational period of the PV system. However, when the degradation rate is greater than zero, the electricity production cannot be estimated because the related equation with the binomial  $(1 - d_x)$  raised to the power  $t$  is discrete, meaning that it cannot be solved unless  $t$  is an integer. Therefore, to perform this calculation, the continuous form of this equation must be used, which is represented as:

$$E_T(d_1, d_2) = \begin{cases} \int_0^{t_{ry}} P_1SY_1e^{t*\ln(1-d_1)} dt + \int_0^{30-t_{ry}-t_{rp}} P_2SY_2e^{t*\ln(1-d_2)} dt, & 0 < d_1, d_2 < 1 \\ P_1SY_1t_{ry} + P_2SY_2(30 - t_{ry} - t_{rp}), & d_1, d_2 = 0 \end{cases}$$

(Equation 5. 4)

For the **repair case**, it is necessary to know the repair period estimation for a single event ( $t_{repair,i,x}$ ). It is assumed that the duration of a maintenance operation is a fixed amount of time of a month plus a period that depends on how many components need to be repaired, based on the hypothesis that it takes one month to remove and install 100 kWp worth of PV components, as established in (Equation 5. 5). The duration of a maintenance operation has been chosen arbitrarily for *FuturePV* given the lack of more accurate data. In the future, further sensitivity analyses could be done to check the effect of changing this value, but for now it is outside the scope of the study.

$$t_{repair,i,x} = \frac{1}{12} + \frac{1/12}{0.1} * r_{repair,i,x}$$

(Equation 5. 5)

Where  $r_{repair,x}$  is the repair rate of the event  $i$ , for the PV infrastructure  $x$ .

As mentioned in a previous paragraph, the repair rate is considered as the sum of the repair rates associated to each event that happened in the studied period because the LCA model is not dynamic. Therefore, to estimate the total electricity that the system "lost" throughout all the repair events, it is necessary to consider the time each repair event took and subtract the energy that would have been produced with the portion of the installed capacity that needs to be repaired. This is represented as:

$$E_x = P_xSY_x t_x - P_xSY_x \sum r_{repair,i,x} t_{repair,i,x}$$



$$E_x = P_x SY_x \left( t_x - \sum r_{repair,i,x} t_{repair,i,x} \right)$$

(Equation 5. 6)

Where:

- $E_x$  is the total electricity produced by the PV system  $x$  in kWh,
- $t_x$  is the period of operations of the PV system in years, and
- $\sum r_{repair,i,x} t_{repair,i,x}$  is the total time when the PV system does not produce electricity, which is considered as the energy loss ratio parameter, represented as  $t_{l,x}$ .

From the resilience study, the DRUID LCI model extracts information on the amount and type of events per lifespan iteration (i.e. 100,000 per decision maker profile) to estimate the total time of repair, which is equal to the sum of the time for each repair event of a certain magnitude. This is done for the repair events related to the base and the repowered PV infrastructure, if applicable. For replacement-type events, only one may happen per lifespan iteration.

Including these considerations with what has been established in (Equation 5. 4), the total electricity production of the studied product system is:

$$E_T(d_1, d_2) = \begin{cases} \int_0^{t_{ry}-t_{l,1}} P_1 SY_1 e^{t \cdot \ln(1-d_1)} dt + \int_0^{30-t_{ry}-t_{rp}-t_{l,2}} P_2 SY_2 e^{t \cdot \ln(1-d_2)} dt, & 0 < d_1, d_2 < 1 \\ P_1 SY_1 (t_{ry} - t_{l,1}) + P_2 SY_2 (30 - t_{ry} - t_{rp} - t_{l,2}), & d_1, d_2 = 0 \end{cases}$$

(Equation 5. 7)

### 5.2.2.3. Impact Model

Similar to the reference model, the impact model for the LCIA is based on the environmental impacts of each life cycle process considered (see Figure 5. 5) relative to the total electricity production in kWh throughout the expected 30 years of operation, i.e. the originally expected lifespan of the base PV system. However, some important differences between the reference LCIA model and the DRUID LCIA model lie in how the impacts are attributed.

For the base PV system, the impacts of the following processes are considered in the DRUID LCIA model: the multi-Si supply chain; the manufacturing of PV modules, the mounting systems, the electric installation, and the inverters; the transport of the components to the installation site; the installation of all the components; the operation of the system; the recycling of some materials; and the maintenance operations, including repair operations of components after damages. The most important change versus the reference model lies in the inclusion of the impacts related to the maintenance process.

The impacts of the same processes as the base PV system are considered for the repowered PV system. However, for all processes except for maintenance, the impacts are allocated only to the portion of the lifespan of the repowered system that operated within the 30-year period considered for the study, as shown in (Equation 5. 8, following the recommendation of Herceg et al. (2022)).

This impact allocation approach was chosen because repowering involves installing a new infrastructure, meaning that the repowered PV system is still useful and can continue producing electricity until the end of its operational lifespan. Since this supplementary period is outside the 30-year scope of the study, it was not deemed relevant for evaluation. Of course, it can be argued that

the repowered PV system could still suffer damages after the original 30-year scope and thus it is important to also consider those potential impacts. Taking such an approach would introduce a variability factor on the actual lifespan of the PV system. Consequently, we estimate that this would make the comparison between DRUID scenarios and the baseline scenario quite unfair because their electricity production would not be considered at the same temporal scale. On a related note, the other impact allocation alternative was to attribute all the impacts of the repowered PV system to the fraction of the 30-year scope it operated for. However, doing so would disregard the fact that the repowered PV system is still useful outside this scope, which would undermine what we consider is a major benefit of choosing to repower. This is the main reason it was not chosen.

The equation representing the processes considered in the total impacts per impact category ( $i$ ) is:

$$\begin{aligned} \text{Impacts}_{Total,i} = & \text{Impacts}_{PV,base,i} + \text{Impacts}_{PV,base,maintenance,i} + \text{Impacts}_{PV,repower,i} \left(1 - \frac{t_{ry}}{30}\right) \\ & + \text{Impacts}_{PV,repower,maintenance,i} \end{aligned} \quad (\text{Equation 5. 8})$$

Finally, the environmental impact results are evaluated in relation to the functional unit, which is 1 kWh of electricity produced by the PV system. Thus, the impact model per impact category ( $i$ ) is:

$$\text{Impacts}_i = \frac{\text{Impacts}_{Total,i}}{E_T(d_1, d_2)} \quad (\text{Equation 5. 9})$$

### 5.3. Results and their Interpretation

As mentioned, the practical development and execution of DRUID LCI was done through Python, using the bases of *Brightway2*, *Ica\_algebraic*, and *PARASOL\_LCA*. The resulting code consists of three files<sup>38</sup>:

- ***druid\_parameters.py***, which contains all the declared parameters,
- ***druid\_inventory.py***, which contains the inventory for all the activities, processes, and flows considered in the assessment, as well as the impact model. In its current version, it also includes supplementary processes for other PV module technologies that have been declared but otherwise not used.
- ***druid\_ica.py***, which consists of the main executable code of DRUID LCI, containing the setup of the LCA project using the *Brightway2* and *Ica\_algebraic* libraries, the declaration of the values of the parameters, the import and transformation of results from the resilience study, and the execution of LCA results for the baseline and DRUID scenarios.

#### 5.3.1. Preliminary tests

Preliminary tests to study the differences in the LCIA results between the baseline scenario using a conventional LCA modeling approach and five deterministic DRUID scenarios were performed with the purpose of verifying that the model was working as expected and thus know where to perform the necessary adjustments. For these tests, four impact categories were evaluated: climate change (g CO<sub>2</sub>-eq), resource use, minerals and metals (kg Sb-eq), land use (Pt), and water use (kg world eq. deprived).

<sup>38</sup> The code will be made available after the PhD thesis defense.

The baseline scenario uses the PV inventory updates recommended by Besseau et al. (2023), with PV module production taking place in China, since the context scenario considers that historical trends are being followed and China has been the main producer of PV components (Masson et al., 2023). With these considerations (see Annex II for details), the results yielded the following results: climate change 30.71 g CO<sub>2</sub>-eq/kWh, land use<sup>39</sup> 3.31 Pt/kWh, mineral and metal resource use 0.8\*10<sup>-7</sup> kg Sb-eq/kWh, and water use 0.02 m<sup>3</sup> world eq. deprived/kWh.

The deterministic DRUID scenarios consider that 25%, 50%, and 100% of the PV infrastructure required repairs, respectively, and one scenario considers that only a repowering event occurred on the 15<sup>th</sup> year. Additionally, an alternative impact model was tested on this last scenario, where the impacts of the repowered PV system were completely attributed to its period of operation. This hypothesis involves that the repowered system is shut down and sent to its end-of-life after the 30-year period the original infrastructure was supposed to operate for was over. For these tests, the climate change results for the repair and repowering scenarios were expected to have higher impacts than the baseline, with the 100% repair scenario doubling the results from the baseline.

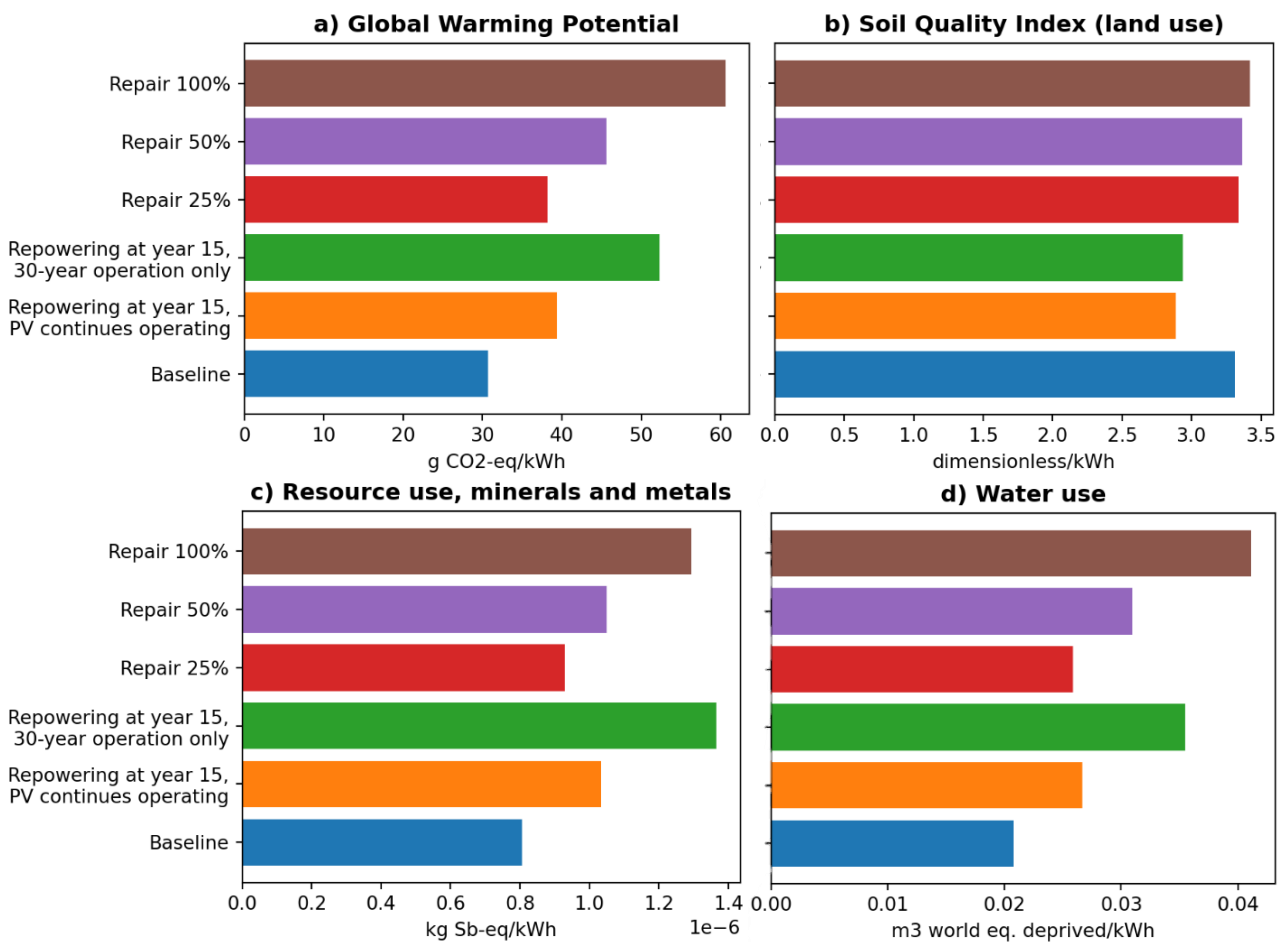


Figure 5. 6. FuturePV preliminary LCIA results for deterministic DRUID scenarios on a) Climate change, b) Land use, c) Resource use, and d) Water use impact categories

<sup>39</sup> This impact category as presented in EF 3.0 no LT (see Table 5. 1) shows that the unit is ‘dimensionless’. This unit is used in the graphical results generated through the Python code. In the text, the unit used is Points per functional unit (Pt) for ease of reading.

As seen in Figure 5. 6. a), the expected trends for these impact categories are obtained. The impacts per kWh increase as the fraction of the infrastructure that is being repaired increases. The different attribution considerations for the repowering scenarios show that stopping the operation of the PV system at the 30-year mark would be environmentally detrimental, and this is without considering the end-of-life impacts, which could have an important contribution in this scenario.

The impact categories of climate change, resource use, and water use follow the same trends with the repair 100% scenario having the most intense impact per kWh, especially when compared with the repowering scenarios. This is because of the higher electricity produced by the repowered PV system. Higher electricity production reduces the relative environmental impacts, even though both the 100% repair and repowering scenario have impacts related to the replacement of the whole PV infrastructure.

When starting to apply the model, an increase of the potential land use impact was observed for some preliminary tested scenarios. The preliminary result was contradictory with the fact that, when repairing or repowering the PV infrastructure, the land it occupies has been already changed by the first installation at the beginning of the 30-year period. Indeed, the installation and land-preparation-related flows that would contribute to land use impact should not be accounted for a second time. Doing so provides overestimated results that are not representative of the actual situation. Therefore, the DRUID LCI model separates these land occupation and transformation flows from the mounting system installation processes, and only includes them once in the product system.

### 5.3.2. LCA results following the resilience study

As a reminder, the results obtained from the resilience study (see §4.3.2.2), from all the tests performed, showed that the infrastructure could be affected by an average number of 1.13 shocks in the 30-year period. In average, the infrastructure may suffer a cumulated damage throughout the 30-year period equivalent to 1.75% of its total components. In 31.5% of cases the PV infrastructure may not experience any damage at all throughout its operational lifespan. The intensity of most shocks tends towards lower values between 0.028% and 1% damage to the PV infrastructure, with an exponentially decreasing trend where higher shock intensity values are less frequent, with scarce occurrences above 50% damage. This is expected given the considerations made on the absorptive capacity and shock levels (see §4.3.2.1).

The LCA results presented correspond to the comparison of 4 decision profiles and 2 repowering thresholds (lower and higher), making a total of 8 profiles.

Regarding the thresholds, for the *FuturePV* resilience study, two thresholds related to the performance of the PV infrastructure were established to estimate the decisions made when potential disaster events affect the PV infrastructure. The first threshold is the repair threshold, whose value corresponds to the expected annual electricity production at the 30<sup>th</sup> year of operation of the undamaged baseline PV infrastructure,  $E_{30}$ . The second threshold is the repowering threshold<sup>40</sup>, whose value is a fraction of  $E_{30}$ . In *FuturePV*, two repowering thresholds are evaluated. The lower repowering performance threshold corresponds to 50% of the repair threshold value, and the higher

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<sup>40</sup> As stated in §4.3.1, the principle behind establishing the repowering threshold is that it could be economically and technically problematic if the damage caused by the disaster event lowered the performance of the critical infrastructure to an unacceptable level. This may put the decision makers in a position of contemplating the situation as an opportunity to upgrade the infrastructure for long-term benefits.

repowering performance threshold corresponds to 75% of the repair threshold value. If the PV infrastructure experiences a shock that lowers its performance but keeps it above the repair threshold, then the damaged components are repaired. In contrast, if a shock lowers the performance below the repowering threshold, then the whole infrastructure is changed with new components to increase its production capacity. If the performance is lowered between the repair and repowering thresholds, then a decision is made to repair or repower based on the likelihood that a decision-maker chooses either option.

The corresponding values of the repair threshold and the two repowering thresholds are shown below, as solutions of (Equation 5. 2):

$$E_{30} = 1000 [kWp] * 1400 \left[ \frac{kWh}{kWp} \right] * (1 - 0.007)^{30} = 1,133,980 [kWh]$$

$$0.5E_{30} = 566,990 [kWh]$$

$$0.75E_{30} = 850,485 [kWh]$$

Regarding the decision profiles, these are related to the likelihood that a decision-maker would choose to either repair or repower, as mentioned above. In *FuturePV*, the four decision profiles are:

1. *Minimum repowering profile*: The first decision profile assumes that decision-makers always choose to repair. Repowering scenarios can still occur if a shock lowers the performance below the repowering threshold. This profile is called “0% repowering” in Chapter 4.
2. *Unlikely repowering profile*: The second decision profile assumes that decision-makers have a strong preference towards repairing when given the choice. Therefore, there is only a 10% probability of deciding to repower. This profile is called “10% repowering” in Chapter 4.
3. *Average repowering profile*: The third decision profile assumes that decision-makers have a 50% probability of deciding whether to either repair or repower. This profile is called “50% repowering” in Chapter 4.
4. *Maximum repowering profile*: The fourth decision profile assumes that decision-makers would always choose to repower when they are able. Therefore, repair scenarios only occur if a shock lowers the performance but does not breach the repair threshold. This profile is called “100% repowering” in Chapter 4.

The graphical results presented in this section correspond to three impact categories, namely climate change, material resource depletion in terms of minerals & metals, and land use, due to their relevance to the PV sector. The complete set of graphs presenting all the impact categories that have been evaluated are available in Annex III.

For all impact categories evaluated throughout the 8 profiles, the graphical results make a distinction between scenarios that include repowering (blue bars), results containing scenarios with repair and repowering events (orange bars), and results representing scenarios where the PV system suffered no damage (purple bars).

#### 5.3.2.1. Comparing the decision profiles

As expected, the LCIA results for all impact categories follow the same trend as the cumulative damage results (see §4.3.2.2). Most damage occurs at shock levels below 2% and 3%. Consequently, most impact results for each impact category in any scenario with damages are very similar to the value for the baseline scenario with no damages for all impact categories (e.g. Figure 5. 7 for the

climate change impact category, high repowering threshold decision scenarios). This suggests the results of the case study have a high probability of being similar to the results obtained with conventional LCA. To better observe the LCIA results for the scenarios with different impact values than the baseline, the y-axis of the graphs presented in the rest of this chapter are on a logarithmic scale.

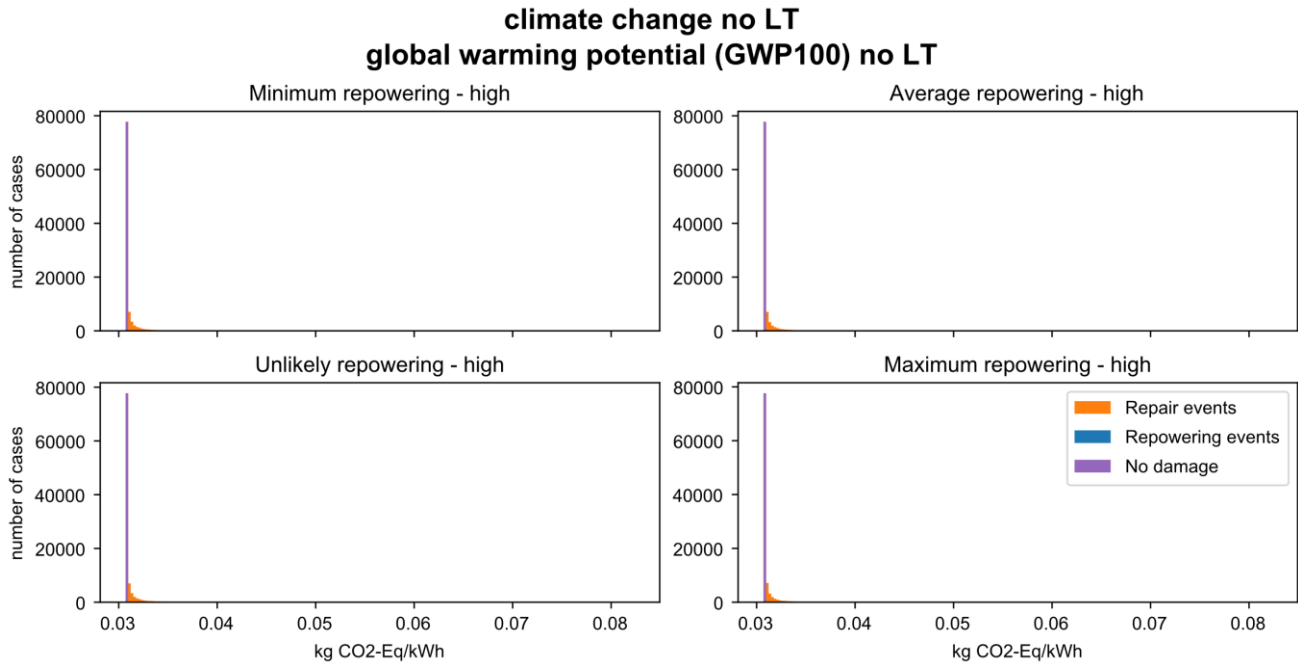


Figure 5. 7. Histograms with LCIA results for climate change impact category for the low repowering threshold

To study the influence of scenarios including repowering in relation to the overall scenarios, the minimum repowering decision profiles vs. the unlikely, average, and maximum repowering decision profiles for the low repowering threshold were compared. The behavior for repair-only scenarios can be better observed through the minimum repowering decision profile because in this decision profile scenarios with repowering only occur when the repowering threshold is breached. As the decision to repower becomes more prominent, the contribution of repowering scenarios to the environmental impact results also increases, appearing within the overall results for each decision profile. In all impact categories, except the land use impact category, LCIA results related to repowering displace the mean environmental impact results to relatively higher values. Nevertheless, due to the low instances of repowering in the overall number of events, this displacement is almost imperceptible.

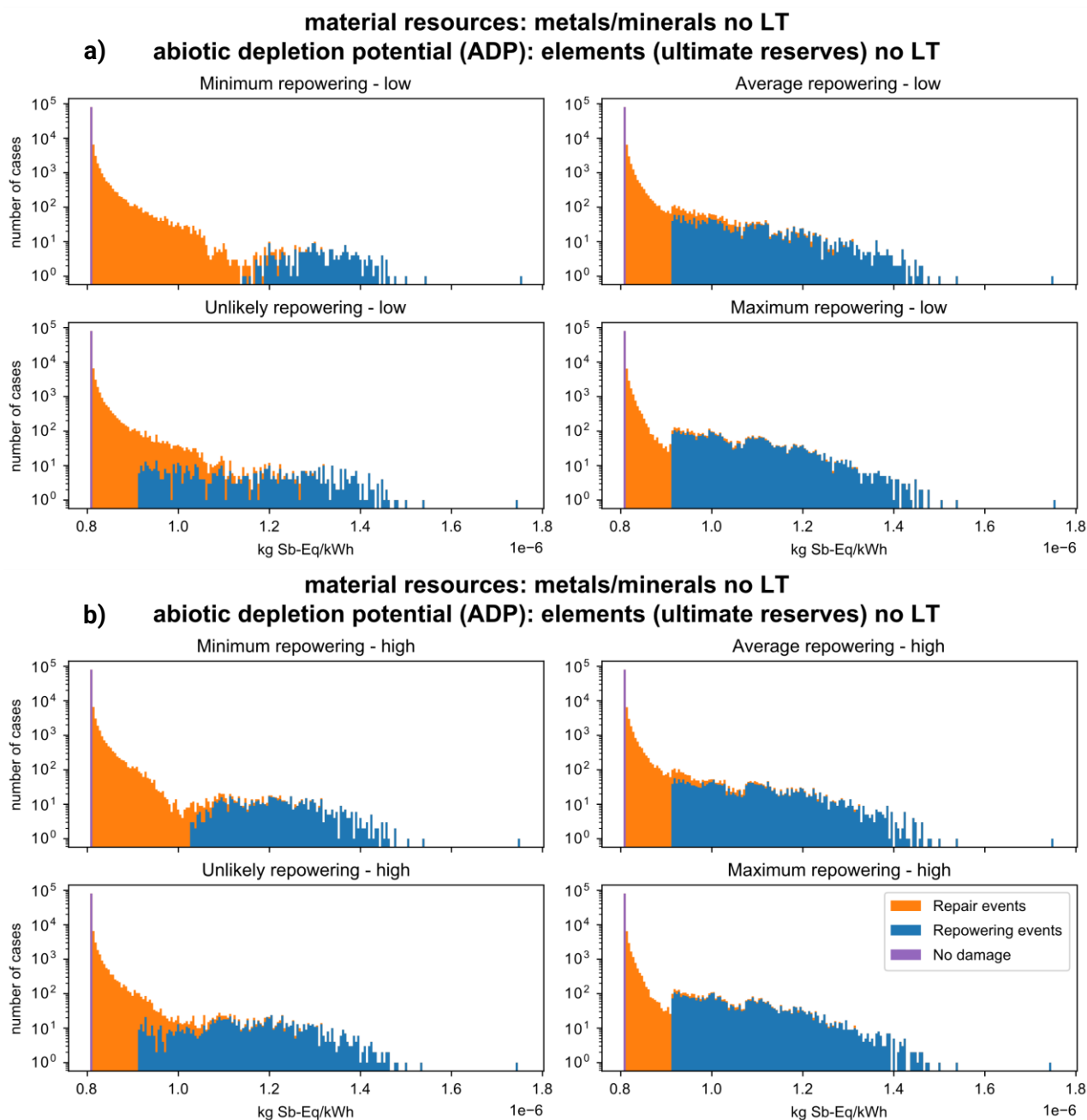


Figure 5. 8. Histograms with LCIA results for material resource use impact category for a) the low and b) high repowering threshold

In the **resource use, minerals and metals impact category** (see Figure 5. 8) the impacts from only repowering scenarios have a minimum value around  $9.1 \cdot 10^{-7}$  kg Sb-eq/kWh and a maximum value around  $1.4 \cdot 10^{-6}$  kg Sb-eq/kWh, with an outlier between  $1.7 \cdot 10^{-6}$  and  $1.8 \cdot 10^{-6}$  kg Sb-eq/kWh. Thus, it is observed that profiles that do not tend to choose repowering, such as the unlikely repowering profile already involves an approximate increase of 12.5% compared to the baseline scenario using conventional LCA. Moreover, as the decision to repower becomes more important, the group of values related to instances when repowering may occur become denser and seem to become a separate instance of the rest of the distribution of results.

The reason why the influence of repowering is more prominent in these results when compared to the results in other impact categories is because this impact category pertains to flows related to the

use of minerals and metals. Manufacturing PV modules involves the use of metals such as silver and copper, and silicon as an important mineral, while the production of inverters involves aluminum and steel, and the production of other electrical components entails copper, aluminum, and other metal elements. In repowering scenarios, the upstream impacts of the whole supply chain for all components that make up the PV system are accounted for a second time, therefore more important quantities of the same materials contribute to higher environmental impact results.

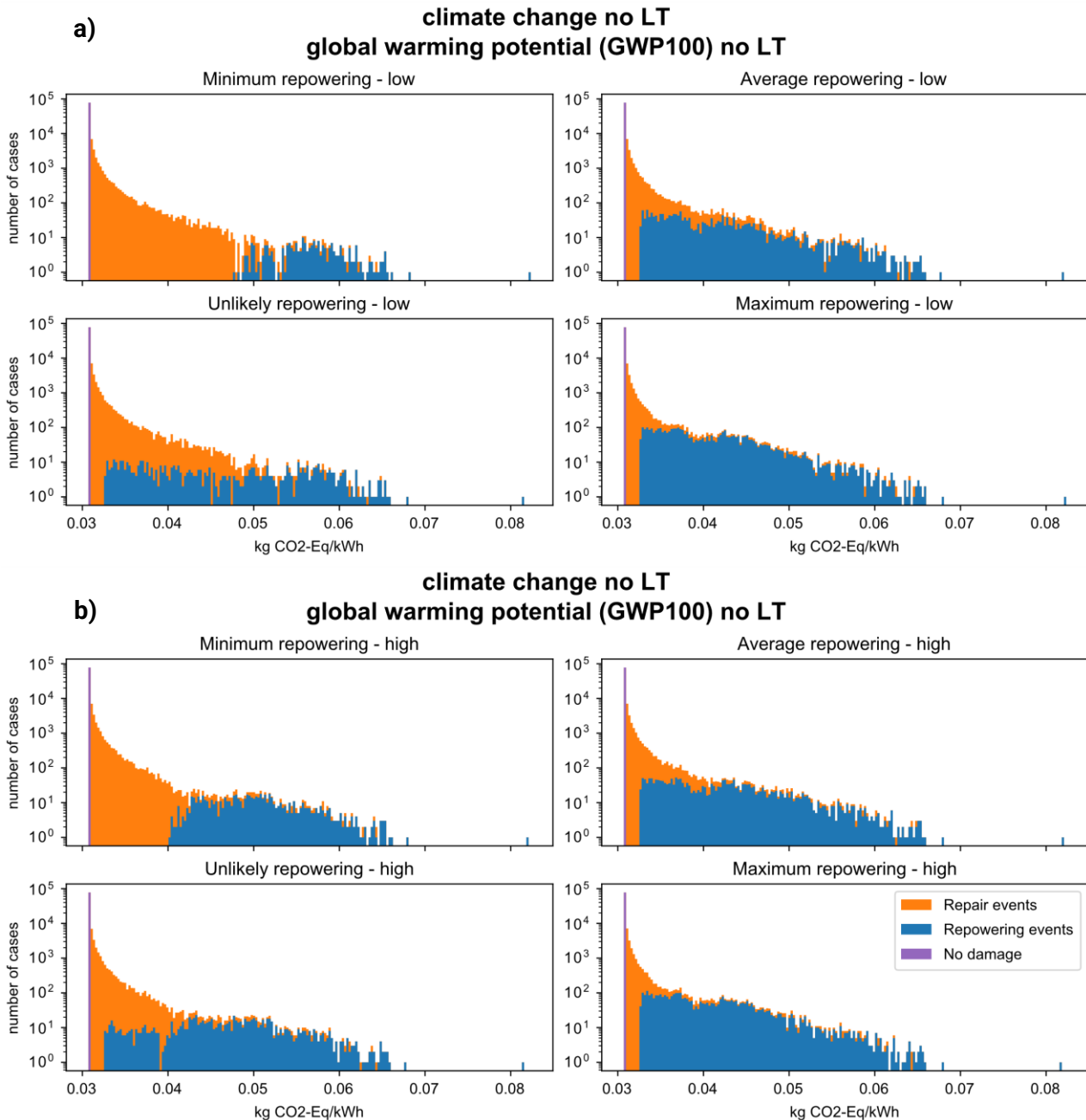


Figure 5. 9. Histograms with LCIA results for climate change impact category for a) the low and b) high repowering threshold

For the **climate change impact category** (see Figure 5. 9), similar observations can be made regarding the influence of repowering scenarios, although the difference is more subtle. Compared to the material resource impact category, the effects of repowering scenarios are not as evident until the average repowering profile where the minimum value related to repowering scenarios is distinguishable. The climate change impacts from only repowering scenarios have a minimum value



around 32.5 g CO<sub>2</sub>-eq/kWh and a maximum value between 60 and 65 g CO<sub>2</sub>-eq/kWh, with an outlier around 80 g CO<sub>2</sub>-eq/kWh. These maximum values are similar to the climate change impact results that could be obtained from an LCA study on an analogous PV system without the LCI-related modifications of PARASOL\_LCA (Besseau et al., 2023).

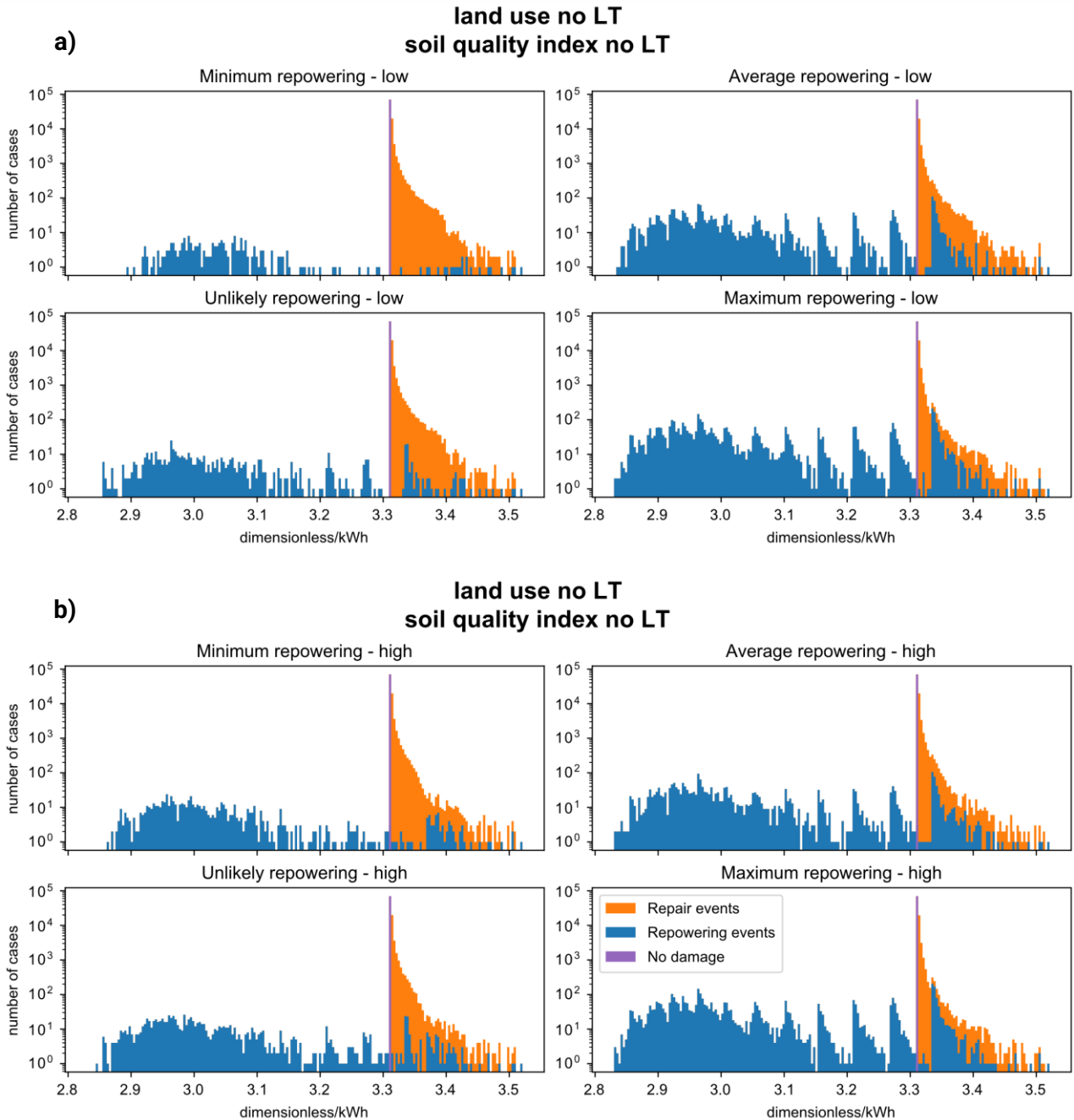


Figure 5. 10. Histograms with LCIA results for land use impact category for a) the low and b) high repowering threshold

The **land use impacts** (see Figure 5. 10) have a different behavior from all the other impact categories. Here, the impact related to the repowering scenarios for all decision profiles mostly has lower results than the baseline scenario and the repair-only cases. This is because the land use impact is related to the transformation and occupation activities, and these activities only happen once, when the PV installation is established at the beginning of its expected 30-year lifespan. Moreover, because environmental impacts are evaluated per kWh of electricity produced throughout the 30-year period,

the higher electricity production in scenarios with PV repowering plays a major role in bringing the value of the land use impact down.

It is worth noting that although land use impact results appear extremely different within each graph, in truth the values change slightly from one another, with a minimum value around 2.8 and 2.9 Pt/kWh and a maximum value around 3.4 Pt/kWh. This is consistent with the results obtained in the preliminary test. Finally, the distinct grouped impact values seen for the repowering-only cases in the land use impact category (see Figure 5. 10) are most likely related to the year the repowering occurred. The earlier the repowering occurs in the operational lifespan, the lower the related land use impacts. A more precise numerical treatment of the results is required to confirm this hypothesis.

In a similar way, the range of variability for all the LCIA results obtained is relatively narrow. The values obtained for all scenarios stay within the same order of magnitude as the baseline scenario, even when looking at the maximum values for each impact category. This is most likely due to the characteristics of PV technologies as a renewable energy source, for whom the consequences of disaster risks are not as catastrophic as they would be for other energy installations relying on fossil or nuclear energy. However, it must not be ignored that in this version of the model only one hazard was evaluated, and the analysis of environmental impacts related to the end-of-life processes was only included in a partial manner for a limited number of materials. For PV systems, end-of-life processes (Komoto et al., 2018) include dismantling, with disposal options of material recycling, reutilization of PV modules, or landfilling in the worst case. It is expected that end-of-life processes will have an important influence on the LCA results, especially when comparing the end of life between damaged equipment in different states of disrepair, and the disposal of still functioning components due to repowering. In this same line of thought, the consideration and attribution of recycling and possible repurposing and/or reuse of the components of the PV infrastructure will play an important role in painting a more comprehensive picture.

#### 5.3.2.2. Comparing the repowering thresholds

As expected, impact results change when comparing the low and high repowering threshold for the minimum repowering decision profile, since the occurrence of repowering events in this case depends entirely on the occurrence of a disaster risk that affects the PV installation with a shock intense enough to breach the repowering threshold. This happens more often for the higher repowering threshold, where scenarios with environmental impacts related to repowering events occur in 0.78% of the cases, as shown in Figure 5. 8. b), Figure 5. 9. b), and Figure 5. 10. b). In contrast, the low repowering threshold scenarios with a repowering event happening correspond to 0.25% of the cases.

For the unlikely repowering profile, the contribution of scenarios with repowering is more important for the cases related to the higher repowering threshold, following the same trend as the 0% repowering scenarios. When examining the average repowering profile, the contribution of scenarios with repowering does not appear to differ significantly between both repowering thresholds, but upon close examination the frequency of repowering events is also expectedly higher for the higher repowering threshold cases.

For the maximum repowering decision profile, impact results between the low and high repowering threshold are the same. This is the case because under this decision profile, the repowering events always occur if the repair threshold has been breached, and the repair threshold value is the same both cases with the low and high repowering threshold.

The plausibility of having the minimum and maximum repowering decision profiles in a real case is debatable but they were chosen to test the sensitivity of the model. For an exhaustive study of this nature, the performance thresholds and the nature of the decision profiles ought to be established in close collaboration with the relevant PV infrastructure actors.

5.3.2.3. Discussion on the relevance of DRUID LCA results for decision-making

Whilst building the resilience and the LCA model for DRUID LCI, it was considered that the people in charge of the critical infrastructure project would do everything in their power so that the PV infrastructure can continue providing a reliable service to the community because this is the purpose of the PV infrastructure. Moreover, it is also in the best interest of the stakeholders and shareholders of the project to maximize the electricity production. Thus, it is beneficial to take the opportunity created by disaster events to increase the production capacity and provide better services. This is a reason why repowering alternatives have an important place in DRUID LCI. As shown in Figure 5. 11, scenarios including repowering can produce up to 20% more electricity throughout the 30-year period compared to the baseline scenario and the repair-only scenarios.

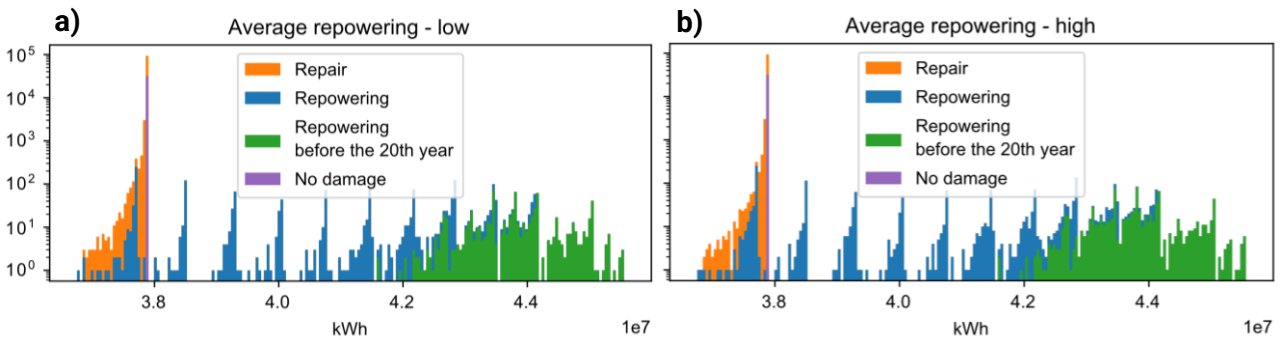


Figure 5. 11. Histograms with the total electricity produced throughout the 30-year period in logarithmic scale for the a) low and b) high repowering threshold cases for the average repowering decision profile

Additionally, the earlier repowering is done with better performing PV modules, the more electricity is produced throughout the evaluated period since the new PV system is operating for longer periods. This phenomenon can be seen in Figure 5. 12, where the climate change impact results are compared to the total electricity production. The different data points accumulated across certain areas of the full interval of variation are related to the year when repowering could occur. Specifically, the green points correspond to years 10 to 19, and the blue points to years 20 to 29. The points further to the right correspond to the earlier years. Some overlap occurs between scenarios that correspond to different repowering years, specifically between years 16 and 20, 17 and 21, 19 and 22. Upon comparison, the results indeed suggest that among scenarios with the same total electricity production, those with the lesser impacts correspond to scenarios where repowering occurred in later years with the more efficient PV modules.

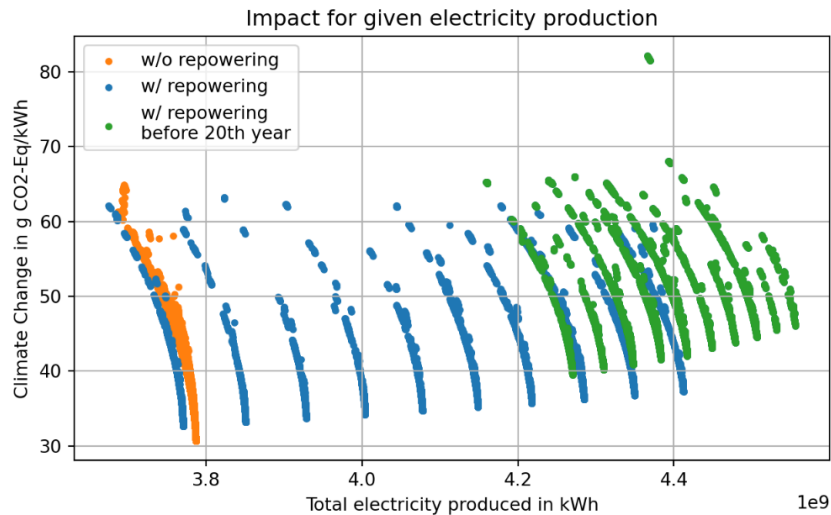


Figure 5. 12. Total electricity production vs. climate change impact over the 30-year period for all decision scenarios

In *FuturePV*, it has been observed that decisions related to repowering have a significant influence over the environmental impact results. For a given series of damage-inducing shocks that may occur throughout the 30-year period of operation of the PV infrastructure, most estimated LCIA results show that repair-only scenarios have lower impacts than scenarios including repowering (see Figure 5. 13). These results are expected because in repowering scenarios the upstream supply chain-related flows are almost doubled. It is also important to note that the increase in electricity production does not compensate for the fact that repowered PV systems have higher potential environmental impacts, as shown in Figure 5. 12. In the context of the case study, repowering entails making the best of an unfavorable situation by turning the loss of production capacity into an opportunity to increase it. Of course, it would be preferable to avoid these unfavorable situations altogether by having more resilient PV infrastructures. Assessing the potential environmental impacts of more resilient PV systems was outside the scope of this study, but it is an aspect that decision-makers involved in the planning of similar infrastructures should consider.

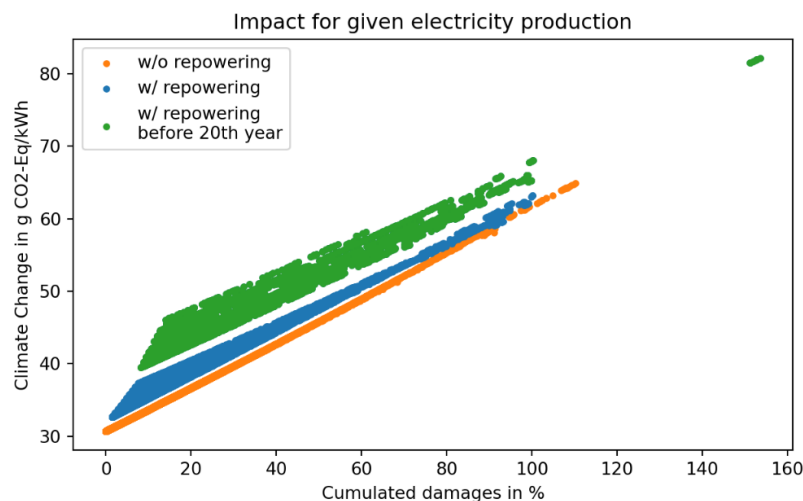


Figure 5. 13. Cumulated damages<sup>41</sup> vs. climate change impact over the 30-year period for all decision scenarios

<sup>41</sup> Cumulated damages refer to total percentage of damage to the components of the PV infrastructure over 30-year period evaluated.

Also, repowering-related impacts before the 20<sup>th</sup> year of operation have relatively higher impact results per kWh for most impact categories when compared to the minimum repowering-related impacts. For example, in the climate change impact category (see Figure 5. 14), the minimum value is 40 g CO<sub>2</sub>-eq/kWh versus the previously stated 32.5 g CO<sub>2</sub>-eq/kWh corresponding to the estimated minimum value related to the repowering only scenarios (see §5.3.2.1). This occurs because PV modules with different efficiencies are used for repowering in different periods. PV modules with 22% efficiency are used for repowering between the 10<sup>th</sup> and 20<sup>th</sup> year, while PV modules with 24.5% efficiency are used between the 20<sup>th</sup> and 30<sup>th</sup> year. When comparing the overall electricity produced between scenarios with repowering at different periods, scenarios without repowering, and the baseline scenario, it is clear that scenarios with repowering before the 20<sup>th</sup> year tend to produce the most electricity overall (see Figure 5. 11). Despite this observation, environmental impacts are consistently higher for these scenarios, suggesting that it could be more beneficial to repower later rather than sooner when more efficient PV module technologies are available in the market. Of course, this is only true if it is assumed that the repowered PV system will continue operating outside the 30-year scope of the study and until the end of its operational lifespan (also considered to be of 30 years). If the system is repowered in a later year but then it is decommissioned at the end of the 30-year original scope, then the impact results would likely be significantly higher than those obtained with the current hypotheses. They would have similar differences to those seen in the preliminary results (see §5.3.1).

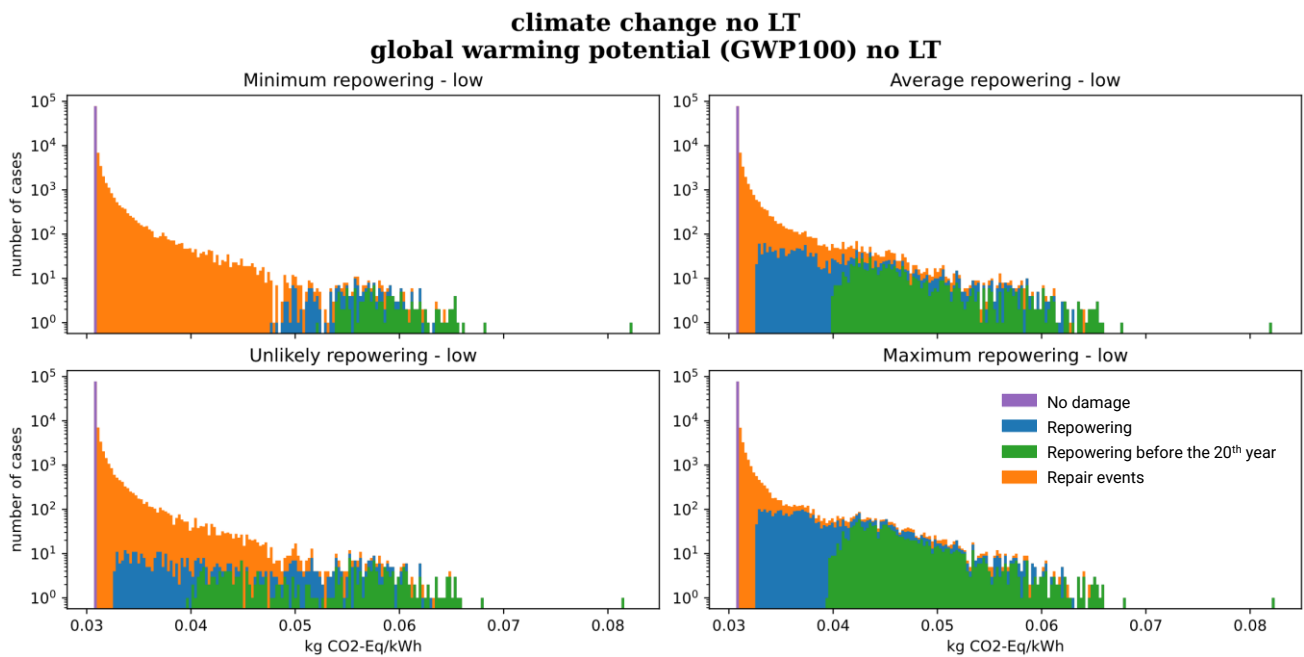


Figure 5. 14. Histograms with LCIA results for climate change impact category for the low repowering threshold

Overall, if *FuturePV* were representative of a real case to develop a PV infrastructure project, it could be concluded that the potential environmental impacts obtained through LCA are being underestimated for most impact categories when compared to the results obtained when using DRUID LCI. This observation could also be made on the potential LCA results versus DRUID LCI-based LCA results of other energy production systems, especially for systems that use non-renewable energy sources and already have non-negligible emissions under normal operations, such large-scale turbines fueled by combustion of coal or natural gas, and nuclear energy. Considering the potential effects of disaster events on the potential environmental impacts of such systems through DRUID

LCI might reveal increased environmental consequences to a larger extent. So, even though the environmental impacts of PV systems may increase, once disaster risks are considered in the assessment, the corresponding increase for other energy production technologies may be even higher. In the end, DRUID LCI needs to be applied to all technologies exposed to a given disaster risk to have a fair comparison between them and determine what is the most attractive alternative for the corresponding decision-makers.

Something that has not been evaluated in these tests is that the manufacturing efficiency of PV technologies in the future can improve. This means that the better performing PV modules used for repowering could be produced using less energy and resources. In the current model, it has been considered that all the components of the PV infrastructure are developed using the same manufacturing techniques with the same efficiency. Moreover, in the context scenario chosen it was determined that China would continue to be the main manufacturer, with no major evolution of its electricity mix accounted for. The electricity mix of the manufacturing country has a significant influence on the environmental impacts of the PV module, and currently in the electricity mix of China fossil fuels have an important contribution. Therefore, if PV modules repowered in the future were produced in countries with a less carbon-dependent electricity mix, the environmental impacts would also change significantly. With these considerations, the environmental impacts of scenarios with repowering could be expected to decrease, thus potentially rendering the repowering decision more attractive in environmental terms. Including these aspects related to the domain of prospective LCA is a task to develop in a future iteration of the DRUID LCI model.

Another point to address is that, unfortunately, factors such as lack of financing and problems related to internal or external politics, policies, management, and insurance, can trigger a situation where it is not possible to restore or upgrade the production capacity of the critical infrastructure. In such cases, the environmental impacts would be related to the energy and materials involved in the life cycle of the infrastructure relative to the reduced electricity production. Thus, expected results would be a reduced overall electricity production and an increase of the environmental impact results across all impact categories evaluated. To study these fatalistic scenarios, another variation of the decision profiles could be added to the resilience model in a future version of DRUID LCI.

Regarding decisions that could be taken after analyzing LCA results that use DRUID LCI, it is expected that a higher absorptive capacity versus specific hazards would decrease the potential impacts caused by said hazards. In practical terms, increasing the absorptive capacity would involve investing more in the resilience of the critical infrastructure in the form of physical and/or non-physical barriers. This would imply an increase in material and energy flows that contribute to increased environmental impacts. Depending on the intensity of the hazards and their possible consequences, tests would need to be made to determine what alternative yields a better potential environmental performance: only increasing resilience, only repairing the damage with possible repowering, or a mix of these two alternatives.

For a sensitivity analysis linked to resilience and absorptive capacity, the variables  $v$  and  $\beta$  of the fragility curve (see §4.2.2.2) can be modified to observe how much the variability of the absorptive capacity affects the likelihood of damage and severe damage to the PV system. Figure 5. 15 shows some examples of possible variations. The  $v$  parameter determines the value of failure with a 50% probability and  $\beta$  modifies the slope. The higher the slope, the less abrupt the changes in probability of failure are from one value to another, but higher  $\beta$  values also make it more likely to higher overall

probabilities of failure at lower wind gust values. Moreover, it is worth remembering that maximizing  $v$  and minimizing  $\beta$  in the model is a representation of more resilient PV systems versus strong wind hazards. To more comprehensively represent these changes in the LCA results, the corresponding modifications to the LCI model should be made, meaning what does in mean in terms of material and energy flows to increase the resilience of the PV system, as mentioned in the previous paragraph. This is an aspect that could be studied in a future version of the case study.

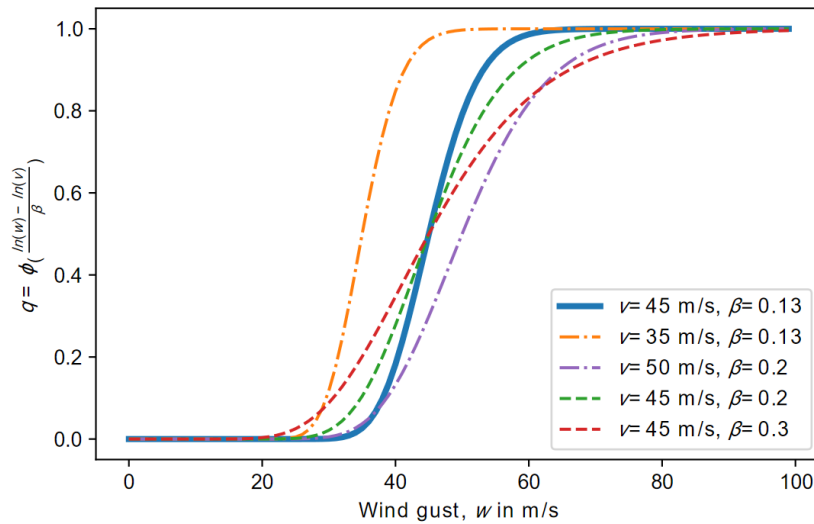


Figure 5.15. Alternate parameter values for the fragility curve

## Conclusions

DRUID LCI constitutes an approach to develop scenarios that guide the estimation of the consequences of potential disaster risks on the environmental performance of a critical infrastructure, particularly addressing energy production infrastructures. These consequences manifest themselves as damage to the infrastructure that hinders its physical integrity and its capacity to fulfill its expected functions. The related potential environmental impacts pertain to the energy and materials expended through the actions taken to restore the infrastructure and its production capacity.

In this chapter, an illustrative LCA study of a PV infrastructure project threatened by strong wind hazards has been developed to illustrate and test the application of DRUID LCI, exploring its strengths and limitations. Moreover, the fourth step of DRUID LCI that guides the implementation of the DRUID decision scenarios into the DRUID LCI model of the critical infrastructure was presented. The purpose of this model is to link the consequences of shocks studied in the DRUID resilience study to maintenance-related processes and inventory flows, as well as defining an inventory and impact model for the LCI and LCIA, respectively. A specific DRUID LCI model ought to be defined for the LCA study of a given infrastructure project, and through the *FuturePV* case study how such a model could look like for a PV infrastructure project has been explored.

The *FuturePV* case study helped examine the relationship between environmental impact results and the severity of damage to PV infrastructure caused by disaster risk shocks. Additionally, it explored how decisions to either repair damaged infrastructure or replace it entirely with upgraded equipment affected both the environmental results and the production capacity. In *FuturePV*, scenarios with repowering have relatively higher environmental impacts than repair only scenarios, despite the additional electricity production benefits. Because scenarios with repowering events also included

repair events, and in both types of events the PV modules were produced with the same value chain, it is expected that these scenarios would result in higher environmental impacts throughout most impact categories, except for land use because the new infrastructure occupies the same land surface area as the original one.

In PV applications, the decision to either repair or repower relies mostly on financial grounds and maximization of electricity production. However, it is also important to present the environmental side in these conversations if countries are to get as close as possible to the Net Zero Emissions goal by 2050. Ensuring the sustainability of all energy systems must be a priority, and perhaps DRUID LCI can contribute to this discourse.

From what has been achieved throughout this project, I can confidently say that DRUID LCI presents a novel methodological framework to study the effects of disaster risks in the context of an LCA study of a critical infrastructure. There is still work to be done regarding the exploration of the limitations and areas of opportunity of DRUID LCI, which are further discussed in the following chapter.

All in all, DRUID LCI has allowed us to open discussions and raise interesting points regarding the consequences of disaster risks on the environmental impact results that would not be so evident whilst only relying on (conventional) standardized LCA.





## Concluding and Looking Forward

The scientific project developed in this PhD thesis had the ambitious objective of proposing a novel methodological approach to enable the consideration of disaster risk consequences on the performance of critical infrastructures, in this case, focusing on an environmental perspective. To guide the development of this proposal, the PhD thesis focused on the Life Cycle Assessment (LCA) of an energy production system. The aim has been to address a research challenge identified in LCA (Finkbeiner et al., 2014), namely that its conventional application does not account for the consequences of disaster risks. Considering that, in the context of accelerated climate change, disaster risks are becoming more intense and frequent (IPCC, 2022), critical infrastructures will likely be more exposed to these phenomena, therefore the effects of disaster risks should be included in the environmental assessment for such projects.

Through the exploration of the domains of LCA, disaster risks, and prospective studies, a novel methodology has been developed, which is an inventory module called the Disaster Risk-gUided scenario Definition (*DRUID*) Method – LCI Module, consisting of four iterative steps: 1) Problem definition, 2) Scenario building, 3) Infrastructure resilience study, and 4) Scenario transfer to LCI. Throughout this PhD thesis, each step has been explored by explaining their methodological structure alongside an illustrative example of a case study, named *FuturePV*, on a photovoltaic (PV) electricity production system.

The purpose of the case study is solely to aid in identifying the strengths, limitations, and areas of opportunity of *DRUID* LCI, and not to draw any actionable conclusion on the case study. In this final section of the PhD thesis, the main conclusions about *DRUID* LCI are expanded upon, specifically addressing the main findings, identified limitations and areas of opportunities by topic.

## Specific Conclusions and Perspectives

### On *DRUID* method and *DRUID* LCI

When comparing Chapter 4 and 5, there is a clear difference in how the proposed novel method is addressed. Chapter 4 refers to the *DRUID method*, and Chapter 5 uses the term *DRUID* LCI instead. This is related to the discussion in Chapter 3 where it is stated that the scenario capabilities of *DRUID method* could also be used in other domains and applications outside of LCA. Therefore, *DRUID* LCI is the *DRUID method* explicitly adapted for LCA.

Regarding the scenario modeling alternatives, one possible evolution of the *DRUID* scenario building step is to go into more detail in dynamic modeling methods to define the context scenarios, especially to address prospective aspects and interactions between complex risks. This could be supported by Integrated Assessment Models (IAMs). However, given the inherent variability and uncertainty of these models, particularly when applied to scenarios involving natural disasters and complex risks, it is essential to collaborate with peers experienced in their use to apply them accurately.

Regarding the trends used to define the context scenarios, it may be problematic to mix global trends with national and regional trends to develop scenarios when using the General Morphological Analysis due to their different temporal and geographic scales. Since SSP-RCP scenarios already concern many possibilities and are based on several hypotheses, it is difficult to establish exclusion criteria for the morphological matrix. This is why normative criteria were used when determining incompatible values between scenario parameters. An alternative, in this case, could be to keep the SSP-RCPs as a frame for other localized trends that guide scenarios. This means that the Cross

Consistency Assessment would be done using the national and regional trends, and at the end these trends are paired up with global pathways to imagine different alternatives. This is a point that needs further thought and development to reach a consistent approach for the definition of context scenarios with qualitative and quantitative elements.

Regarding the choice of representative scenarios, certain criteria to make this choice have been suggested, but it should be noted that this does not completely prevent practitioners from arbitrarily choosing the scenarios they want to test. The purpose of representative scenarios is to allow practitioners to investigate the different circumstances the infrastructure could find itself in so they can ultimately inform decision makers. As analysts, practitioners have the responsibility to choose and study these scenarios as objectively, explicitly, and transparently as possible.

Through DRUID LCI, practitioners can choose which types of risks they want their study to focus on. Limiting the perspective of a study with only one type of risk at the beginning can be a good compromise, even if the critical infrastructure is not isolated from all but one hazard. This may allow the practitioners to build up the complexity of the problem progressively as they include the analysis of complex risks. In other words, by analyzing a single risk at first, it is easier to focus on the characteristics that allow said risk to later couple it with other hazards that could put the infrastructure in danger. In contrast, if complex risks were analyzed from the beginning, the practitioners managing the study could get overwhelmed with the amount of information necessary to build such context scenarios, and some critical elements might get overlooked. The inclusion of complex risks in more depth is missing from the examples that accompany the explanation of the DRUID LCI steps that have been presented in this manuscript. This aspect is to be addressed in the next phase of development of DRUID LCI, with the idea of including, for example, forest fire risk and its interaction with wind-related risk in a more complete version of the current case study *FuturePV*.

Something that should be mentioned is that DRUID LCI does not intend to replace a comprehensive disaster risk study or a risk assessment for a critical infrastructure project. Each assessment tool is made for a specific purpose, and DRUID LCI does not fulfill the same role as a risk assessment. DRUID LCI offers a new perspective on the environmental side that risk assessments perhaps overlook. Moreover, DRUID LCI can use the results from risk assessment to obtain the information required for its application, acting as a complementary tool rather than an intrusive one.

As seen throughout this manuscript, DRUID LCI enables the discussion of the effects of disaster risks on the environmental performance of a critical infrastructure. The case study chosen to illustrate this has focused on renewable energy systems. However, non-renewable energy systems and other infrastructure types that provide critical services to communities are also concerned by the potential effects of disaster risks. Perhaps it is even more urgent to address the potential consequences of disaster risks on critical infrastructures that handle hazardous chemicals and materials, which could have serious and potentially catastrophic short- and long-term effects on human and environmental health.

Finally, it is important to highlight that DRUID LCI proposes an approach that is exceptionally different from the traditional inventory phase in LCA. Even when scenarios are introduced in LCA, they are used in the context of steady-state or standard operations for comparative studies. Coming back to Finkbeiner et al. (2014), it is important consider the effects of improbable events such as natural and technological disasters from the goal and scope definition and included in the LCI to consider all the potential environmental impacts of product systems. Especially in the context of sustainable

development and the Next Zero Carbon by 2050 goals, it is critical to consider the environmental consequences of “what can go wrong” to evaluate strategies for the best course of action.

### On LCA

As mentioned in Chapter 5, because we are dealing with a large-scale problem that explores the consequences of decisions made throughout the life cycle, applying consequential LCA might be the most pertinent alternative for the model. However, there were several challenges to be addressed for the use consequential LCA, which would add more complexity into an already complex approach. Some of these challenges included time constraints and the expected difficulties in developing a prospective consequential LCA model. To keep the focus on the main goal of the thesis, namely developing an approach to account for disaster risks in LCA, it was decided to develop the DRUID LCI and LCIA model of the *FuturePV* case study with attributional LCA, benefiting from an existing parametric LCA model for the baseline case. Nevertheless, the feasibility of developing a consequential model for DRUID LCI is a topic worth exploring.

Another aspect to be further explored is related to the prospective dimension of the studies using DRUID LCI, which could benefit from the tools and approaches developed by the prospective LCA community. One of such tools is *premise* (Sacchi et al., 2022), a prospective LCA library that helps modify the LCI to reflect its state at a certain point in the future. It is based on the results generated by IAMs that include SSP and RCP scenarios (see §1.2.3.1), among others. Using *premise* could be relevant when using DRUID LCI, especially when addressing changes that occur during the operational lifespan of the studied infrastructure. For example, replaced components and repowering activities use technologies that are produced close to the time the disruption occurred. Thus, the upstream energy and material flows used to produce the components are different from those used years prior (i.e. at the beginning of the operation of the installation), mainly due to changes in the energy mix of the country or region where these components were potentially manufactured. This would bring the approach closer to the principles behind prospective LCA by using future inventories and scenarios. However, it would add to the vast number of uncertainties that already exist in the model, so this option should be explored very carefully in future iterations of DRUID LCI. Furthermore, sensitivity and uncertainty analyses will be performed in more complete versions of the case study, although I expect this to be a difficult task given the vast number of uncertainties introduced by hazards and complex interactions with critical infrastructures.

As also mentioned in Chapter 5, a more elaborate inclusion of the end-of-life stage is missing from the DRUID LCI model developed for the case study. By including end-of-life in the model to a larger extent, impacts related to, for example, the chemicals contained in PV modules, dismantling activities, and more detailed recycling processes could be considered. These could reveal the different potential environmental impacts of different PV technologies considered for repowering in a comparative assessment, among other sources of environmental impacts. The reason a more detailed end-of-life process was not currently included in DRUID LCI was because there are numerous suggestions as to how to model the end-of-life stage in LCA. Each modeling approach would yield different results and therefore lead to different conclusions (Ekvall et al., 2020). An in-depth reflection is required to decide what would be the most appropriate end-of-life model to adopt, but this is outside of the scope of the PhD thesis. Moreover, many flows and processes related to the end-of-life treatment of complex infrastructures are not yet included in commercialized LCA databases. This means that someone would need to build this inventory for a given case study, which requires a lot of time and resources.

Despite the challenges, it is important to include the end-of-life implications in the baseline and the disaster risk scenarios because they could change the results of the LCA study. For example, in *FuturePV*, broken or destroyed PV modules would not have the same end-of-life treatment as a slightly damaged but salvageable module, which can be recycled. The differences would be more significant when addressing the repowering decisions. In such cases, modules in objectively good condition are changed for newer ones to increase the installed capacity and possibly extend the lifespan of the project. The modules in good condition can be reused elsewhere, and how this potential reuse is accounted for in terms of potential impacts or “reductions” in the impacts are considered needs to be well established when defining the impact model for LCA. Moreover, depending on the depth of the assessment, it can reveal more or less intrinsic differences between repair and repowering decisions. These are all important points of discussion to present to the decision-makers of the critical infrastructure.

### **On the case study**

*FuturePV* was developed to illustrate the application of DRUID LCI and, at the same time, aid in its development. Therefore, as stated in Chapter 4, the quantitative results obtained are not meant to be conclusive. This means that they do not provide information for direct use by decision-makers regarding the future of a PV infrastructure in a similar context. The discussions that can be made on the results pertain to the sensitivity of the models, their future capabilities in a more comprehensive and realistic study, and specificities regarding the DRUID LCI model for PV infrastructures.

Regarding the choice of the hazard for the case study, strong wind alone does not appear to be a dangerous hazard under the mountainous conditions and at the geographical location where the PV infrastructure project was imagined. This is partially due to the limited site-specific data available on the absorptive capacity, specifically the parameters defining the fragility curve, which were derived from studies conducted in the United States and the Caribbean. However, coupling strong winds with other hazards such as forest fires and their combined effects with dry soil and potential ground movement could present more important hazards and potential risks that are interesting to study in a mountainous setting. Thus, it is interesting and relevant to further develop the case study in this direction to see what else DRUID LCI can help bring into the discussion regarding compound risks and their potential environmental impacts.

In terms of territorial evolution, one possible trajectory a region in the south of France could follow for a widespread development of the PV sector is the use of large anthropized surfaces. This concerns the deployment of PV systems on large rooftops, and in abandoned or degraded terrains. Considering such cases in *FuturePV* could yield different LCA results, especially in the land use impact category given that these infrastructures would be operating in already artificialized terrains. From an environmental point of view, it is not the same to modify a natural habitat to place a PV plant than to re-use an already modified terrain. It is possible to study such differences in the potential land use impacts if the characterization factors for the different types of soils or land to compare are available. This is something worth analyzing in a future version of the case study after exploring the different characterization factors available in the Ecological Footprint method (see §5.1.3).

Regarding the flows and processes that are triggered by repair-type events in the life cycle of the PV infrastructure, inspiration can be taken from Chhabra et al. (2018) to develop inventories related to maintenance processes. In the current version of the model, it is assumed that broken components are replaced with an equivalent component with the same characteristics. To obtain a more accurate

estimation of the environmental impacts related to specific repair activities in a PV infrastructure, it is essential to know the nature of these repairs and their related material and energy flows. This would be a time-consuming task that would require working very closely with industrial partners. Also, it is possible that the contribution to the environmental impacts is of minimal magnitude, and thus could be explained by or attributed to the uncertainty and variability of results. Therefore, we must think carefully if this is a research pathway that ought to be pursued in the short-term.

Regarding the resilience study, the operational performance of the studied infrastructure could be modeled with more temporal details. For the resilience model conceived for *FuturePV*, each iteration only makes a tally of the overall electricity produced in a year and the reduced electricity production due to shocks is reflected per year. In the LCA model, the electricity production is estimated also through the annual production. However, the level of shocks is known in advance, thus the model considers that the percentage of installed capacity to be repaired is not producing electricity for a certain portion of the year depending on the level of shocks perceived. This means that in the resilience study, the impacts on electricity production year by year are currently overestimated. A more refined estimation may allow for the direct input of electricity production data from the resilience study into the LCA model.

When addressing the prospective perspective in the resilience study, it must be considered that the PV modules installed after repowering could change. Newer PV modules built with different materials tend to be more sensitive to external effects and can be more easily damaged when operating out in the open (Aghaei et al., 2022). Moreover, PV failure modes are complex and as technologies evolve, they are expected to increase in complexity. This introduces challenges at the absorptive capacity level. The related failure modes and fragility curves are different for each PV module type to be produced at different points in the future. This means that newer PV modules most likely will not react the same way versus the same type of hazard as those installed for the baseline PV system. Introducing these dynamic aspects to the resilience model could lead to a very complex model with many uncertainties from the prospective side, the disaster risk characterization, the possible failures and their intensities, as well as the repair or repowering possibilities. In turn, this could introduce too many uncertainties to the LCA results to the point where the results themselves might not be significant or too stochastic to draw any relevant conclusions. Thus, the inclusion of complex dynamic aspects is a point that requires further thought but may be worth exploring.

In *FuturePV*, the same type of multi-Si module was chosen for the baseline and the repowered PV system. The only difference between the two was the module efficiency. Thanks to this assumption, the need to consider different fragility curves versus wind gust for each module type was avoided. Something that was not considered in the case study is that even if the same type of PV module is used for repowering, we can expect slight changes in inventory flows, probably making the environmental impact results slightly less intense than what has been obtained in the case study. This could be due to manufacturing processes that are potentially less material and energy intensive.

Another assumption made in *FuturePV* was regarding the increase in module efficiency depending on the repowering year. Specifically, a PV system repowered after the 20<sup>th</sup> year was more efficient (24%) than those repowered after the 10<sup>th</sup> year (22%). This was done to represent possible changes in future PV modules in the model, thus introducing a dynamic aspect mentioned previously in a relatively simple way. Results obtained pointed to potential advantages on the energy production side by as much as 20% increase versus the baseline in scenarios when repowering was done as early as

possible, but environmental impacts were higher. Repowering after the 20<sup>th</sup> year with the more efficient modules also showed increased electricity production when the repowering was done as early as possible (i.e. exactly at the 20<sup>th</sup> year), with environmental impact results generally lower than the scenarios with less efficient modules. Results of this type could be valuable to decision-makers in the planning phase of an infrastructure project of this type.

It should also be noticed that, in the context considered for *FuturePV*, the environmental consequences of the damages to the PV infrastructure components only result in additional consumptions of the input elements and the upstream emissions associated with their manufacturing stages. However, other types of damage could involve additional emissions that occur at the installation site itself, as well as upstream and downstream emissions that in principle are not expected when modeling the baseline LCA. For example, the consequences of damages to PV systems due to forest fires could involve the release of pollutants as components burn on site, the manufacturing-related impacts to replace said components, and the end-of-life-related impacts to dispose of burnt components containing plastic, glass, minerals, and metals. In the future, it would be interesting to apply DRUID LCI in such contexts.

While collecting information in the PV sector in France, I have gained some insights that I think are worth sharing at this stage.

From comments received throughout the development of this thesis, I am aware that repowering possibilities as financial strategies are becoming more important in the PV industry, with some companies even incorporating a financial analysis to determine the best moment to repower. Despite the deployment of repowering schemes, to my knowledge, there is currently no requirement to consider their influence on the environmental assessments needed to respond to “calls for projects” for PV infrastructure projects in France. Based on the results from this PhD, it seems important to consider repowering during this planning phase from an economic and environmental point of view, with emerging crucial questions related to the possibilities recycling versus reusing.

Finally, when it comes to addressing project proposals to develop PV in a region, it is important to be strict about the sustainability criteria used to determine the projects that are submitted and admitted. Of course it is a business venture for some actors, but the sustainable development of the energy sector is fundamental to that of surrounding communities, and the wellbeing of the population should be the priority. This well-being includes looking out for the health of the people and of the environment around them since they are intrinsically connected. Thus, projects accepted should be as close as possible to the sustainability principles while considering all that can go wrong with the project because of external factors that we cannot permit ourselves to ignore, such as natural and technological disasters. If projects can perform well despite these misgivings, and the possible actions that can be taken in the face of disasters are well documented, implemented, and there is the right support such as insurance, land use management, and protective barriers, then these goals have a better chance of being achieved.

### **Future work**

Due to time constraints, it was not possible to carry out the General Morphological Analysis (GMA) to the letter as recommended by Ritchey (2011b), specifically the workshops with up to 7 subject-matter experts for the morphological matrix exercise. Revisiting the GMA method, how it has been used for scenario building based on future trends, and reflecting on its advantages, disadvantages, and the opportunities it offers to DRUID LCI is an ongoing exercise. This PhD thesis has made a novel

methodological proposition that aids in revealing additional insights on LCA results, and by continuing to test and analyze the method it can further evolve to provide more robust results through science-based approaches.

In general, the idea behind presenting DRUID LCI through *FuturePV* in this PhD thesis is to give content to the methodological concepts presented since some of them can be rather abstract. As previously mentioned, the short-term goal is to further refine the method and properly develop a manual with the methodological guidelines, accompanied by multiple examples at each step. A 12-month post-doctoral project has been established to pursue this objective. It is financed in the framework on the Carnot M.I.N.E.S. flagship project 2023-2026 ELECTRE (Electrification des usages pour la Transition Énergétique).

## Closing thoughts

In general, LCA reveals information about the potential environmental impacts of a project. This method aims to translate complicated results into clear science-based estimations that provide aid to critical decision-making activities. I think this role that LCA plays is especially needed now, while the world is changing due to accelerated climate change and its multi-dimensional consequences on human populations and natural systems. As I am writing this, we are experiencing the hottest recorded day of summer, and I am sad to say it will likely not be the last time such a record is beaten. Fortunately, there are a lot of people working day and night to contribute to the change that needs to happen to mitigate the impacts of hotter summers. The LCA community has a lot of people like this.

When I look at the people working in LCA, I see a community that wants to convey an important message. It's not about being alarmist or condemning someone or an institution. It also goes beyond awareness. Of course, to figure out how to fix a problem, we first need to know how to fix it. The messages we want to transmit, why we bother with looking at the whole life cycle, why we want to get a global and comprehensive view of the potential environmental impacts of a product system is because we want decisions to be taken with conscience founded in scientific facts and methods. Granted, science relies in estimations and calculations, and contrary to what we might expect, it is not always exact. However, to make the best possible estimations that reflect the potential consequences of a product system, it is crucial to have the necessary information, which relies on the cooperation of stakeholders across the lifecycle stages. It is difficult or outright impossible to measure the exact input and output flows involved in a process; something is only perfect in pure calculations. But with sufficient understanding, communication, transparency, and regulation, the LCA scientific community can aid in producing assessments that generate pertinent information for industrial, political, and regulatory actors and their activities.

In a more critical note, LCA is not a silver bullet that will reveal all truths of the environmental impacts of a system, nor will it provide all the information decision-makers need to make the best possible choices in the context of sustainable development. What LCA can do, and an important reason why the LCA community continues to innovate, is provide a glimpse of the potential impacts we have on the environment, and as these glimpses become clearer and clearer, we gain a better idea of the actions that can be taken at different levels to mitigate and hopefully avoid certain damages.

I believe that DRUID LCI has the potential to make a significant contribution that can help make these glimpses clearer. Of course, it still needs more work to make itself clearer, and that is why I have chosen to continue working on this research topic.





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## Conferences and Publications

**33rd Annual Meeting of the Society of Environmental Toxicology and Chemistry (SETAC) in Europe**, hosted in Dublin, Ireland from April 30 to May 4, 2023. Oral presentation titled: “*Methodological approach to account for natural hazards in the Life Cycle Assessment of the energy production sector*”, in the session “LCA and Beyond – Integrating Sustainability and/or Other Dimensions for a More Comprehensive Analysis”. The abstract was published in the Abstract Book.

**French-German Ph.D. Workshop on “Increasing resilience of pandemic-disrupted supply chains through international cooperation and the use of artificial intelligence”** at the Freiberg University of Mining and Technology, in Freiberg, Germany, from March 20 to 22, 2023.

**10<sup>th</sup> Resilience Engineering Symposium**, in Sophia-Antipolis, France from June 26–30, 2023, organized by the Resilience Engineering Association, that has its head offices at CRC in Sophia Antipolis, France. Poster presentation.

**34<sup>th</sup> Annual Meeting of the Society of Environmental Toxicology and Chemistry in Europe**, hosted in Seville, Spain, from May 5 to 9, 2024. Poster and flash oral presentation: “*Considering the evolution of the risk of natural and technological disasters while applying Life Cycle Assessment: a morphological analysis-based prospective method*”, in the session “LCA and Beyond – Integrating Sustainability and/or Other Dimensions for a More Informed Decision-Making”. The abstract was published in the Abstract Book.

**41<sup>st</sup> European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC)**, held in Vienna, Austria, from September 23 to 27, 2024. Poster presentation: “*Considering the environmental consequences of the evolution of the risk of extreme natural events on a PV installation: a morphological analysis-based prospective method applied to Life Cycle Assessment*”, in the session “Topic 5: PV in the Energy Transition, Subtopic 5.2: Sustainability of PV”.

## Annexes

### Annex I. Data description

#### Wind speed and wind gust data

##### Coordinates:

Lat	43.7936
Lon	6.653777

##### **Reanalysis**

*CERRA sub-daily regional reanalysis data for Europe on single levels from 1984 to present*

DATA DESCRIPTION	
<b>Data type</b>	Gridded
<b>Projection</b>	Lambert conformal conical grid
<b>Horizontal coverage</b>	Europe. The model domain spans from northern Africa beyond the northern tip of Scandinavia. In the west it ranges far into the Atlantic Ocean and in the east it reaches to the Ural Mountains.
<b>Horizontal resolution</b>	5.5 km x 5.5 km for CERRA high-resolution reanalysis 11 km x 11 km for CERRA ensemble members
<b>Vertical coverage</b>	From below the surface to the top of the atmosphere
<b>Vertical resolution</b>	Single level
<b>Temporal coverage</b>	September 1984 - June 2021
<b>Temporal resolution</b>	Analysis data: 3-hourly for high-resolution, 6-hourly for ensemble members Forecast data: hourly for forecast range 1 - 6 (high-resolution and ensemble members), 3-hourly for forecast range 6 - 30 (high-resolution only)
<b>File format</b>	GRIB2
<b>Update frequency</b>	New data will be added towards the end of 2024

VARIABLES		
Name	Units	Description
10m wind gust since previous post-processing	m s <sup>-1</sup>	The 10 metre wind gust speed is the maximum wind speed since the last post-processing at the grid area. It is determined for a height of 10m above the surface. The value is the maximum since the previous post-processing. For instance, for the first saved time step at forecast 1h it is the maximum wind speed, which occurred within the first hour of the forecast. For the second saved time step at forecast 2h, it is the maximum wind speed which happened in the second forecast hour, hence between fc1 and fc2.
10m wind speed	m s <sup>-1</sup>	The 10m wind speed is the wind speed valid for the grid area determined for a height of 10m above the surface. It is computed

		from both the zonal (u) and the meridional (v) wind components by $\sqrt{u^2 + v^2}$ . Given values are instantaneous.
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Source: <https://cds.climate.copernicus.eu/datasets/reanalysis-cerra-single-levels?tab=overview>

## Prospective

*Climate and energy indicators for Europe from 2005 to 2100 derived from climate projections*

DATA DESCRIPTION	
<b>Data type</b>	Gridded and aggregated over shapes
<b>Horizontal coverage</b>	European domain (27N - 72N; 22W - 45E)
<b>Horizontal resolution</b>	0.25° x 0.25°
<b>Vertical coverage</b>	0 to 100 metres depending on the variable
<b>Vertical resolution</b>	Single level
<b>Temporal coverage</b>	From 2005 to 2100
<b>Temporal resolution</b>	3 hourly or daily
<b>File format</b>	NetCDF or CSV (spatial aggregation dependant)
<b>Versions</b>	Only one version of the dataset is available
<b>Update frequency</b>	No updates expected

VARIABLES		
Name	Units	Description
Wind speed at 10m	m s <sup>-1</sup>	Magnitude of the two-dimensional horizontal air velocity at 10 metres. The data represents the mean area average over three area aggregations: grid point, country level (NUTS level 0), sub-country level (NUTS level 2) and maritime regions (MAR level 0 and MAR level 1). The data values are instantaneous measures.

Source: <https://cds.climate.copernicus.eu/datasets/sis-energy-derived-projections?tab=overview>

## Annex II. Parameters for the LCA inventory

The parameters and parameter groups are based on PARASOL\_LCA, developed by Besseau et al. (2023).

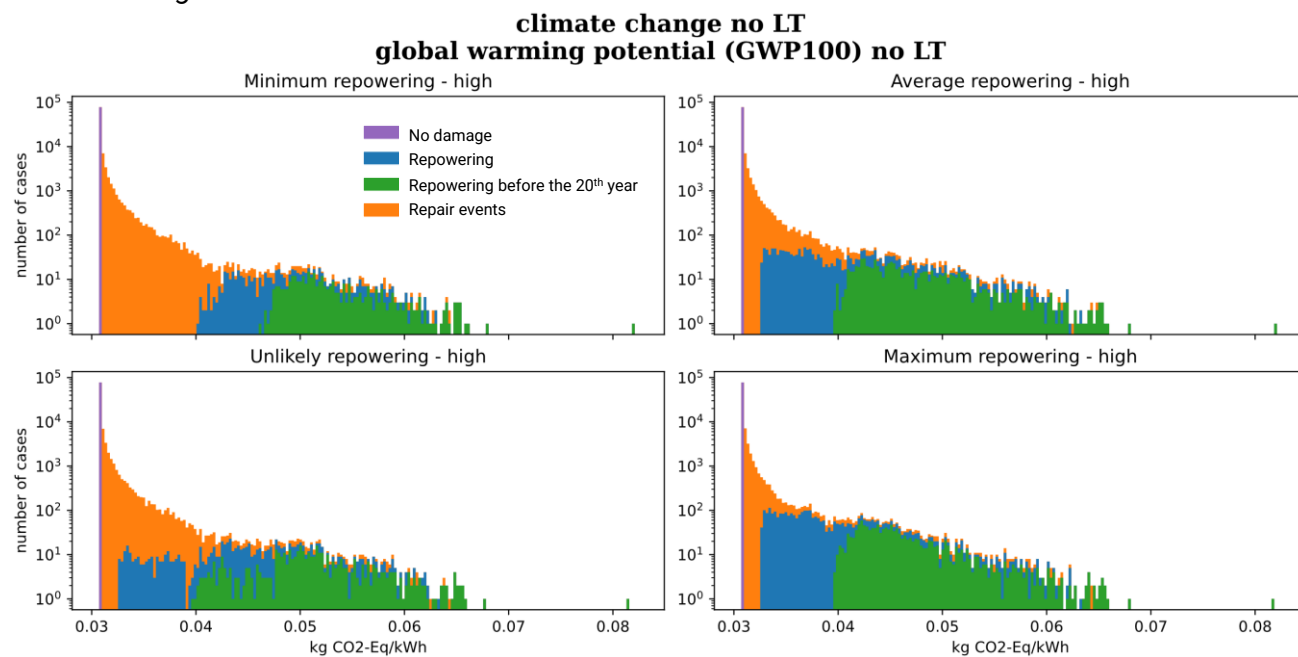
Parameter group	Parameter name	Description	Case study value	Unit
<b>Mounting system</b>	Roof vs. ground ratio	Proportion of rooftop installations	0	Fraction
	Mounting system total weight	Total weight of the mounting system	5	kg/m <sup>2</sup>
	Mounting system aluminum weight	Total weight of aluminum contained in the mounting system	1.5	kg/m <sup>2</sup>
	Mounting system wood weight	Total weight of wood contained in the mounting system	0	kg/m <sup>2</sup>
	Ground coverage ratio	The ratio of a PV array area to the total ground area	0.45	Fraction
<b>Silicon production</b>	Silicon electricity intensity	Electricity used for refining and ingot production	30	kWh/kg
	Silicon heat intensity	Heat used for metallurgical silicon production	0	MJ/kg
	Silicon casting electricity intensity	Electricity used for silicon casting	19.125	kWh/kg
<b>Wafer production</b>	Diamond wiring	Use of the diamond wire cutting process for silicon panels	1	Boolean
	Wafer thickness	Thickness of the Si wafer	180	μm
	Kerf loss	Share of material that is lost in the form of powder during the cutting process	0.5	Fraction
	Silicon carbide recycling rate	Share of the recycled silicon carbide used	0.69	Fraction
	Manufacturing electricity gains	Introduced to consider the effect of a potential improvement in future manufacturing processes	0	Fraction
<b>PV manufacturing</b>	Electricity mix	Electricity mix used to manufacture the PV modules	CN (China)	-
	Silver content	The amount of silver used in the metallization paste	2	g/m <sup>2</sup>
	Aluminum frame surface weight	Weight of the aluminum frame per square meter of PV module	1.5	kg/m <sup>2</sup>
	Bifacial modules	Use of bifacial modules, i.e. a backsheet PV panel or a glass–glass PV panel	0	Boolean
	Glass thickness	Thickness of the glass used on PV panels	3	mm
<b>PV system</b>	PV module efficiency, system 1	Efficiency of the PV module technology used in the base system	0.175	kWp/m <sup>2</sup>
	PV module efficiency, system 2	Efficiency of the PV module technology used in the repowered system	$\eta_2$	kWp/m <sup>2</sup>

	Electrical installation specific weight	Weight of the electrical installation components, i.e. cables, low voltage panel, etc. per installed capacity	2.5	kg/kWp
	Inverter weight	Weight of the inverter per installed capacity	2	kg/kWp
	Inverter lifetime	Operational lifetime of an inverter	15	Years
	PV installation capacity, system 1	Installed capacity of the PV installation	1000.00	kWp
	PV installation capacity, system 2	Installed capacity of the repowered PV installation	$P_2$	kWp
<b>Transportation</b>	Transport distance, freight	Distance travelled by freight to transport the PV installation's components to the installation site	8000	km
	Transport distance, train	Distance travelled by train to transport the PV installation's components to the installation site	500	km
	Transport distance, lorry	Distance travelled by lorry to transport the PV installation's components to the installation site	1000	km
<b>Operation</b>	System lifetime	Expected operational lifetime of the PV installation	30	Years
	Annual specific yield	Normalized annual electricity produced per kWp installed	1400	kWh/kWp /year
	Degradation rate, system 1	Degradation rate of PV module technology used in the base system	0.7	Percent
	Degradation rate, system 2	Degradation rate of PV module technology used in the repowered system	0.7	Percent
<b>Recycling</b>	Aluminum recycling rate	Rate of recycling of aluminum	0.96	Fraction
	Copper recycling rate	Rate of recycling of copper	0.75	Fraction
	Glass recycling rate	Rate of recycling of glass	0.9	Fraction
	Recycling rate	Overall recycling rate for other materials	0.9	Fraction
	Electricity consumption for recycling	Amount of electricity necessary to recycle the PV panels based on the IEA task 12	50	kWh/t
	Heat consumption for recycling	Amount of heat necessary to recycle the PV panels based on the IEA task 12	76	MJ/t

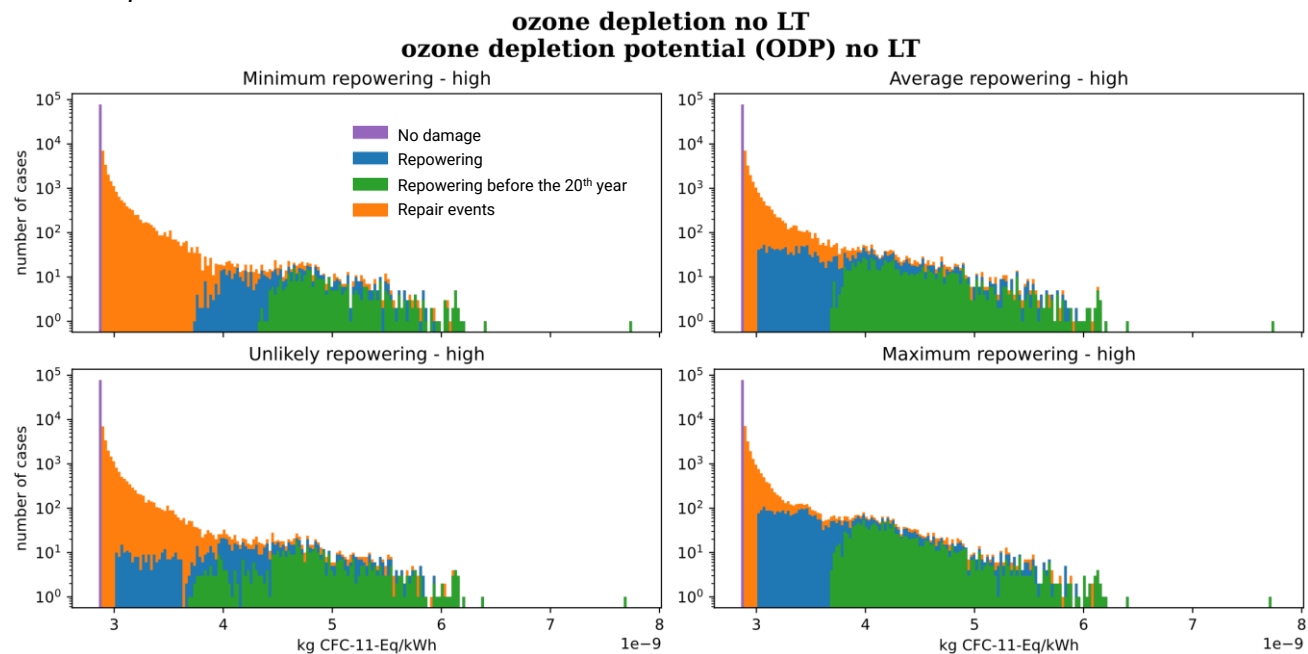
## Annex III. LCA results

### Higher repowering threshold

#### Climate change

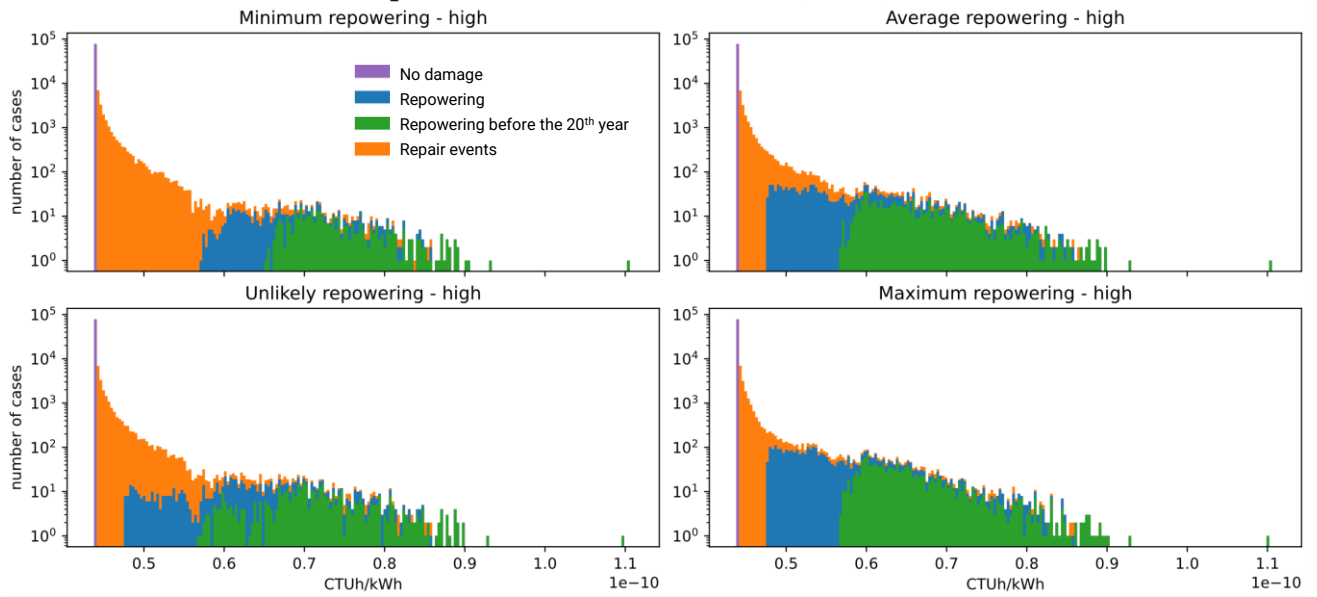


#### Ozone depletion



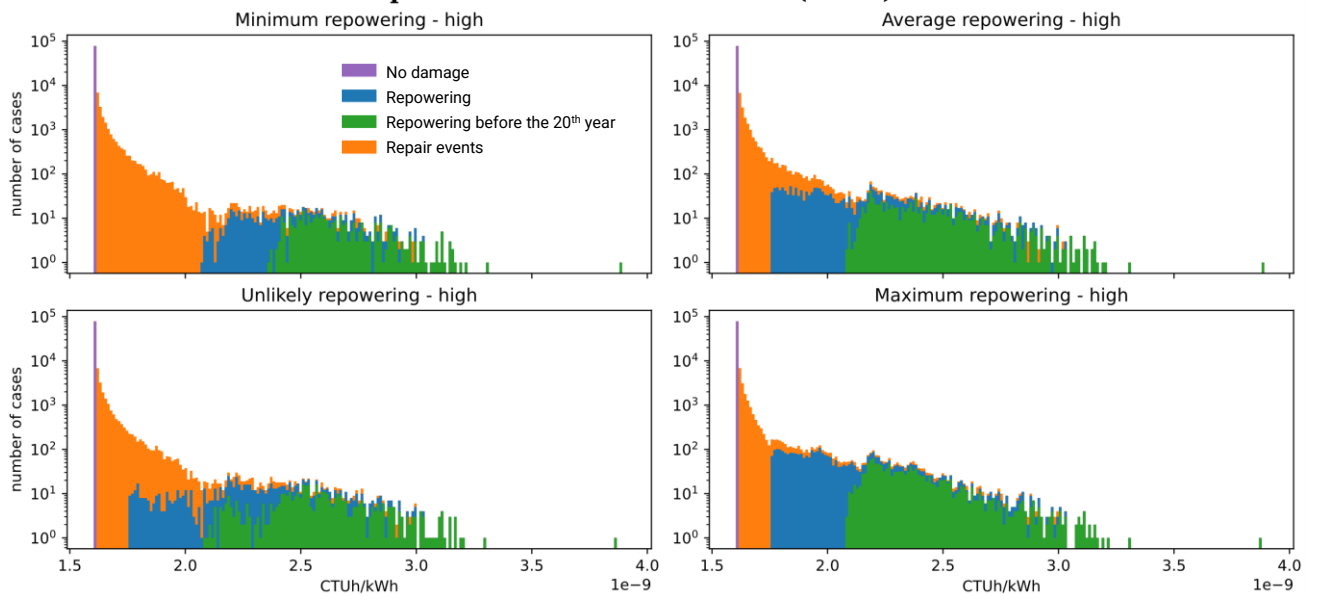
Human toxicity: carcinogenic

**human toxicity: carcinogenic no LT  
comparative toxic unit for human (CTUh) no LT**



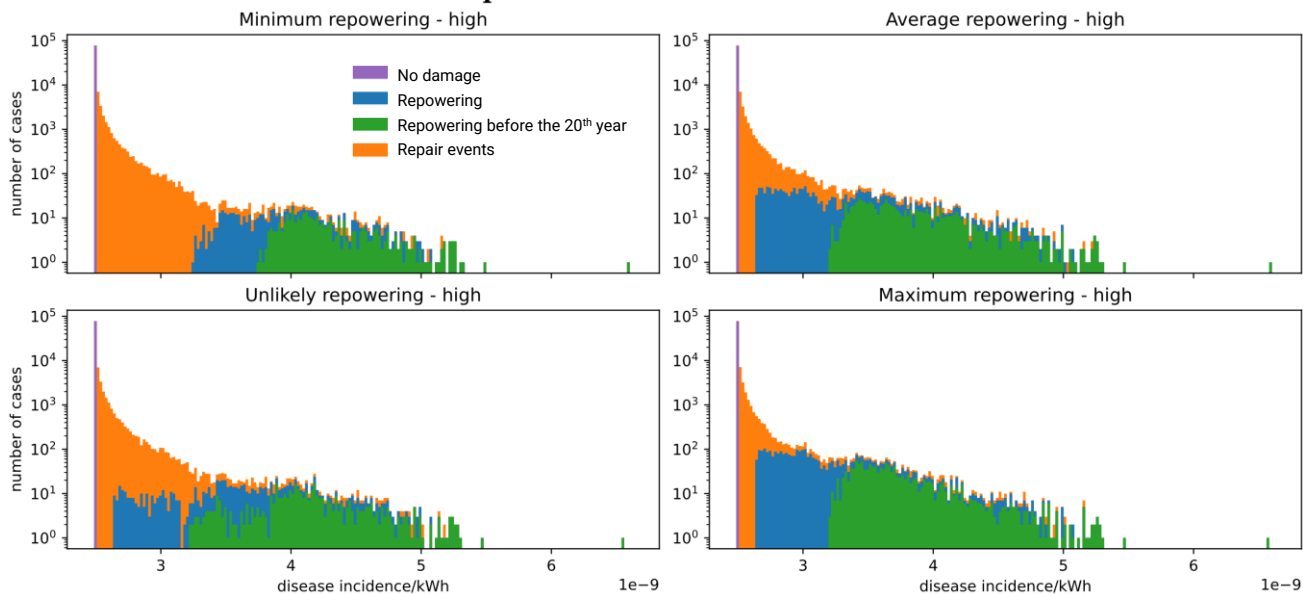
Human toxicity: non-carcinogenic

**human toxicity: non-carcinogenic no LT  
comparative toxic unit for human (CTUh) no LT**



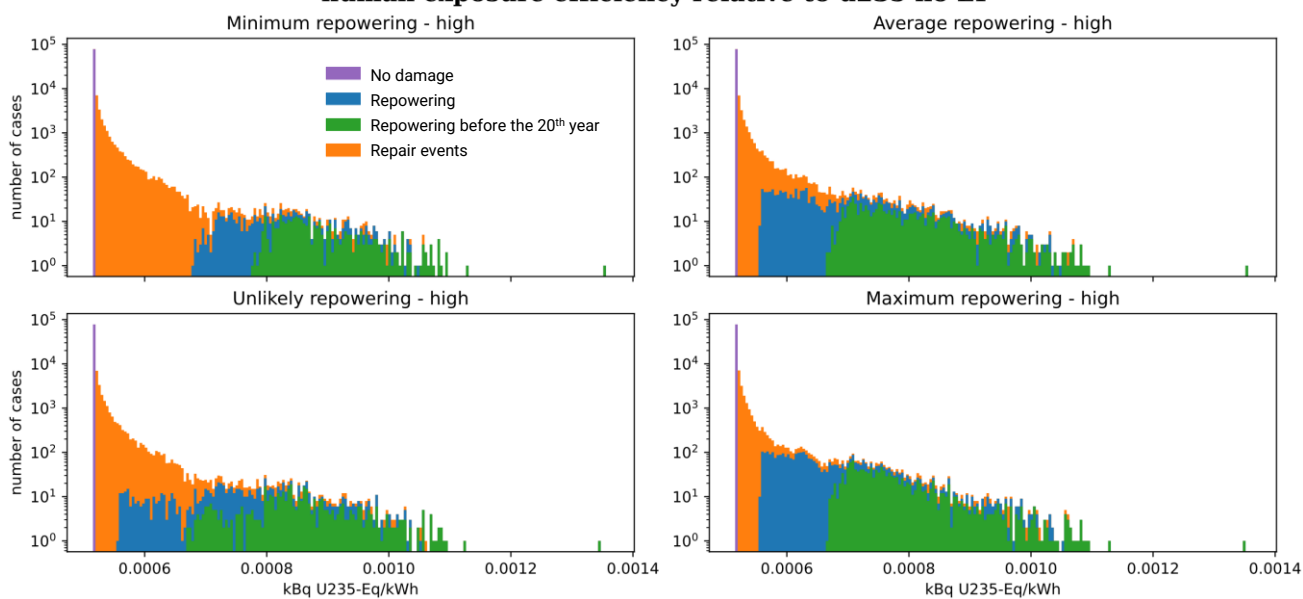
## Particulate matter

**particulate matter formation no LT  
impact on human health no LT**



## Ionizing radiation

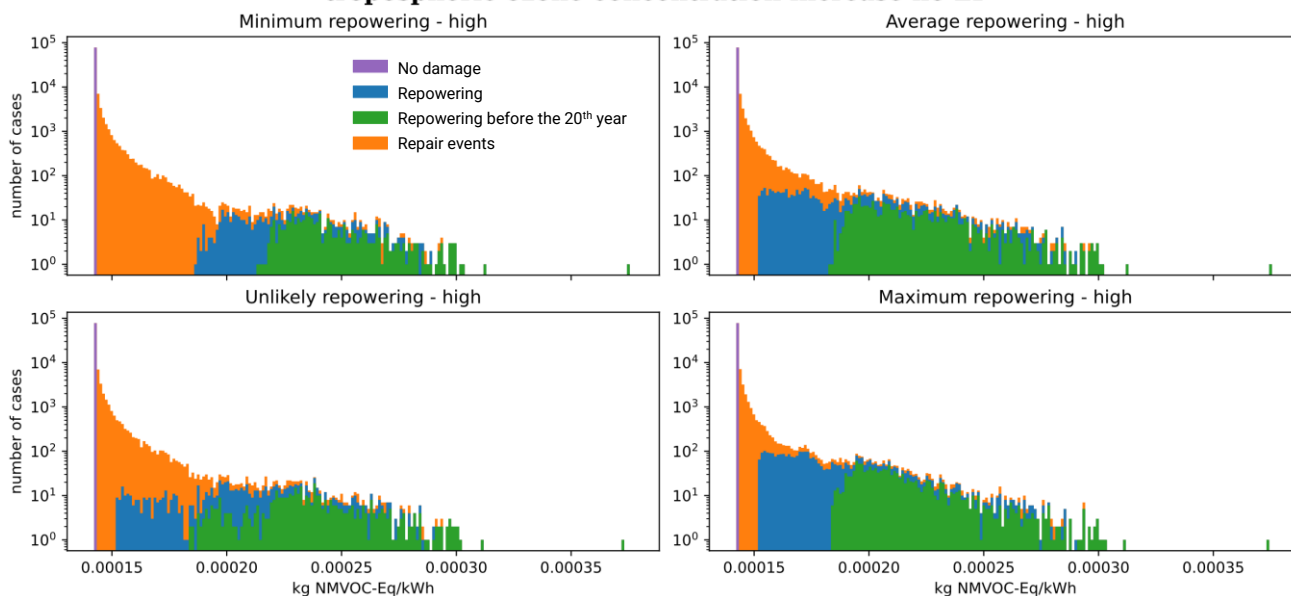
**ionising radiation: human health no LT  
human exposure efficiency relative to u235 no LT**





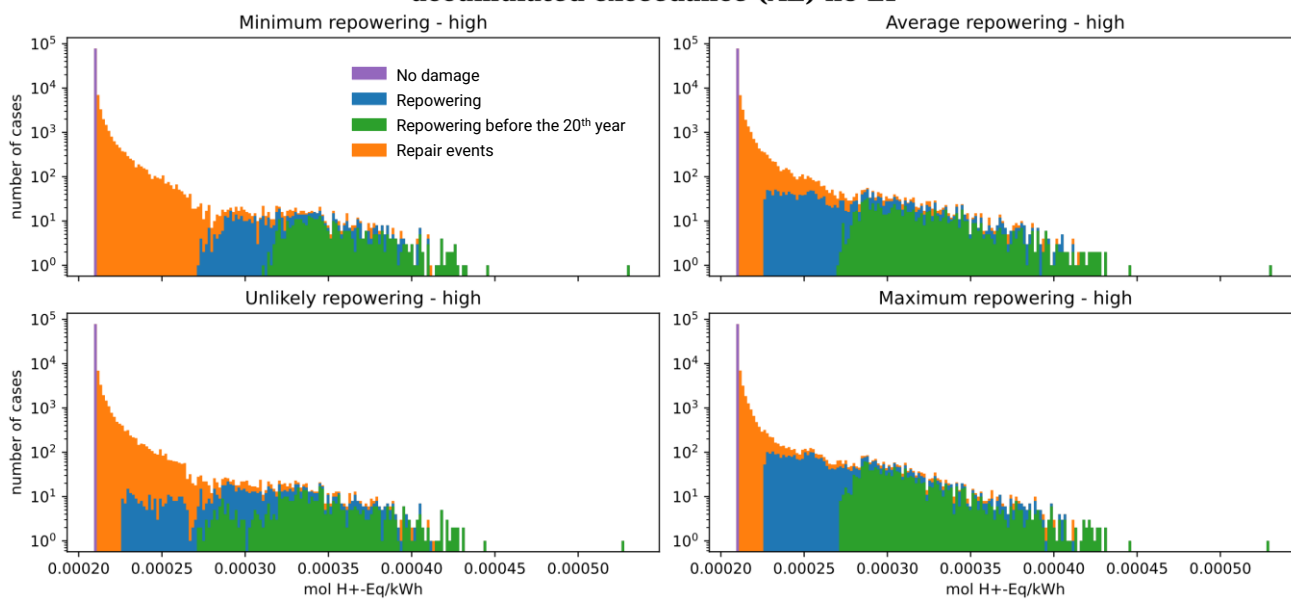
Photochemical oxidant formation

**photochemical oxidant formation: human health no LT  
tropospheric ozone concentration increase no LT**

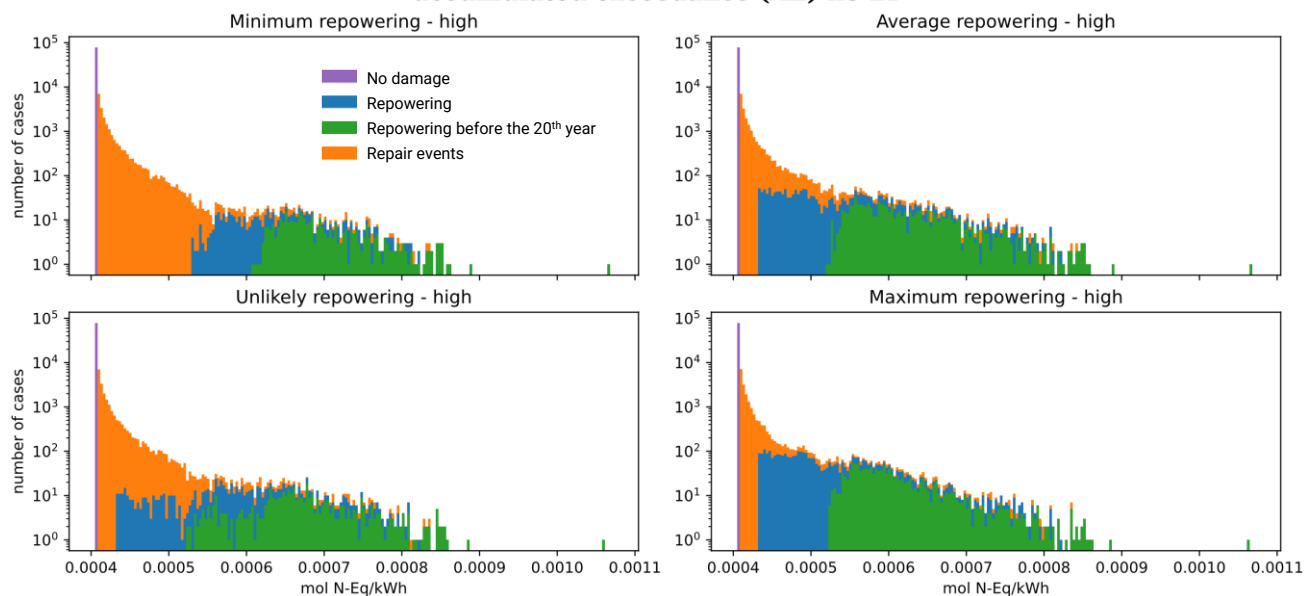


Acidification

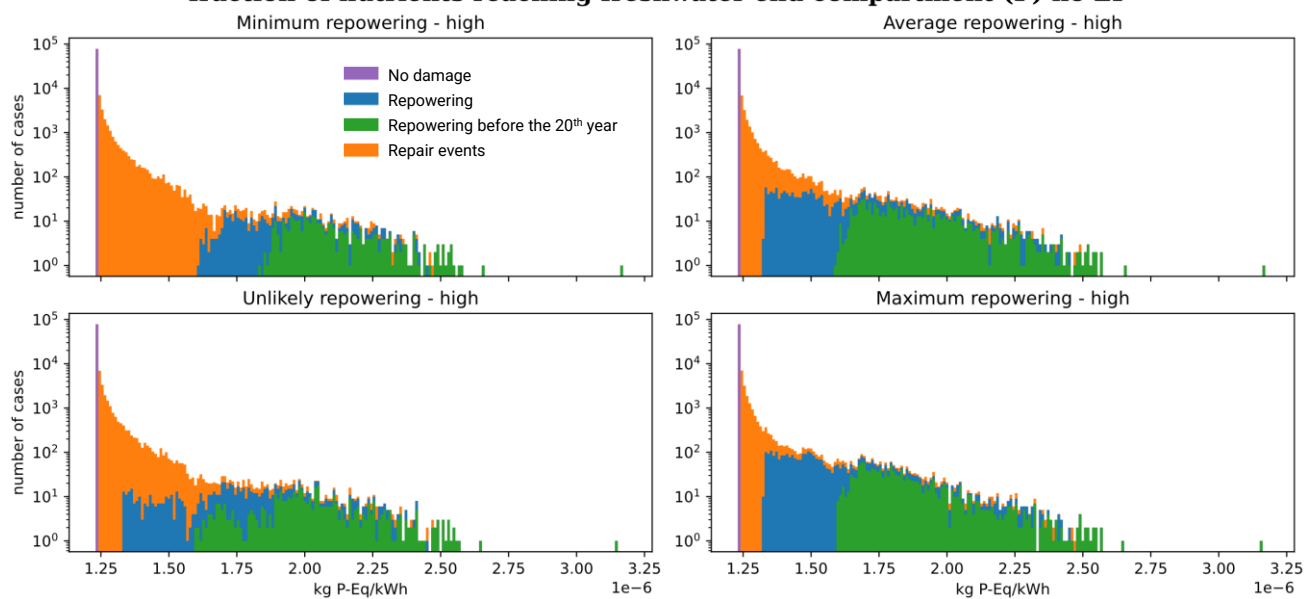
**acidification no LT  
accumulated exceedance (AE) no LT**



## Eutrophication: terrestrial

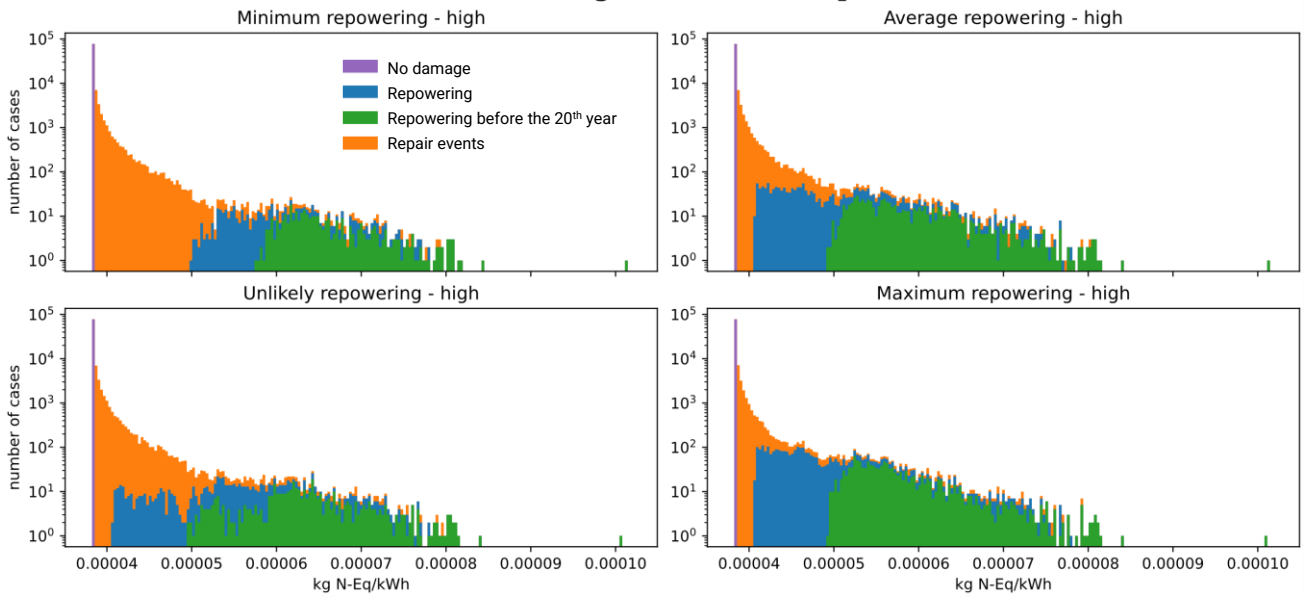
eutrophication: terrestrial no LT  
accumulated exceedance (AE) no LT

## Eutrophication: freshwater

eutrophication: freshwater no LT  
fraction of nutrients reaching freshwater end compartment (P) no LT

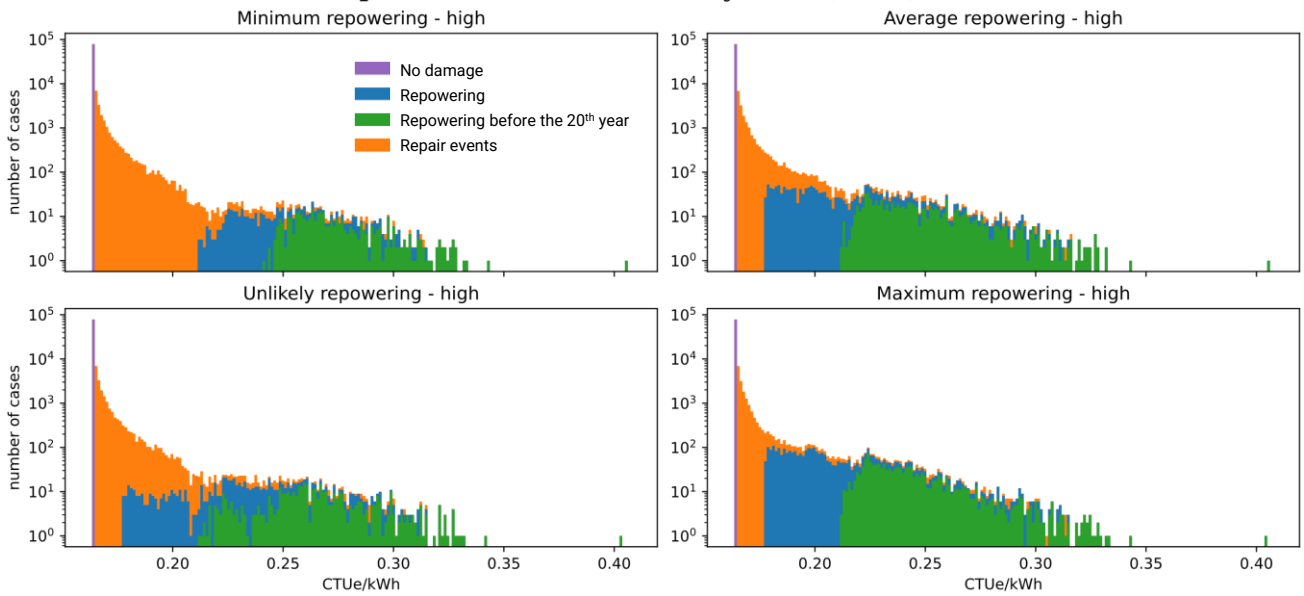
Eutrophication: marine

**eutrophication: marine no LT**  
**fraction of nutrients reaching marine end compartment (N) no LT**

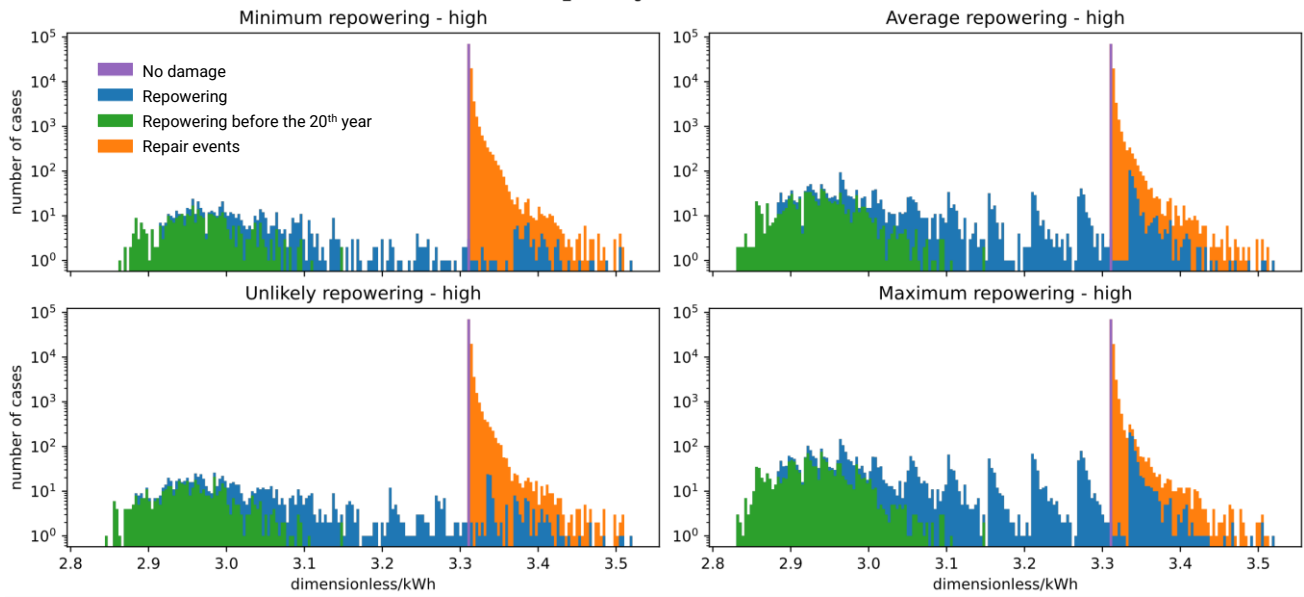


Ecotoxicity

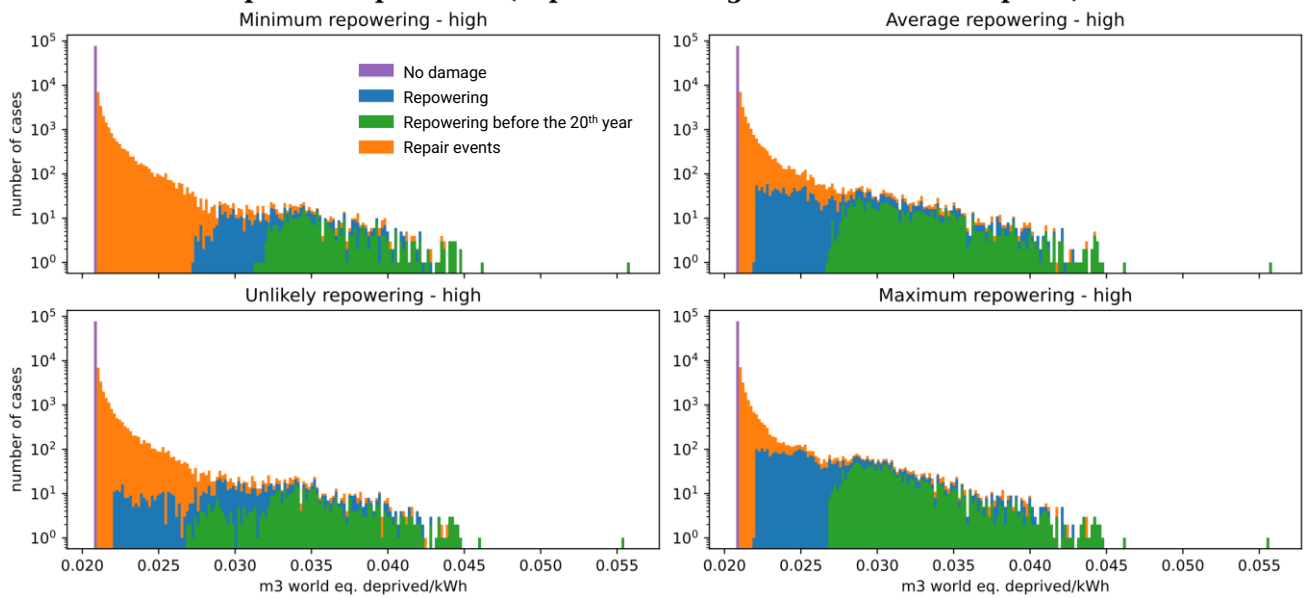
**ecotoxicity: freshwater, inorganics no LT**  
**comparative toxic unit for ecosystems (CTUe) no LT**



## Land use

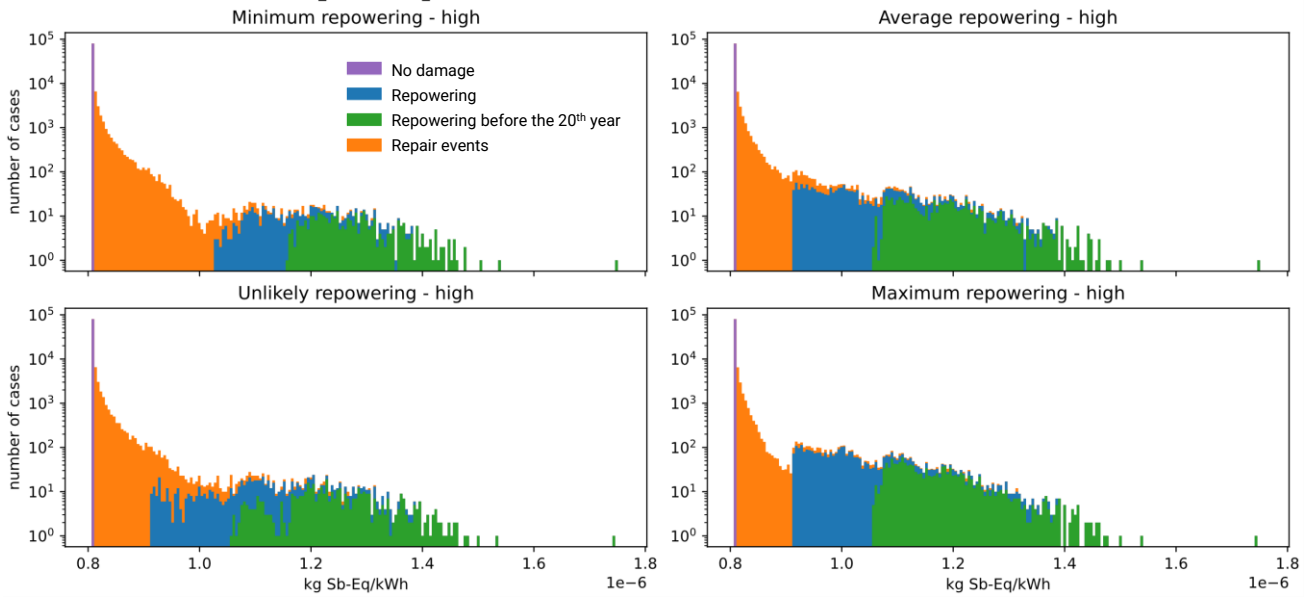
land use no LT  
soil quality index no LT

## Water use

water use no LT  
user deprivation potential (deprivation-weighted water consumption) no LT

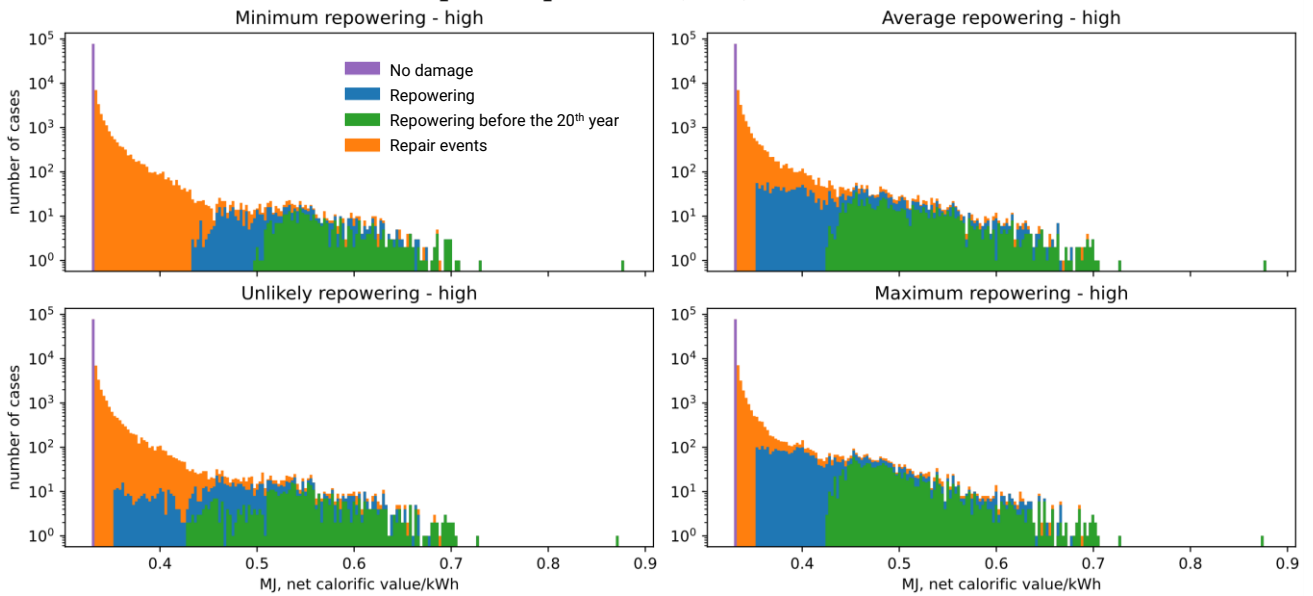
Material resources: metals and minerals

**material resources: metals/minerals no LT**  
**abiotic depletion potential (ADP): elements (ultimate reserves) no LT**



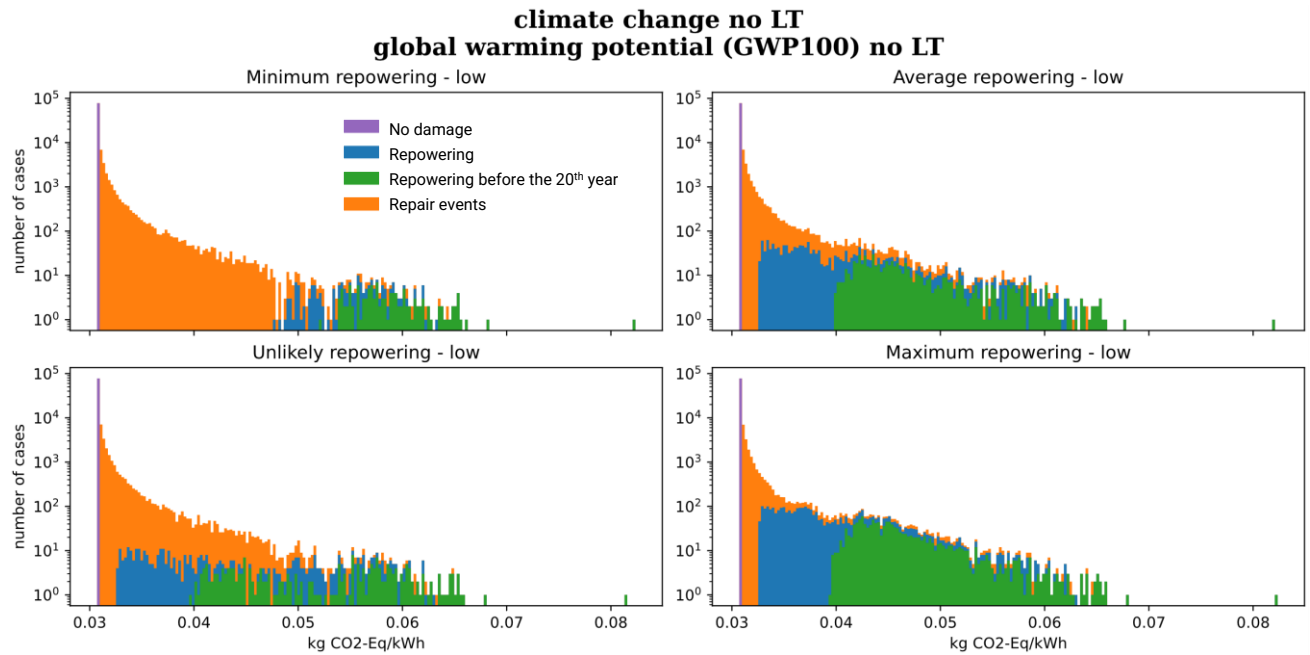
Energy resources

**energy resources: non-renewable no LT**  
**abiotic depletion potential (ADP): fossil fuels no LT**

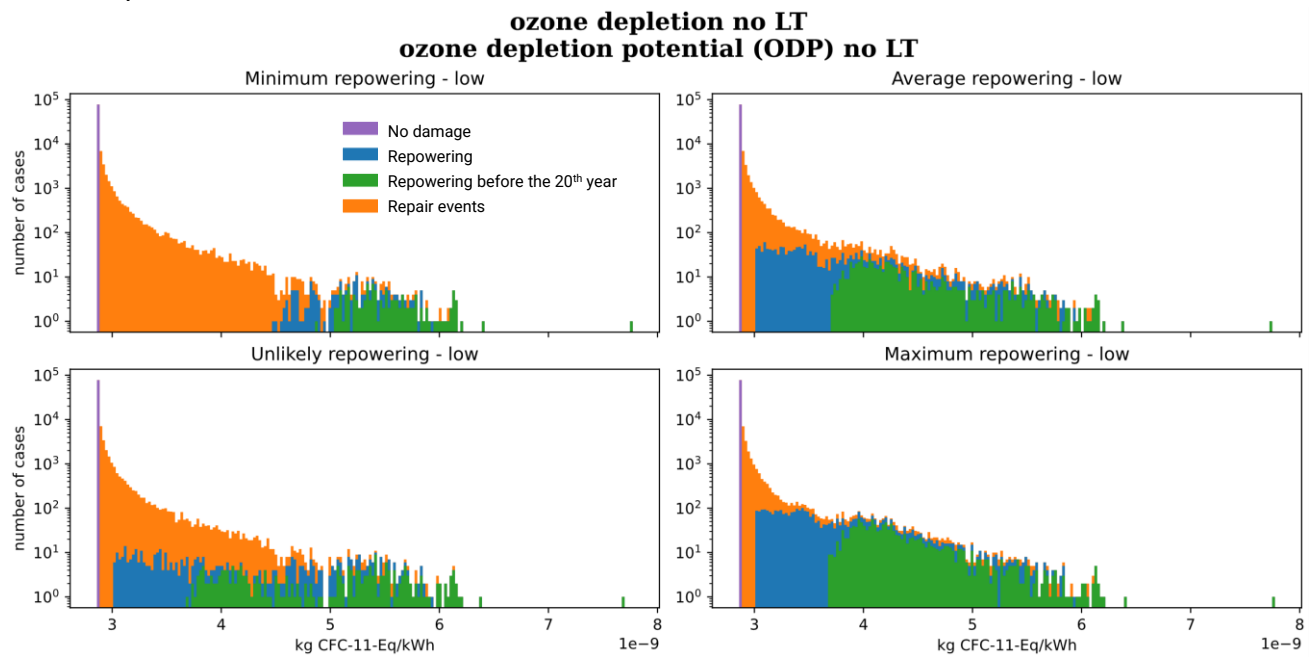


## Lower repowering threshold

### Climate change

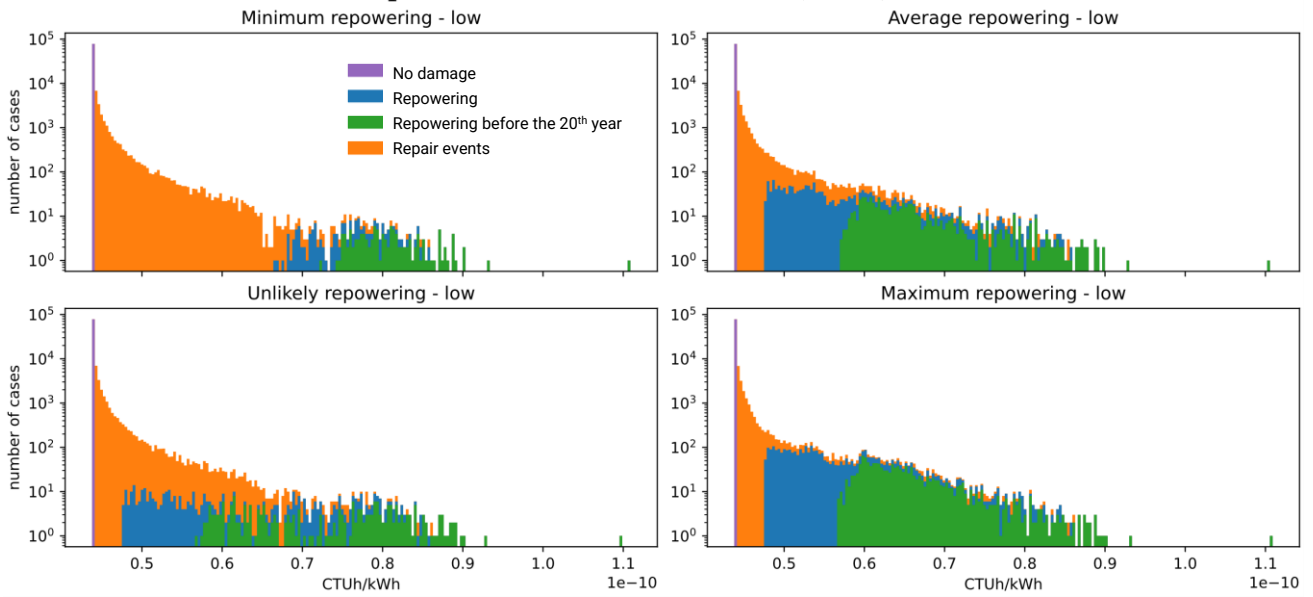


### Ozone depletion



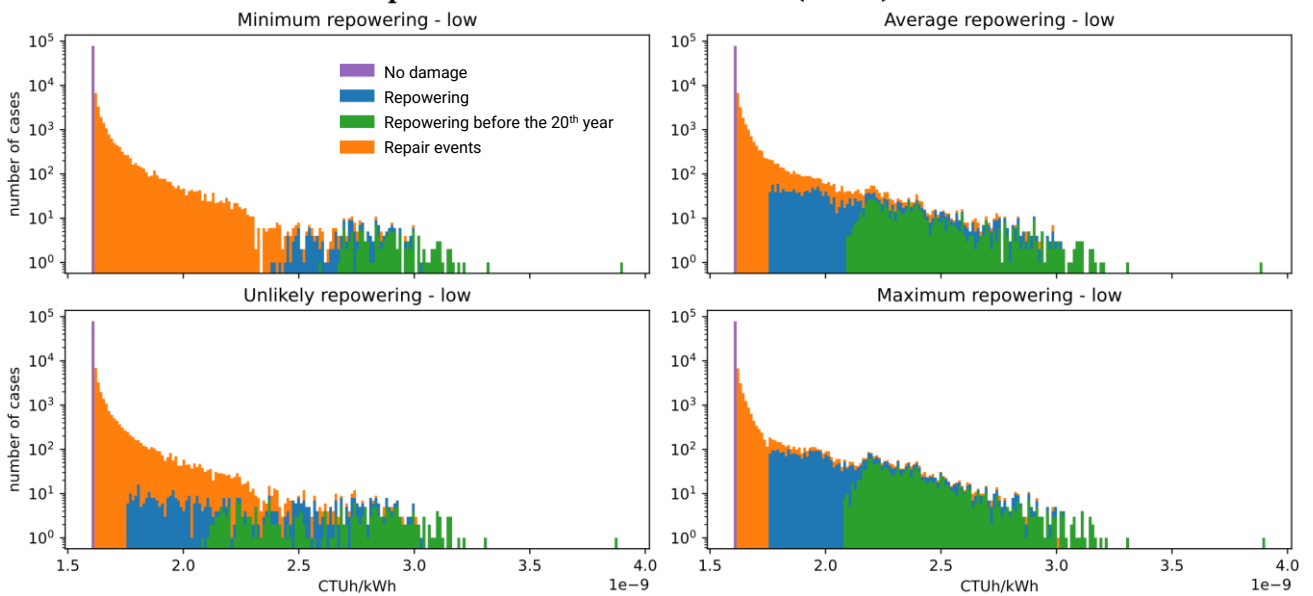
Human toxicity: carcinogenic

**human toxicity: carcinogenic no LT  
comparative toxic unit for human (CTUh) no LT**



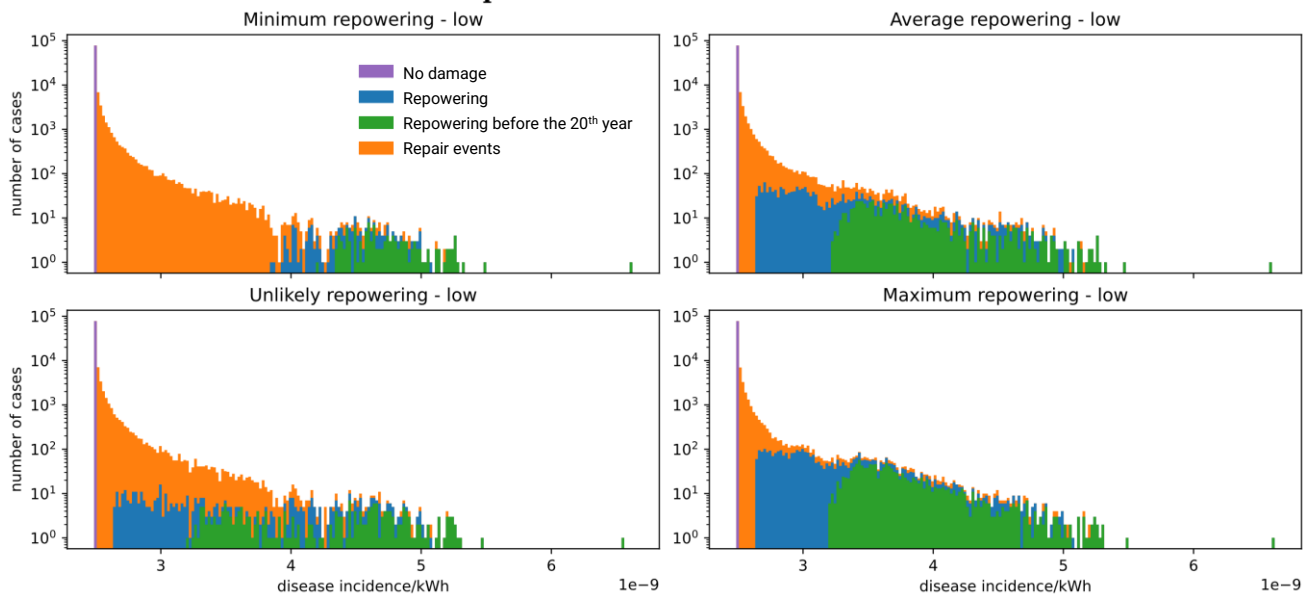
Human toxicity: non-carcinogenic

**human toxicity: non-carcinogenic no LT  
comparative toxic unit for human (CTUh) no LT**



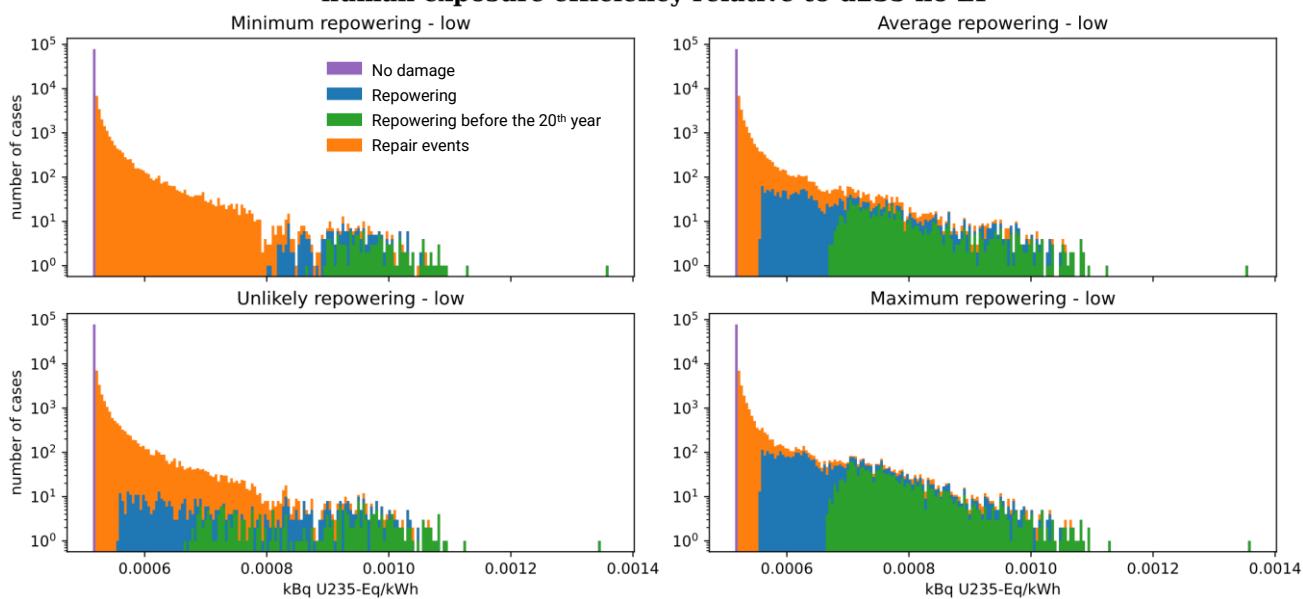
## Particulate matter

**particulate matter formation no LT  
impact on human health no LT**



## Ionizing radiation

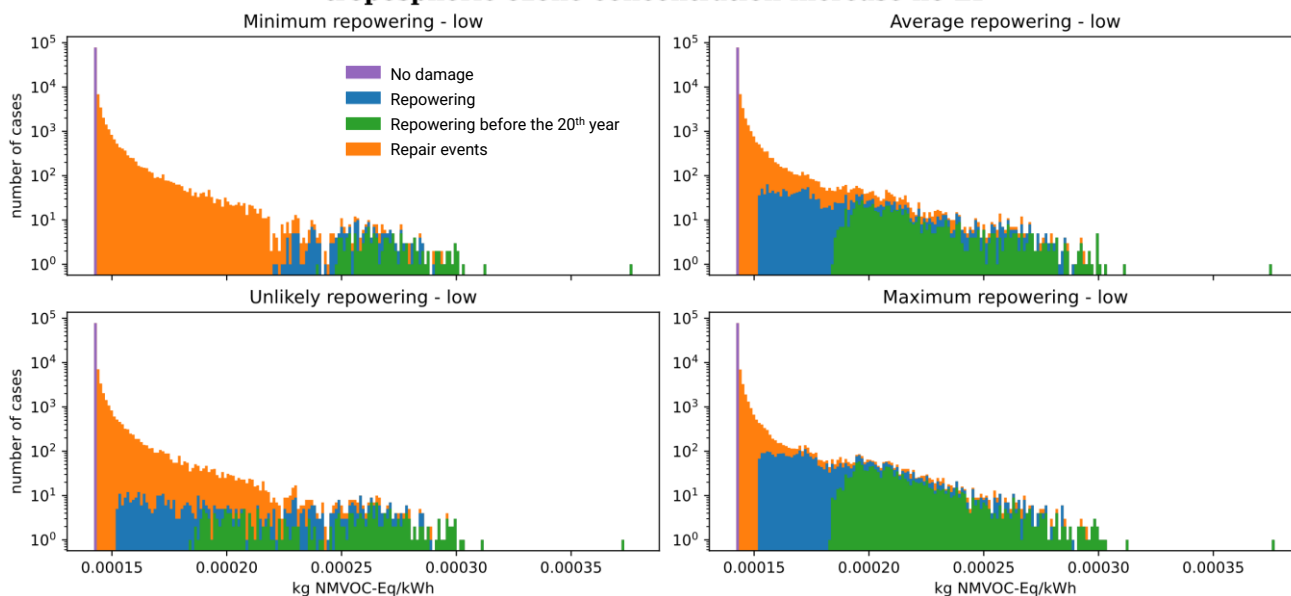
**ionising radiation: human health no LT  
human exposure efficiency relative to u235 no LT**





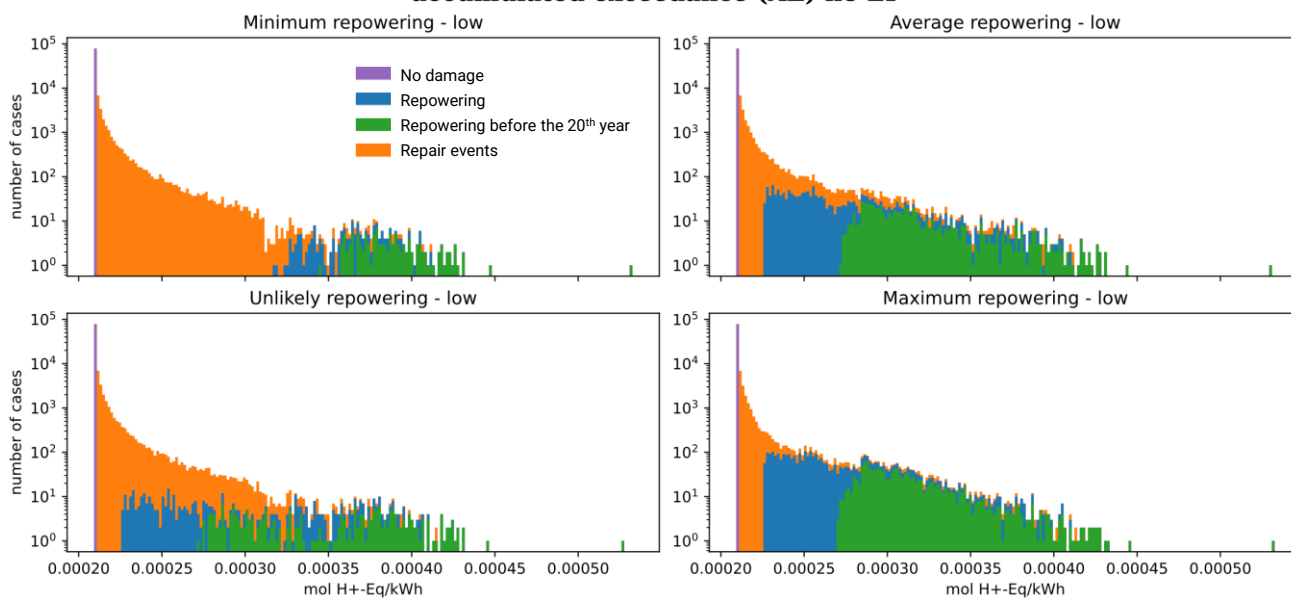
Photochemical oxidant formation

**photochemical oxidant formation: human health no LT  
tropospheric ozone concentration increase no LT**

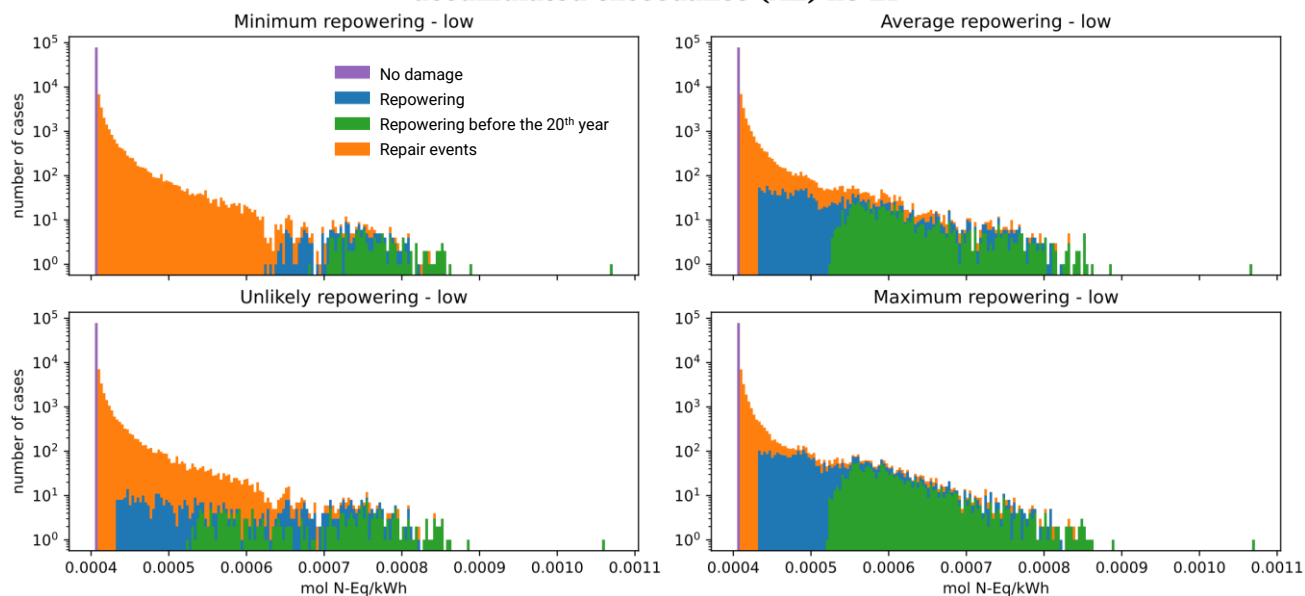


Acidification

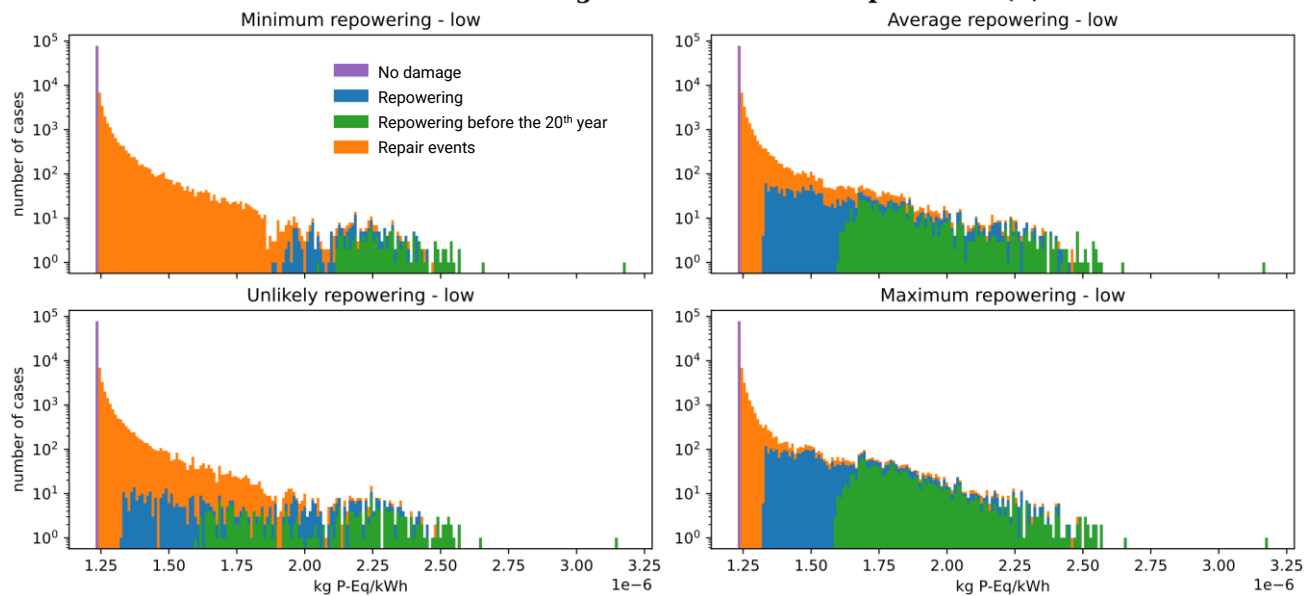
**acidification no LT  
accumulated exceedance (AE) no LT**



## Eutrophication: terrestrial

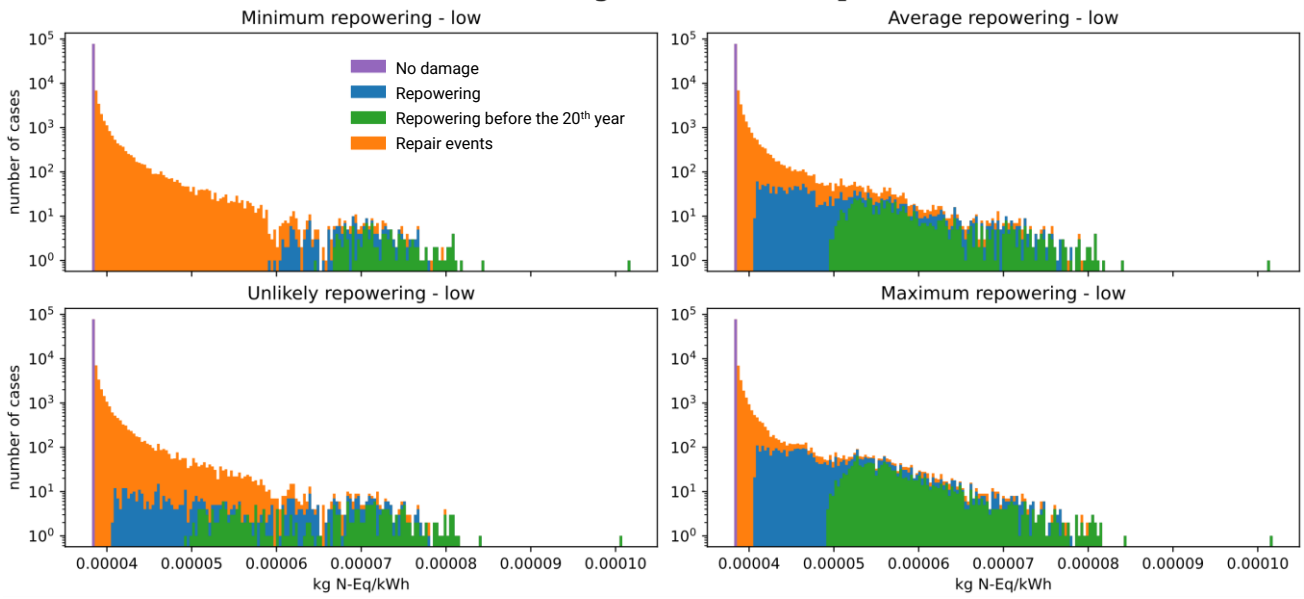
eutrophication: terrestrial no LT  
accumulated exceedance (AE) no LT

## Eutrophication: freshwater

eutrophication: freshwater no LT  
fraction of nutrients reaching freshwater end compartment (P) no LT

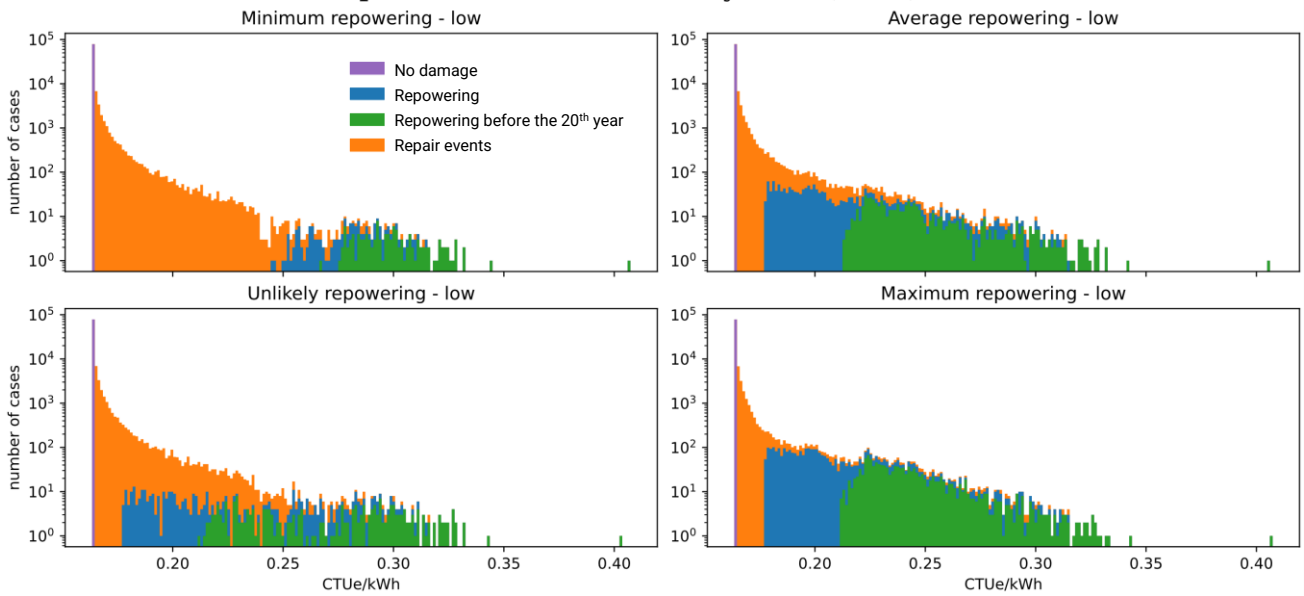
Eutrophication: marine

**eutrophication: marine no LT**  
**fraction of nutrients reaching marine end compartment (N) no LT**

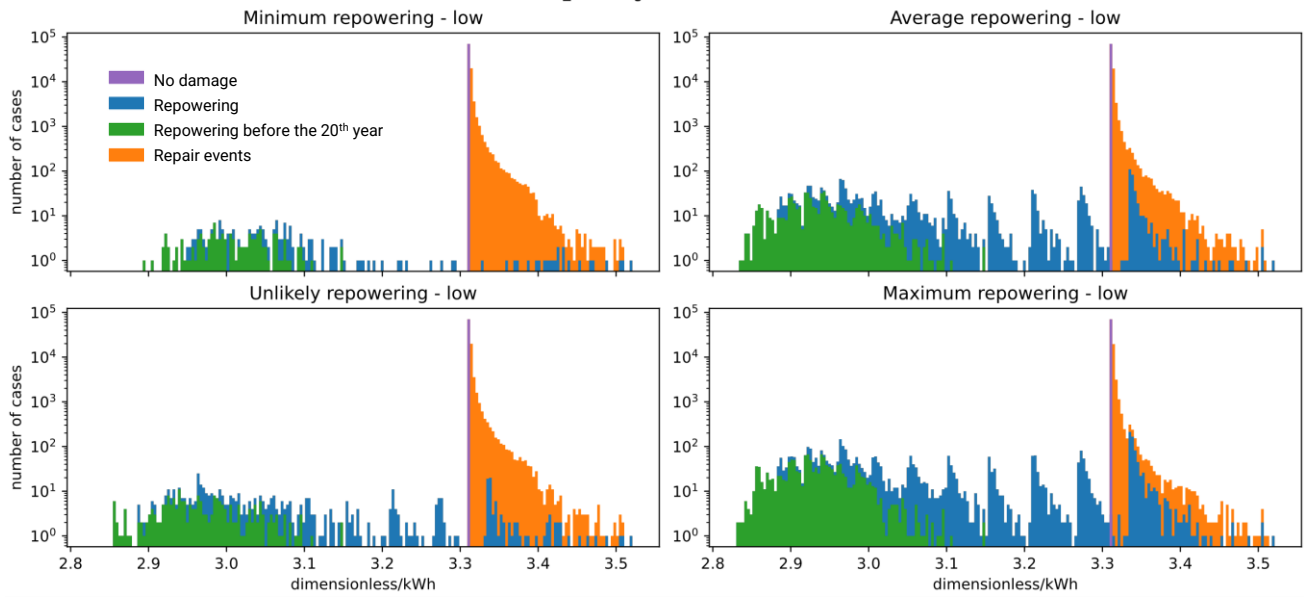


Ecotoxicity

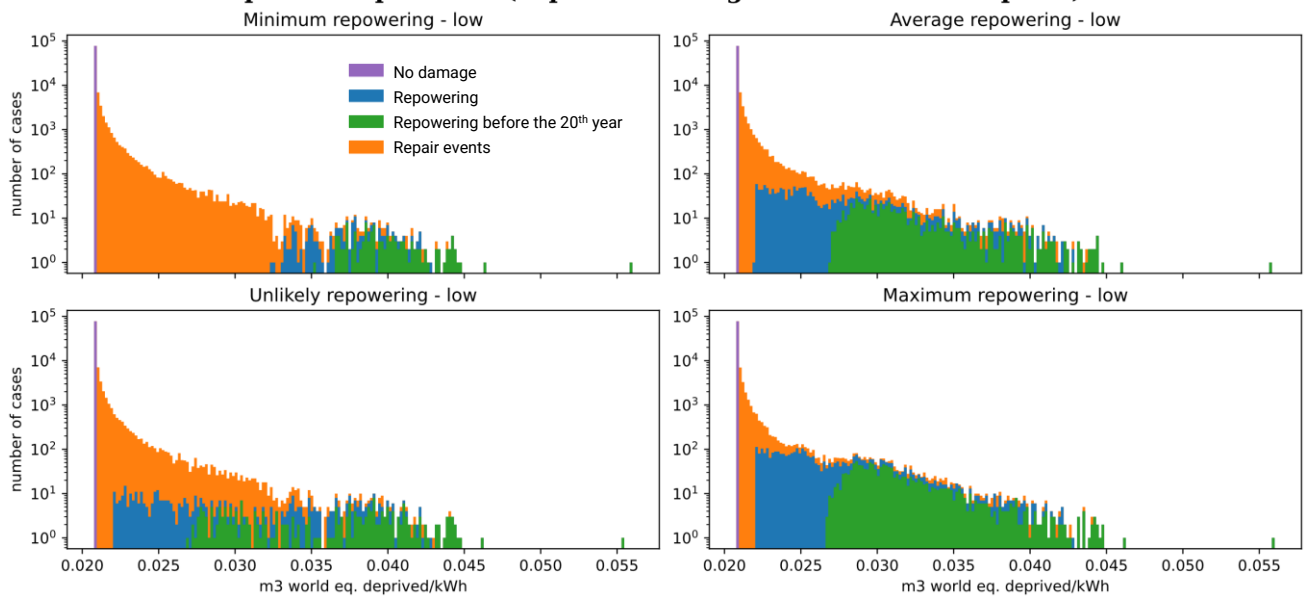
**ecotoxicity: freshwater, inorganics no LT**  
**comparative toxic unit for ecosystems (CTUe) no LT**



## Land use

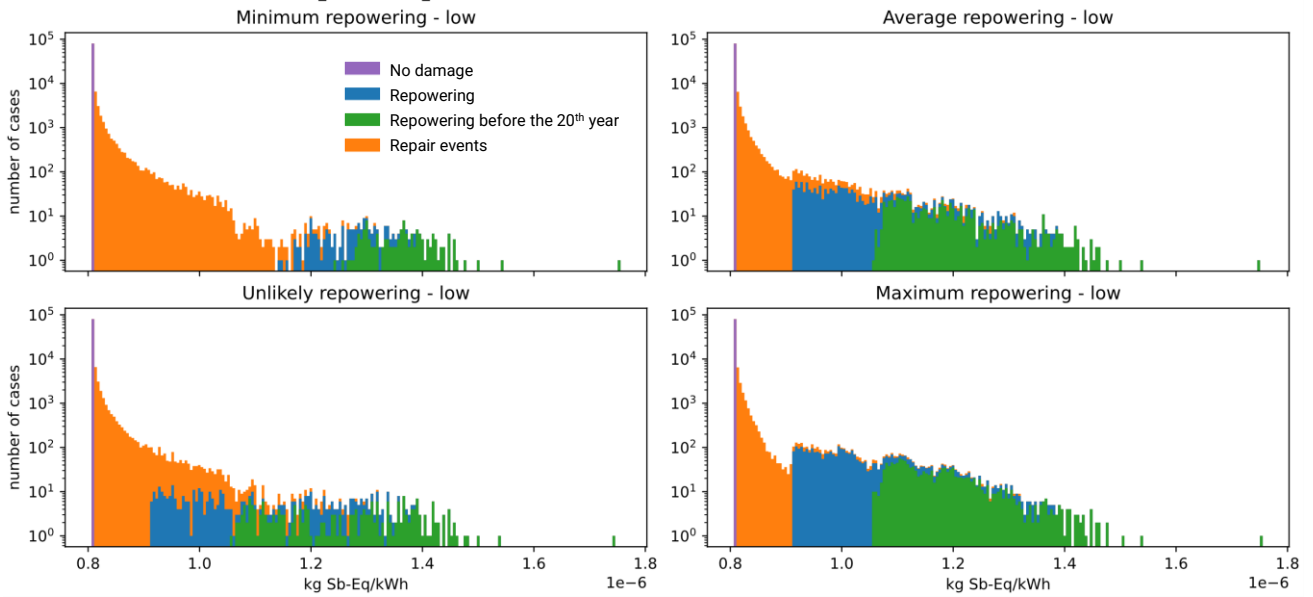
land use no LT  
soil quality index no LT

## Water use

water use no LT  
user deprivation potential (deprivation-weighted water consumption) no LT

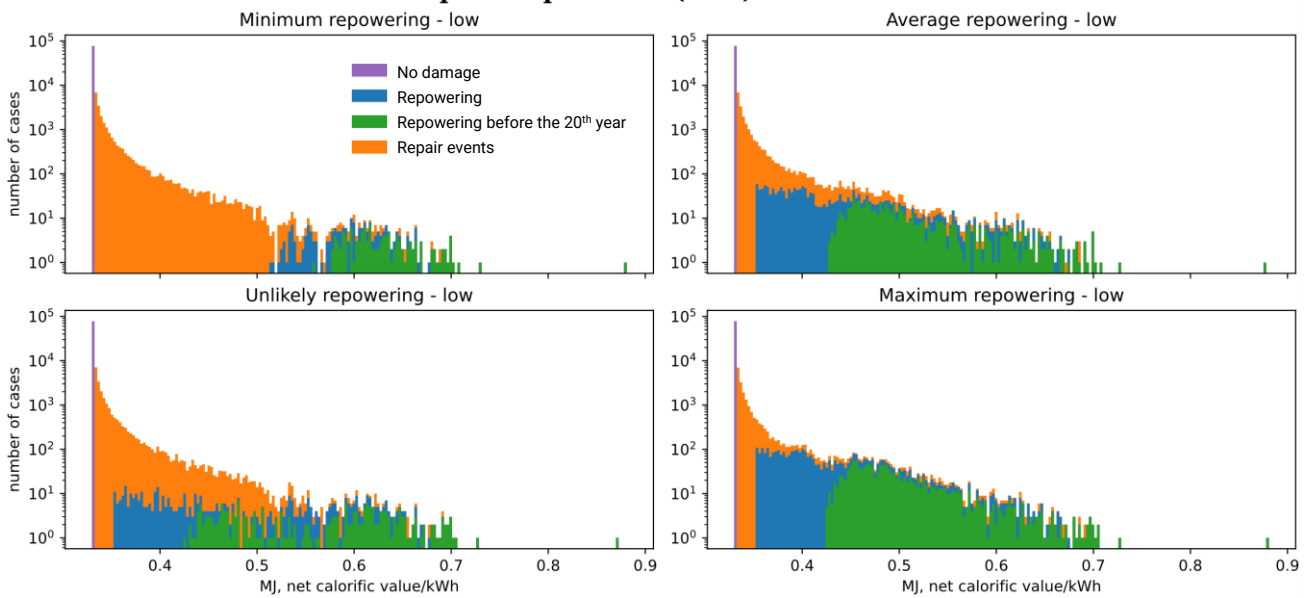
Material resources

**material resources: metals/minerals no LT**  
**abiotic depletion potential (ADP): elements (ultimate reserves) no LT**



Energy resources

**energy resources: non-renewable no LT**  
**abiotic depletion potential (ADP): fossil fuels no LT**





## RÉSUMÉ

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Le développement d'infrastructures critiques pour la production d'énergie doit répondre à la demande croissante d'énergie tout en minimisant les impacts sur la santé humaine et environnementale. L'analyse du cycle de vie (ACV) est un outil d'aide à la décision qui permet d'estimer les impacts environnementaux potentiels de ces infrastructures. L'ACV est généralement appliquée pour modéliser les systèmes en fonction de leurs conditions de fonctionnement moyennes, et les déviations ne sont pas prises en compte. Pour permettre des applications plus complètes de l'ACV, ces déviations devraient être prises en compte. Parmi les sources de déviations et de dommages possibles pour les systèmes de production d'énergie figurent les risques de catastrophes en évolution.

Cette thèse de doctorat aborde ce défi de recherche. L'objectif est de permettre la prise en compte des conséquences de l'évolution des risques de catastrophes sur les performances opérationnelles et environnementales des infrastructures critiques à moyen et long terme. L'objectif spécifique est la conception d'un cadre méthodologique pour développer un module d'inventaire guidé par les risques de catastrophes, appelé « Disaster Risk-guided scenario Definition (DRUID) Method – Life Cycle Inventory (LCI) Module » en anglais. La méthode DRUID comprend quatre étapes : 1) définition du problème, 2) élaboration des scénarios, 3) étude de la résilience des infrastructures et 4) transfert des scénarios. Le développement de la méthode DRUID est guidé par une étude de cas d'ACV comparative basée sur le secteur de l'énergie photovoltaïque (PV) en France, où une centrale PV est potentiellement affectée par des vents violents.

Les résultats obtenus démontrent les capacités de la méthode DRUID à guider la définition de scénarios complexes, à étudier les dommages potentiels causés à l'infrastructure par des aléas probables et à traduire ces dommages en impacts environnementaux potentiels par l'ACV. L'étude de cas illustrative considère que les composants de la centrale photovoltaïque peuvent être réparés de manière sélective ou que la centrale entière peut être complètement remplacée pour augmenter sa capacité de production. La comparaison des résultats de l'ACV entre un scénario de base appliquant une approche ACV conventionnelle et des scénarios définis avec la méthode DRUID a montré que les impacts environnementaux pouvaient augmenter de manière significative, en particulier si les stratégies de remplacement sont privilégiées par rapport aux réparations de composants.

La méthode DRUID peut être généralisée pour l'évaluation environnementale d'autres systèmes énergétiques, ainsi que pour l'évaluation d'autres types de performances liées aux infrastructures critiques.

## MOTS CLÉS

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Analyse du cycle de vie, Risque de catastrophes, Production d'énergie, PV solaire, Scénarios

## ABSTRACT

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The development of critical infrastructure for energy production must meet the growing energy demand while minimizing impacts on human and environmental health. Life Cycle Assessment (LCA) is a decision-support tool to estimate the potential environmental impacts of these infrastructures. LCA is usually applied to model systems according to their average operation conditions, and deviations are not considered. To enable more comprehensive LCA applications in decision-making, such deviations should be considered. Among the sources of possible deviations and damage to energy production systems are evolving disaster risks.

This PhD thesis addresses this research challenge. The objective is to enable the consideration of the consequences of evolving disaster risks on the operational and environmental performance of critical infrastructures in the mid- to long-term. The specific objective is the design of a methodological framework to develop a disaster risk-guided inventory module, called the Disaster Risk-guided scenario Definition (DRUID) Method – Life Cycle Inventory (LCI) Module. The DRUID method consists of four steps: 1) Problem definition, 2) Scenario building, 3) Infrastructure resilience study, and 4) Scenario transfer. The development of the DRUID method is guided by a comparative LCA case study based on the photovoltaic (PV) energy sector in France, where a PV plant is potentially affected by strong wind hazards.

The results obtained showcase the capabilities of the DRUID method to guide the definition of complex scenarios, study the potential damages to the infrastructure due to likely hazards, and translate said damages to potential environmental impacts through LCA. The illustrative case study considers that components of the PV plant can be selectively repaired, or the whole plant can be completely replaced to increase its production capacity. Comparing LCA results between a baseline scenario applying a conventional LCA approach and scenarios defined with the DRUID method showed that environmental impacts could increase significantly, especially if replacement schemes are favored more than component repairs.

The DRUID method may be generalized for the environmental assessment of other energy systems, as well as to assess other performance types related to critical infrastructures.

## KEYWORDS

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Life Cycle Assessment, Disaster risk, Energy production, Solar PV, Scenario