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Sustainability of industrial heat decarbonisation strategies through 4E (energy, exergy, economic and environmental) optimisation

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Résumé étendu

Contexte et enjeux

Il existe aujourd'hui un grand nombre de scénarios climatiques pour estimer les conséquences des activités humaines sur l'évolution de la température moyenne de surface globale, et qui sont compilés dans le dernier rapport d'évaluation du Groupe d'experts Intergouvernemental sur l'Evolution du Climat (GIEC). Plus cette température augmente, plus les changements irréversibles dans les cycles naturels et les conséquences sur les moyens de subsistance des individus sont importants. C'est pourquoi il est essentiel de maintenir cette augmentation de température bien en deçà de 2 °C par rapport aux niveaux préindustriels. Le dernier rapport de la Plateforme Intergouvernementale scientifique et politique sur la Biodiversité et les Services Ecosystémiques montre que le réchauffement climatique n'est pas la seule préoccupation actuelle et que d'autres problématiques environnementales (utilisation des terres, pollutions, etc.) s'y ajoutent. Cette conclusion est également partagée par le Stockholm Resilience Center dans sa proposition de définition des limites planétaires.

Dans ce cadre de limitation des émissions de gaz à effet de serre (GES), la décarbonation de la chaleur industrielle est un enjeu clé pour l'industrie. Bien qu'un certain nombre de technologies soit aujourd'hui disponible pour répondre à ce besoin, il n'est pas aisé de choisir la meilleure pour diverses raisons, d'autant plus que les industriels font aujourd'hui face à de nombreuses incertitudes (économiques, techniques, réglementaire, etc.). Les technologies les plus à même de répondre à ces contraintes peuvent varier en fonction des caractéristiques de la demande de chaleur, du mix électrique du pays si le procédé est basé sur l'électricité, de la durée de vie de la future installation, etc. En outre, l'objectif de réduction n'est pas nécessairement clair pour les industriels, à la fois sur sa mise en œuvre temporelle mais également sur les critères à prendre en compte pour déterminer quantitativement cette réduction. Par ailleurs, la décarbonation entraîne d'autres impacts environnementaux, qui peuvent également être non soutenables du point de vue des limites planétaires, et qui doivent être quantifiés. Ces impacts environnementaux liés au changement de technologies sont à ce jour très mal évalués en comparaison aux aspects techniques ou économiques.

L'objectif de cette thèse est de répondre à ces questions par le développement d'une méthode d'optimisation multiobjectifs combinant l'énergie, l'exergie, les aspects économiques et environnementaux. Cette méthode intègre le développement d'indicateurs environnementaux et économiques pour analyser les résultats de l'optimisation.

Un séjour au sein du laboratoire « Section for Quantitative Sustainability Assessment » de DTU (Denmark Technical University) d'une durée de 5 mois a permis de développer la méthode d'analyse ACV et la détermination des seuils soutenables adaptés au cas d'étude.

Chapitre I - Etat de l'art et problématique

Dans ce premier chapitre, un état de l'art montre qu'il existe aujourd'hui de nombreux scénarios (IEA, Union Européenne, ...) pour évaluer la faisabilité des stratégies de décarbonation de l'industrie. Ces différentes stratégies reposent sur trois piliers :

- L'efficacité énergétique
-

- Le remplacement des énergies fossiles par des sources non-carbonées
- L'intégration de système de capture et stockage du CO₂

Pour atteindre ces objectifs, il est nécessaire de transformer l'ensemble des secteurs où les énergies fossiles sont substituables. C'est le cas de la production de chaleur à basse température (< 200 °C) pour l'industrie. Les alternatives existent aujourd'hui mais disposent d'un niveau de maturité technologique (Technology Readiness Level, TRL) très variable. L'une des pistes les plus prometteuses est l'électrification des process par utilisation de pompes à chaleur à haute température. Le niveau de développement de cette technologie ne permet pas encore de couvrir l'ensemble des process mais de nombreuses recherches sont en cours pour y pallier. D'autres technologies sont disponibles, comme les chaudières électrique ou biomasse disposant aujourd'hui de niveaux de TRL suffisamment élevés pour être considérées. Il existe donc une diversité de solutions envisageables, ayant chacune des points faibles et des points forts. Il s'agira de les comparer entre elles pour évaluer leur potentiel de décarbonation de l'industrie, ainsi que leurs autres impacts environnementaux pour évaluer et limiter les transferts entre catégories d'impacts.

L'étude bibliographique montre une évolution dans les méthodes utilisées pour analyser les solutions d'optimisation et de transformation des systèmes. Celles-ci étaient initialement basées sur des études purement techniques et économiques, les aspects liés au changement climatique, et même plus récemment à d'autres impacts environnementaux, y sont maintenant de plus en plus intégrés. Ce type d'analyse environnementale augmente la complexité des études, car les Analyses du Cycle de Vie (ACV) nécessitent de considérer un périmètre d'étude plus grand que celui du système industriel seul (chaîne d'approvisionnement par exemple). En revanche, il existe une réelle synergie entre les deux types d'analyse : les modèles énergétiques bénéficient de l'approche environnementale pour la complétude de l'analyse et, en retour, l'analyse environnementale bénéficie de données d'entrée issues d'un modèle énergétique bien établi.

Malgré ces récentes avancées méthodologiques, ce type d'analyse compare des solutions entre elles sans pouvoir conclure sur leur soutenabilité. C'est pour répondre à cet objectif que depuis plusieurs années des études portant sur la soutenabilité voient le jour dans la littérature. L'objectif de ce type d'approche est de définir un « droit à impacter » pour un secteur de manière à comparer les différentes solutions, non pas entre elles, mais vis-à-vis de ce seuil soutenable. Ce type d'approche implique la définition d'une clé de répartition entre secteurs, alors qu'il n'existe aujourd'hui aucune règle faisant consensus. Les principales méthodes qui pourraient être utilisées reposent sur :

- Des critères basés sur l'économie : chaque secteur aurait le droit à une part équivalente à sa contribution à l'économie mondiale
- Des critères basés sur un juste répartition entre les individus : chaque individu aurait le droit à la même contribution
- Des critères basés sur la faculté d'un process à réduire ces émissions : chaque process aurait un droit correspondant au niveau qu'il est capable d'atteindre après transformation.

La problématique de recherche est donc de définir une méthodologie pour évaluer la meilleure manière de produire la chaleur industrielle en limitant le dépassement des seuils soutenables. Pour cela, un modèle d'optimisation multi-objectifs, appliqué au cas de la production de chaleur industrielle, combinant les aspects énergétiques, économiques et environnementaux est proposé.

Cette approche doit permettre l'évaluation des limites de chaque stratégie et la mise en œuvre des configurations les plus appropriées.

Chapitre II - Méthodologie

Le cadre méthodologique (Figure 1) de ce modèle d'optimisation multi-objectifs est développé dans le chapitre II. La première étape est la modélisation des performances énergétiques des systèmes de production de chaleur, qui est basée sur des données d'entrée spécifiques à la configuration étudiée en lien avec :

- le type de demande industrielle,
- le type de technologies disponibles et leurs caractéristiques techniques,
- le type et les caractéristiques de l'énergie présente sur le site.

À l'aide de ces données, les performances énergétiques de la production de chaleur peuvent être calculées au pas de temps horaire pour répondre aux besoins industriels. Ce modèle énergétique intègre les contraintes opérationnelles, en particulier les phénomènes dynamiques (par exemple, le temps de montée en charge, la perte d'efficacité en charge partielle, etc.) des technologies afin de disposer d'une intégration réaliste de la technologie et de pouvoir prendre en compte la variabilité des prix et des impacts environnementaux de l'énergie. Le choix des mix électriques est basé sur une étude des projections de mix électriques en Europe à l'horizon 2050. Sur la base de 96 scénarios, un clustering est réalisé de manière à identifier cinq mix électriques représentatifs des tendances en Europe. Parmi ces mix, trois sont composés majoritairement d'énergies renouvelables, un est composé d'un mix nucléaire et renouvelable et le dernier d'un mix de thermique (gas et biomasse) combiné avec des énergies renouvelables.

Ce modèle énergétique est ensuite utilisé comme données d'entrée pour :

- Le modèle d'ACV, qui bénéficie de la modélisation horaire pour calculer les impacts environnementaux à partir de données environnementales issues de la base de données Ecoinvent. Cette modélisation suit les standard ACV ISO 14040/14044, et utilise la méthode d'évaluation de l'impact EF 3.0.
- Un modèle économique simplifié pour calculer le coût de chaque solution sur son cycle de vie (énergie, investissement, exploitation).

Toutes ces données énergétiques, environnementales et économiques sont ensuite utilisées pour le modèle d'optimisation, présenté en détail dans le chapitre IV, pour identifier les solutions minimisant ces trois critères. Une des spécificités de ce travail est de baser l'optimisation des systèmes énergétiques sur des critères environnementaux. En effet, les modèles développés dans la littérature fonctionnent dans l'autre sens, en optimisant dans un premier temps les systèmes du point de vue énergétique et en évaluant dans un second temps leur impact environnemental. Le modèle d'optimisation génère un jeu de solutions non-dominées, c'est-à-dire qu'il n'y a pas de solution qui domine les autres sur tous les critères. Par la suite, ces solutions sont classées pour définir la meilleure option pour répondre aux besoins industriels. Deux indicateurs sont proposés pour ce classement :

- La durabilité environnementale, basée sur un niveau soutenable à ne pas dépasser pour limiter les impacts en dessous des limites planétaires
-

- Le niveau de contribution du processus, qui pénalise les processus responsables d'une grande proportion de l'impact environnemental et qui sont utilisés afin de définir un "droit à impacter" pour chaque secteur.

Ces deux indicateurs sont utilisés dans le chapitre V pour définir les méthodes de classements des différentes solutions.

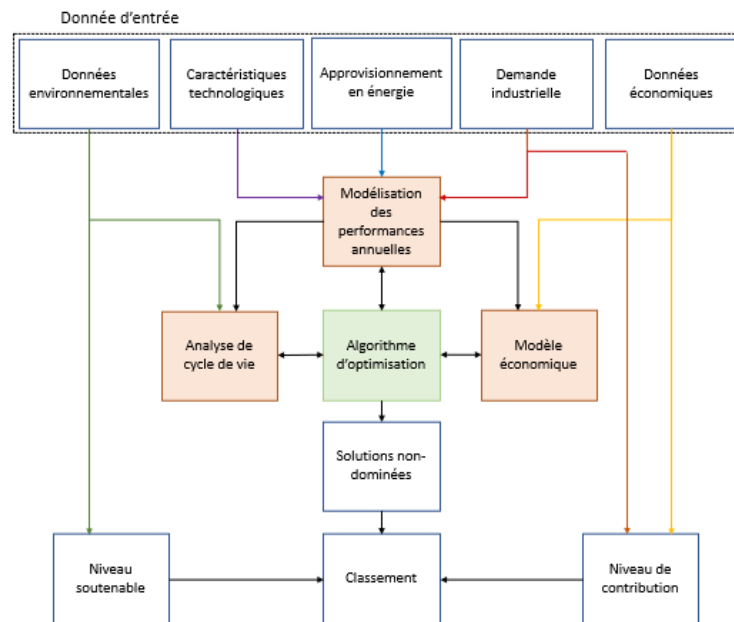


Figure 1 – Schéma de principe du modèle d'optimisation

Chapitre III – Application simplifiée de la méthode : électrification des process industriels

Dans ce chapitre, deux applications de la méthodologie développée dans le chapitre II sont présentées, utilisant une approche simplifiée par rapport à l'approche générale. En effet, dans ces deux cas, l'utilisation d'un algorithme d'optimisation n'est pas nécessaire, car le but n'est pas de comparer plusieurs options pour la production de chaleur industrielle, mais d'évaluer l'adéquation de certaines solutions dans des contextes simplifiés. Des évaluations combinant les méthodes énergétiques, économiques et environnementales sont utilisées pour obtenir des informations générales sur l'impact de l'électrification sur la production de chaleur industrielle.

Dans une première partie, un premier cas simple, ne considérant que le critère *changement climatique* comme indicateur environnemental est présenté. L'objectif de cette étude est d'identifier les conditions environnementales et économiques permettant de respecter les objectifs de l'Accord de Paris pour les pompes à chaleur (PAC) utilisant la chaleur fatale et l'électricité. Celle-ci est appliquée à plusieurs secteurs industriels pour 24 pays de l'union européenne et prend comme référence les années 2030 et 2050. Cela permet de définir pour chaque pays, en fonction de son mix électrique, les process pouvant respecter les objectifs de réduction des émissions de GES en utilisant les PAC. Cette analyse montre que la majorité des projections de mix électriques en Europe permet d'atteindre les objectifs pour la majorité des process, mais cela implique l'utilisation d'un fluide frigorigène à faible potentiel de réchauffement global en 2050. A l'horizon 2050, seuls 3 pays (Belgique, Pologne et Slovénie) n'arrivent pas à respecter ces objectifs car leur mix est trop carboné. Une analyse économique montre que la compétitivité de la solution PAC

par rapport à la solution gaz est possible dans certains cas à l'horizon 2030. Mais pour de nombreux pays - pour lesquels l'électrification permet d'atteindre les objectifs de réduction de GES - la viabilité économique est un point bloquant en 2030 et peut le rester en 2050 si le niveau de la taxe carbone n'est pas suffisamment élevé.

Ce premier cas montre que l'électrification permet d'atteindre les objectifs de réduction de GES dans la plupart des pays européens, il est alors intéressant d'analyser l'ensemble complet d'impacts environnementaux de cette transformation. Cette analyse est réalisée sur un deuxième cas d'étude : celui de l'électrification de l'industrie agroalimentaire au Danemark et en France. Cette étude a été réalisée en collaboration avec le laboratoire du département de génie mécanique de DTU, qui travaille sur l'électrification du secteur agroalimentaire danois. Plus d'informations sur leur travail concernant l'électrification de l'industrie peuvent être trouvées dans le rapport de projet Elforsk¹. Cette deuxième partie du chapitre III illustre comment les différents indicateurs de durabilité développés dans le chapitre II (soutenabilité et niveau de contribution) peuvent être utilisés pour évaluer la soutenabilité d'un système de production de chaleur vis-à-vis des limites planétaires. Une des conclusions de cette étude est la présence systématique de contreparties environnementales. Il est possible d'atteindre un niveau durable pour l'indicateur de changement climatique comme évoqué dans la première partie de ce chapitre, mais cela entraîne le dépassement des limites soutenables pour plusieurs impacts (par exemple *écotoxicité* ou *eau douce*). Cette contrepartie environnementale met en évidence la nécessité d'une approche globale pour évaluer les transferts d'impacts de manière à définir la meilleure stratégie sur le long terme.

Chapitre IV – Modèle d'optimisation

Sur la base des conclusions du chapitre précédent, nous nous sommes intéressés à l'étude de scénarios reposant sur différentes technologies possibles de manière à mettre en avant les avantages et les inconvénients de chacune d'entre elles et à évaluer s'il n'existe pas des combinaisons de technologies permettant de limiter les impacts. Pour répondre à ce besoin, un modèle d'optimisation multicritère basé sur l'algorithmie génétique a été développé. Ce modèle intègre 19 critères d'analyse décomposés en :

- 16 critères environnementaux issus des résultats ACV en lien avec leurs limites soutenables (comme défini dans le chapitre II)
- 2 critères énergétiques : rendement énergétique et rendement exergetique
- 1 critère économique sur le coût total de la solution (énergie, CAPEX et OPEX).

Cette méthode génétique d'optimisation convient à ce type de configuration car elle combine des configurations initiales bien définies permettant de couvrir rapidement un large panel de combinaisons de solutions possibles. Le principe de fonctionnement de cette méthode est basé sur la reproduction et la mutation, combinées à un phénomène dit de sélection naturelle. L'idée est de conserver les éléments les plus performants à chaque pas de temps, ainsi qu'un certain nombre de solutions moins performantes mais apportant de la diversité génétique pour conserver une exploration de l'ensemble de l'espace. La performance étant d'évaluer les 19 critères présentés auparavant sans pondération ou monétisation de ces critères (chaque critère a un poids égal et peut permettre à une solution d'être considérée comme non-dominée). L'objectif de cette optimisation

¹ <https://elforsk.dk/>

est de générer un front de Pareto composé d'un ensemble de 35 solutions non-dominées, c'est-à-dire pour lesquelles il n'existe pas de solution meilleure sur l'ensemble des critères.

L'une des problématiques rencontrées pour ce type d'approche est la nécessité de disposer d'une résolution horaire et annuelle du modèle afin d'intégrer les phénomènes dynamiques liés aux variations saisonnières et à la demande industrielle. La résolution devient complexe du fait du nombre de pas de temps à considérer et du nombre d'itérations du modèle d'optimisation. Pour réduire l'ampleur du problème et limiter le temps de calcul, les données horaires sont regroupées sur 100 pas de temps représentatifs de l'année. Cela permet au modèle d'optimisation d'évaluer un grand nombre de modes de production en combinant les différentes technologies et de retenir les solutions non-dominées, qui doivent ensuite être classées. Ce regroupement (clustering) permet de rendre le calcul possible dans un temps limité (environ 5 minutes de calcul pour la génération d'un front de Pareto), sans compromettre les résultats, avec une validation du modèle de clustering réalisé dans des conditions extrêmes montrant dans la pire configuration moins de 4 % d'erreur.

Les premiers résultats issus du modèle d'optimisation montrent qu'aucune des solutions du front de Pareto ne respecte les niveaux soutenable pour l'ensemble des critères environnementaux. Il est donc nécessaire de pousser l'analyse plus loin et de définir une (des) méthode(s) de classement pour différencier ces 35 solutions du front de Pareto. Ces méthodes et leur analyse sont présentées dans le chapitre V.

Chapitre V – Application de la méthode à la production de chaleur industrielle

Pour tester la méthodologie en intégrant le modèle d'optimisation multicritère, plusieurs configurations sont définies :

- 3 profils horaires de demande de chaleur par des processus industriels représentatifs sur 1 an
- 5 pays avec un mix électrique représentatif de l'une des trajectoires envisagées d'ici 2050 en Europe
- 3 périodes différentes (2015-2040, 2040-2065 et 2065-2090) afin d'intégrer l'augmentation des exigences de réduction des émissions de gaz à effet de serre et la disponibilité de certaines technologies.

Pour répondre au besoin de classification des solutions, trois approches de classement sont proposées : R1, qui considère une approche de référence en utilisant des pondérations dérivées des méthodes d'analyse d'impact de l'ACV, R2, qui inclut une pénalité linéaire pour le dépassement des seuils de soutenabilité, et R3, qui inclut cette fois une pénalité exponentielle pour le dépassement des seuils soutenable et qui a également la particularité de ne pas permettre de compensation liée à la capture de CO₂.

Une des conclusions de cette étude est l'absence de solutions répondant à tous les seuils durables et cela quelle que soit la technologie étudiée (chaudière électrique, chaudière à gaz, chaudière à biomasse et pompe à chaleur mécanique) et quel que soit le mix électrique. Le dépassement des limites durables concerne différents impacts selon les technologies :

- Les solutions d'électrification pour les mix électriques basés principalement sur les énergies renouvelables dépassent le seuil durable pour l'utilisation des ressources minérales et métalliques d'un facteur compris entre 7 à 9, les mix basés sur l'énergie nucléaire dépassent le seuil soutenable pour l'utilisation des ressources fossiles d'un facteur 5, et les mix avec une proportion élevée de production d'électricité thermique à partir de biomasse et de combustibles

fossiles dépassent également le seuil soutenable pour l'utilisation des ressources minérales et métalliques d'un facteur 1,5 et l'utilisation des ressources fossiles d'un facteur 1,3.

- Les chaudières à gaz dépassent les seuils soutenables pour le changement climatique d'un facteur 2 pour la période 2015-2040, cette valeur passant à un facteur 13 pour la période 2065-2090, et l'utilisation des ressources fossiles d'un facteur 5.
- Les chaudières à biomasse dépassent très significativement les seuils soutenables pour plusieurs indicateurs tels que l'utilisation des sols avec un dépassement d'un facteur 5 et l'émission de particules avec un dépassement d'un facteur 15.

Étant donné qu'aucune technologie unique ou combinaison de technologies n'est capable d'atteindre des niveaux durables, un système de classement est utilisé pour mettre en évidence les solutions ayant l'impact environnemental le plus faible. Pour poursuivre le développement, plusieurs solutions pourraient être envisagées. La première serait de trouver des alternatives ou des améliorations pour les catégories non durables, par exemple en améliorant le recyclage des métaux. La deuxième option pourrait être de modifier la répartition des "droits à l'impact" et donc de définir des secteurs non prioritaires dont la part serait réduite.

Pour le classement R1, basé sur les pondérations actuelles de l'ACV, la solution PAC émerge comme la solution qui limite le plus les impacts pour la période 2015-2040 et 2040-2065. En 2065-2090, la chaudière biomasse combinée à la capture et stockage de carbone (CCS) devient la meilleure solution car elle permet une séquestration du carbone sur l'ensemble du cycle de vie et limite les impacts sur la catégorie *changement climatique*.

Les classements R2 et R3 pénalisent d'avantage les technologies qui entraînent un fort transfert d'impact d'une catégorie d'impact à une autre. Pour ces classements, les meilleures solutions sont le résultat d'une combinaison de technologies visant à limiter le dépassement des seuils durables. Les solutions mieux classées ont donc souvent plus de catégories non soutenables, mais avec des dépassements plus faibles. Pour les mix électriques composés principalement d'énergies renouvelables, la stratégie consiste à ajouter du gaz (entre 30 et 50 %) afin de limiter le dépassement de l'indicateur d'utilisation des ressources minérales et métalliques, au détriment de l'indicateur de changement climatique ; pour le mix basé sur le nucléaire, la compensation consiste à ajouter une proportion de biomasse (entre 5 et 10 %) afin de limiter le dépassement de l'indicateur d'utilisation des ressources fossiles, au détriment d'une augmentation de l'usage des sols et de l'émission de particules. Enfin, pour le mix basé sur la production d'électricité thermique à partir de biomasse et de combustibles fossiles, il n'y a pas de compensation pour réduire l'impact avec les technologies étudiées, celle-ci étant déjà réparties entre plusieurs catégories d'impact (ce qui est dû à la présence de gaz, de biomasse et de renouvelable dans le mix électrique).

La dernière étape consiste à combiner les approches énergétiques, exergétiques et économiques à l'approche environnementale. Cette combinaison montre une corrélation entre le classement R1 et la performance exergétique. Pour tous les mix, l'optimisation exergétique entraîne une réduction de l'impact environnemental. Cependant, cette tendance n'est plus valide pour les classements R2 et R3, pour lesquels il y a un optimum pour certains mix. Cela reflète le fait que l'efficacité exergétique n'est pas nécessairement pertinente pour évaluer les transferts d'impact et les dépassements des seuils soutenables. L'analyse économique révèle l'absence de corrélation entre la performance environnementale d'une solution et le paramètre économique quelles que soient les méthodes utilisées (R1, R2 ou R3). En d'autres termes, pour ces indicateurs, la performance environnementale n'est pas seulement corrélée au coût de la technologie, mais aussi à un ensemble de facteurs spécifiques à chaque processus (type de mix électrique, fiscalité, etc.).

Conclusions

La méthodologie mise en place permet de répondre à l'objectif de recherche en développant un cadre d'analyse et de classement des différentes technologies et combinaisons de technologies vis-à-vis de seuils environnementaux soutenables. La première conclusion de ce travail est qu'il n'existe aucune solution permettant de décarboner la chaleur industrielle sans dépassement d'au moins une limite planétaire. Une autre conclusion de ce travail est l'existence du lien entre le choix de la meilleure technologie et le type d'objectif visé. En effet, la méthode R1 sélectionne les solutions ayant l'impact global le plus faible, mais autorise un dépassement important de certaines limites, notamment celles relatives aux ressources minérales et métalliques, tandis que le classement R3 propose une solution non soutenable dans plus de catégories d'impacts, mais sans dépassement trop importants des limites planétaires. Il existe donc un risque important d'atteinte d'un seuil non-soutenable si la méthode R1 était appliquée sur une grande partie de l'économie, alors que la méthode R3 permettrait une meilleure répartition des impacts. En effet, à l'échelle globale, il peut être possible pour certains secteurs de compenser les impacts d'autres secteurs et vice versa, mais si certaines limites sont trop largement dépassées, cette compensation serait plus difficile. La méthode R3 peut donc sembler plus robuste à grande échelle.

Ce travail propose une première approche de définition des seuils soutenables afin d'évaluer la viabilité des solutions de décarbonation de l'industrie. Ce travail permet de mettre en avant la nécessité d'utiliser une telle approche pour évaluer la performance des stratégies de décarbonation pour éviter les transferts d'impact de l'indicateur changement climatique vers d'autres impacts, en particulier l'impact sur la consommation de ressource.

En perspectives à cette thèse il serait nécessaire de poursuivre le développement de l'ensemble des éléments de la méthode, comme par exemple :

- L'intégration spécifique sur un process pour considérer les contraintes d'intégration et le potentiel de valorisation de la chaleur fatale et mettre en place une modélisation énergétique plus précise.
- Le développement d'un modèle économique plus robuste pour mieux quantifier les impacts sur les coûts de productions.
- La mise à jour des seuils soutenables pour intégrer les évolutions en cours dans ce secteur de recherche, comme par exemple l'intégration du recyclage pour l'évaluation de l'impact sur la consommation de ressources minérales et métalliques.

Pour aller plus loin, ce type méthodologie pourrait être appliquée à grande échelle pour définir les impacts de l'ensemble des secteurs des activités humaines afin d'évaluer les possibilités de compensation entre eux, ce qui permettrait de respecter les niveaux soutenables à l'échelle globale - certains secteurs étant en-dessous de leur « droit à impacter ». Si les compensations entre secteurs ne permettaient pas de respecter ce niveau soutenable, il serait alors nécessaire d'aller plus loin en modifiant la définition du droit à impacter. Cela impliquerait la création d'un cadre interdisciplinaire, associant les sciences physiques aux sciences humaines et sociales pour identifier d'autres critères comme la notion d'utilité permettant d'affecter une part plus importante aux secteurs jugés prioritaires.

Mots clés : Optimisation multi-objectifs, process industriel, limites planétaires, soutenabilité, évaluation environnementale

Abstract

The aim of this work is to assess the overall annual performance of different industrial heat production solutions, using a multi-objective 4E method (energy, exergy, economy and environment). The annual dynamics of industrial demand and energy supply are taken into consideration in the approach. All the energy sources used to cover this demand (including those used to produce electricity) are studied on an hourly basis, including their environmental impacts and costs. This approach is in line with strategies to reduce greenhouse gas (GHG) emissions, by incorporating a more complete range of analyses, based on life cycle analysis, quantifying the reduction in the climate impact of the solutions considered, as well as their synergy or counterbalance with other environmental impacts. As the analysis is multi-criteria, it is possible to find a set of feasible, non-dominated solutions that meet the optimisation problem, also known as the Pareto front. These non-dominated solutions represent the best possible solutions within the scope of the criteria studied but are not necessarily sustainable from an environmental point of view. The multi-criteria analysis is therefore supplemented by an analytical framework based on global limits and the importance of the industrial sector under consideration in relation to all human activities, which can be used to rank the different solutions.

The methodology is applied to the European case for three reference industrial processes. Five countries with an electricity mix representative of the different trajectories envisaged in 2050 are selected. While it may be possible to meet GHG emission reduction commitments in most of these cases, the economic and environmental trade-offs are not all in line with global limits. It may therefore be necessary to find compromises with other sectors of activity to compensate for these excesses.

Keywords: Multi-objective optimisation, Industrial energy process, Planetary boundaries, Sustainability, Environmental assessment

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Nomenclature and abbreviations

Nomenclature		Units
B_c	Over cost of electricity grid due to batteries integration	$\text{€}/\text{MWh}_{\text{grid}}$
b_r	Battery power to grid consumption ratio	$\text{GW}_{\text{bat}}/\text{GWh}_{\text{grid}}$
B_r	Battery requirement to balance the grid	$\text{kg}_{\text{bat}}/\text{GWh}_{\text{grid}}$
c	Cost per unit ¹	$\text{€}/\text{unit}$
C	Specific cost per year	$\text{€}/\text{year}$
Cl	Contribution level	
C_y^*	Correcting factor for ranking R2	
C_y'	Correcting factor for ranking R3	
d	Average distance among pareto elements	
D	Industrial demand	MW
E_d	Batterie energy density	Wh/kg
E_{in}	Final energy consumption of industrial process	MWh
E_{out}	Final energy demand of industrial process	MWh
EtP	Batterie energy to power ratio	Wh/W
EVA	Economic value added of process	M€
h	Operating hours per year	h/year
i	Impact per unit ¹	<i>Specific</i> ²
I	Impact over a year	<i>Specific</i> ²
I_{BAU}	Current environmental level of process	<i>Specific</i> ²
La	Annual refrigerant leakage	%
Le	End of life refrigerant leakage	%
LT	Technology life time	years
m_{wf}	Mass of refrigerant	kg
p	Electricity price	$\text{€}/\text{MWh}$
\hat{p}	Regression electricity price	$\text{€}/\text{MWh}$
\bar{p}	Average electricity price over the year	$\text{€}/\text{MWh}$
P	Heat production from a technology	MW
PBP	Payback period	years
PL	Partial load	%
$R1$	Ranking method 1	
$R2$	Ranking method 2	
$R3$	Ranking method 3	
Rf	Reduction factor to reach sustainable level	
S	Energy available in storage	MWh
Sl	Environmental sustainable level	<i>Specific</i> ²
Sr	Sustainability ratio	-
t	Time step	h
T	Temperature	K
\dot{W}_{el}	Electrical power	MW
W_s	Weighting score	%
y_{PL}	Biomass load ratio	%

¹ The impact is given for 1 unit of the system, e.g., 1 kWh for energy, 1 kg for refrigerant.

² The unit is specific to each of the impact categories studied. A further level of detail is provided in section II.4.1

Grec letters

α	Technology power	MW
δ	Share of waste heat recoverable	%
γ	Storage energy level	MWh
Δ_{Pareto}	Spread of Pareto front	
ε_{sto}	Share of energy losses by the system	%
η	Efficiency	%
ρ	Number of element on the Pareto front	
μ	Sum of the distances between the current minimum and the previous iteration minimum	
σ	Standard deviation	
τ	Share of “right to impact” of industrial process	

Subscripts

bat	Batterie
CC	Climate change
d	Design value
el	Electric
en	Energy
EoL	End of life
indu	Industrial sector
lift	Temperature lift
max	Maximum admissible value
MHP	Mechanical Heat Pump
min	Minimum admissible value
n	Time step
ng	Natural gas
rec	Recovered
ref	Reference case
s	Sector
syst	System
tot	Total (Worldwide)
up	Upgraded to be used by process
wf	Working fluid
x	Heat production technology
y	Impact category

Abbreviations

BAU	Business As Usual
CAPEX	CAPital EXpenditure
CC	Climate Change
CED	Cumulative Energy Demand
CExD	Cumulative Exergy Demand
COP	Coefficient Of Performance
EU	European Union
ESM	Energy System Modelling
GHG	GreenHouse Gas
GPR	Gaussian Process Regression
GVA	Global Value Added
GWP	Global Warming Potential
IPCC	Intergovernmental Panel of Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MHP	Mechanical Heat Pump
OPEX	OPERational EXPenditure
PBP	PayBack Period
PH	Process Heat
RMSE	Root-Mean-Square Error
RRMSE	Relative Root-Mean-Square Error
TRL	Technology Readiness Level
TSO	Transmission System Operator
TTES	Tank Thermal Energy Storage

Introduction

Industrial heat accounts for two-thirds of industrial energy demand and nearly one-fifth of global energy consumption [1]. In the context of the transition to a low carbon economy, electrification is seen as a major path to decarbonise industrial heat that is primarily generated by fossil fuel combustion today [2]. Despite a huge potential for decarbonisation, there are fewer studies in this sector compared to mobility and building ones, as highlighted by Sorknæs et al. [3]. The few studies dedicated to this topic are often specific to each site and/or each industrial process, which makes it more difficult to generalise the results. Furthermore, according to the same authors, the overall impact of increasing power generation to cope with the electrification of the industrial sector is not sufficiently considered, the focus being put on the technology used (e.g. refrigerant choice for industrial heat pumps in [4]), the change in demand [5], [6], or on techno-economic criteria (e.g. Mallapragada et al. [7] for the chemical sectors, Lincoln et al. [8] for the dairy one). On the other hand, as illustrated for example by Slorach and Stanford [9] for the building sector, environmental assessment is required to have a fair picture of the impacts and hence make informed decision. Furthermore, energy consumption by industry is expected to rise by 1.4 %/year until 2030, according to the IEA [10]. Energy efficiency alone will not be enough to meet this new demand, while at the same time meeting commitments to reduce emissions of greenhouse gases (GHG). It is therefore essential to reconsider the energy model, and in particular the production of heat, if these objectives of decarbonisation are to be met. The aim of this thesis is therefore to develop an analysis methodology for determining the best heat production system, in a given energetic and industrial context.

To achieve this objective, a framework of analysis needs to be defined, based on a set of criteria that can be used to classify different possible technological solutions, single or combined, used to respond to an industrial heat production demand. In most of the studies, technical and economic criteria are often combined with CO₂ emissions to tackle the problem of reducing GHG emissions. The limitation of this type of analysis is that it only provides the economic trade-offs linked to GHG reductions, but does not consider the other environmental counterparts of any transition to another form of energy. One of the methods that has been developed over the last few years to integrate a broader range of environmental criteria is the so-called 4E multi-criteria analysis (energy, exergy, economy and environment). This analysis method has the advantage of incorporating a large range of environmental criteria, although this adds to the complexity of the analysis with the need to carry out a life cycle assessment (LCA).

Most LCA studies are comparative, i.e. they assess the environmental performance of one solution against another. However, a solution that is better than another is not necessarily acceptable from an environmental point of view. An alternative approach is to use LCA to define a sustainable environmental threshold for each of the environmental impacts and to compare all the possible solutions against these thresholds. The recent definition of planetary boundaries by the Stockholm Resilience Center [11] offers a unique opportunity to assess these thresholds. An approach based on the planetary boundaries is also implemented in this thesis.

The following 5-chapter plan is proposed to respond to the problem defined above:

- Chapter 1 begins with an overview of the global energy system, which leads us to focus on industrial heat production, both worldwide and in Europe, and more specifically on its technical, energy and environmental characteristics. This introduction is followed by a presentation of current and potential developments in the energy sector, particularly as

regards the production of industrial heat, with a view to meeting the challenge of reducing greenhouse gas emissions. Finally, energy and environmental analysis methods are presented, with particular emphasis on life cycle assessment in an industrial context. All these introductory elements support the description of the objectives and the choice of the field of application of the thesis.

- Chapter 2 describes the analytical framework developed to assess the energy, economic and environmental aspects of industrial heat production. After identifying all the environmental, technological, process-related, energy and economic data required to address the problem, the environmental, economic and energy models used in the multi-criteria analysis are developed. Then, the multi-objective optimisation method itself is described briefly so that its results can be analysed. This method enables to bring out a set of non-dominated heat production solutions, based on environmental, energetic and economic consideration. The optimisation method is described exhaustively in Chapter IV, which is dedicated to it. Finally, various criteria used in this thesis to analyse the sustainability of heat production solutions and their contribution to the global impact are presented. These criteria are at the core of the methods used to classify the different solutions, presented in chapter 5.
- Chapter 3 presents two applications of the method developed in Chapter 2, for which the optimisation algorithm is not required. In the first application, the goal is to find the environmental and economic conditions enabling MHP fed with waste heat and electricity to comply with the targets from the Paris Agreement. It is applied to several industrial sectors for 24 EU countries and takes 2030 and 2050 as reference years. The second application considers the electrification of the French and Danish food processing sector. This application illustrates how the different indicators of sustainability developed in chapter II can be used to assess the sustainability of a heat production system and more particularly the environmental counterparts of electrification.
- Chapter 4 presents the multi-criteria optimisation model used to generate the non-dominated heat production solutions. The genetic algorithm used for this purpose is described, along with the various parameters that need to be defined to run it. Various test cases with harsh numerical conditions are used to demonstrate the capabilities of the algorithm; the influence of numerical parameters is also analysed. With the incorporation of intermittent energies into the energy mix, it is necessary to consider a representative period of at least one year for the analysis to be relevant. In order to keep calculation times acceptable, a model reduction is also proposed in this chapter. Finally, a detailed example is presented to highlight the type of results that it is possible to obtain with this method.
- Chapter 5 presents a detailed analysis of the annual industrial heat production solutions in a representative cluster of European countries based on their current and future energy mix and considering different types of industrial demand. These different case studies represent a set of 45 different configurations, which are analysed in this last chapter. As the optimisation algorithm presented in chapter IV provides a set of several non-dominated solutions for each configuration, it is necessary to classify these solutions. An analytical framework based on global limits and the importance of the industrial sector under consideration in relation to all human activities, is proposed to rank the different solutions. The aim is to highlight the most appropriate solutions for each country, process and time period. After a presentation of the general trends that can be found across all testing

configurations, a detailed environmental analysis is presented for each configuration. This environmental analysis is then coupled with energy and exergy efficiency to assess any correlation between these energy indicators and environmental impacts. Finally, an economic and environmental impact analysis is carried out to assess whether the most environmentally efficient solutions are economically competitive.

The work presented in this manuscript took place in a collaborative context. Although the thesis is funded by the French Ministry of Higher Education and Research, it is nevertheless part of a collaboration between INSA Lyon/CETHIL, which has expertise in energy and modelling, and DTU's Department of Management Engineering, which has expertise in LCA of large systems. A 5-month stay at DTU, with ERASMUS+ funding, enabled to develop skills in LCA aspects and the practical implementation of these environmental assessments in the context of industrial heat production.

This work relies on a large number of hypotheses and requires a large amount of data that are not always easily accessible and for which we have sometimes had to make approximations. All of these elements were necessary in order to produce first results based on our methodology, which was developed in the relatively short time span of a French PhD, including a few months' training in life cycle analysis in Denmark. We are aware of these limitations, which need to be further addressed in future work, but we can nevertheless present the initial results of our methodology in configurations that we hope will be as realistic as possible.

Chapter I

I. Context, challenges and state of the art

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I.1 Industrial heat production: from global context to study scope

I.1.1 World energy demand in the context of global change

Human use of energy has been growing steadily since the end of the 18th century to reach a little more than 160,000 TWh in 2021 (Fig. 1), a quantity of energy representing approximately one 10,000th of the annual solar energy reaching the top of the Earth's atmosphere. Starting with a mix composed almost exclusively of 100 % biomass before the industrial revolution, new energy sources have gradually accumulated without supplanting previous ones in absolute terms. Vaclav Smil has thoroughly investigated the various stages of this historical evolution [12]. These historical perspectives - a brief summary of which is given below - are of great interest in understanding the current trajectory in the context of a necessary transition to a less carbon-intensive energy mix [13].

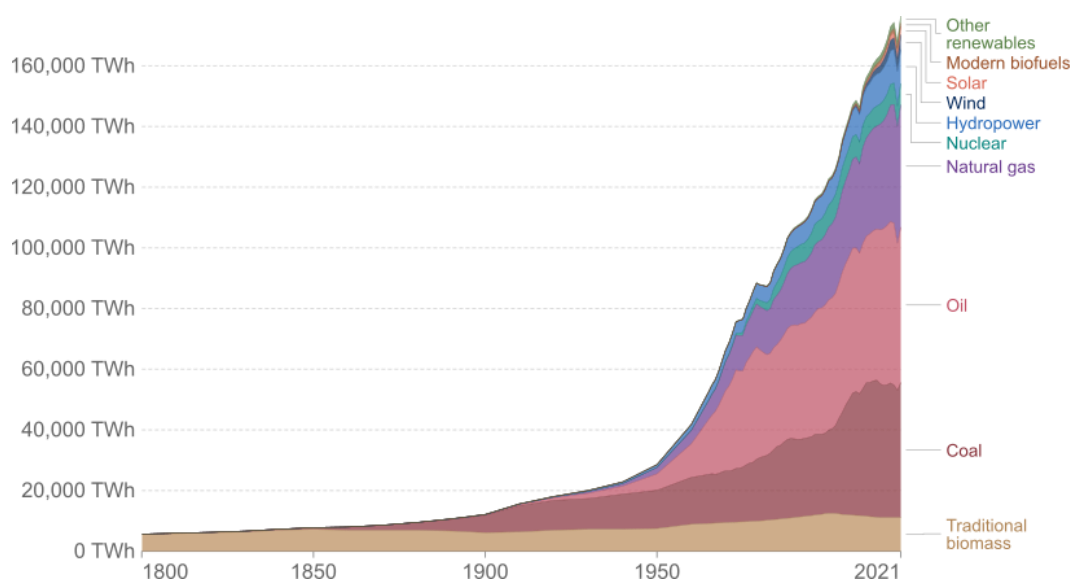


Fig. 1 - Global primary energy consumption by source, from [14]

Coal provided half of England primary energy as soon as 1620, rising to over 95 % by 1850. The second country to reach this threshold of 50 % of coal in the primary energy was France in 1870, followed by the USA in 1880, while the world reached this threshold in the early 20th century. Initially driven by heating and craft needs, coal gradually replaced human and hydraulic power in industrial applications with the invention and the improvement of the steam engine during the 18th century. It started also to replace animal and wind power in the transport sector in the first half of the 19th century.

Initially driven by the needs for light, oil saw a similar rise to that of coal with the exploitation of the first American deep well in 1859. This increase was then fuelled by the development of the automobile at the end of the 19th century and the other modes of transport in the first half of the 20th century linked to the invention of the internal combustion engine, powered by both gasoline and diesel.

From 1880 onwards, Edison's patent launched the massive development of electrical energy. Electricity was initially generated through the conversion of the chemical energy of coal into the first steam turbines invented at the same time, and the conversion of hydraulic energy into water turbines that were invented during the 19th century and progressively replaced waterwheels for

mechanical applications. The development of electricity prompted a massive build-up of large dams, which peaked in the 1970s in OECD (Organisation for Economic Co-operation and Development) countries and where development potential is now limited. More recently, non-OECD countries have seen a similar increase, particularly Latin America and South-East Asia, which have substantial resources but limited growth potential due to the physical limits of hydraulic energy.

While gas was frequently present in early oil wells, it was initially only marginally exploited due to a lack of infrastructure for its transport over long distances. The development of arc welding during the First World War paved the way to modern pipelines and gas gradually replaced coal for heating and many industrial processes, which in turn considerably improved urban air quality. The invention of the gas turbine in the 1930s also led to its widespread use in power generation. The latter also enabled the development of mass aviation, thanks to the extreme power density generated by these machines powered by kerosene, making it possible to fly much larger aircraft than with internal combustion engines.

In addition to their use for energy purposes, gas, coal and oil also saw new developments in various non-energy industrial processes. Coal, for example, is essential to the iron and steel industry, whose massive development is linked to the invention of coke at the end of the 18th century. Gas is massively used in fertilizer production, with the invention of the Haber-Bosch process just before the First World War and the massive development of petrochemicals after the Second World War.

In 1973, 14 % of the world's primary energy came from renewable sources, essentially biomass and hydroelectricity, while fossil fuels accounted for 86 % of the energy mix. From the 1970s, civil nuclear power has been added to the mix, mainly for electricity generation and reached a plateau in the 1990s. It took a century of unsuccessful attempts before wind power began to be exploited commercially in Denmark and California in the early 1980s, but it has only really taken off since the beginning of the 21st century. The same is true for photovoltaics, whose first commercial cells were invented by Bell in 1956, but whose prohibitive cost meant that they could only be developed in niche markets, like space industry, for many years. However, with a virtually linear learning curve since then, the price has fallen by 25 % with each doubling of production over the last forty years. Therefore, as for wind, PV started to take off at the beginning of the 21st century. Geothermal energy has been used to generate heat and electricity since the early 20th century, but its use really took off in the 1980s, but at a much slower pace than PV and wind power, and its share of the current energy mix is lower than either of these. The development of marine energies and their short- and medium-term outlook are marginal.

Even with the recent development of these last renewable energies, the primary energy mix in 2018 is made up of 14 % renewable energies as in 1973, the share of fossil fuels has decreased slightly from 86 % in 1973 to 81 % and nuclear represents the last 5 %. Therefore, in 2018, over 80 % of primary energy is still highly carbonated, and above all humanity uses 3 times more primary energy than in 1973. After a reduction in final energy consumption in 2019 and 2020 as a result of the COVID pandemic, consumption has since increased again, rising by 5.8 % in 2021 to exceed the pre-COVID level [15].

With this unprecedented growth in human activities, environmental issues - due to energy use, but also to the use of land and oceans for food purposes - have taken on greater importance in public debate. In 1972, the United Nations Conference on the Human Environment (UNCHE) was the

first major conference on the issue of the environment organised by the United Nations¹. It leads to the creation of the United Nations Environment Program (UNEP) that is the global authority on the environment within the United Nations. In 1992, at the Rio Earth Summit, the parties agreed on the United Nations Framework Convention on Climate Change (UNFCCC), which is the international framework for discussing actions to tackle climate change and its effects. During the same summit, the participants decided to hold annual Conferences of the Parties (COP) which bring together all countries to collectively plan the reduction of Greenhouse gas (GHG) emissions. These annual conferences were marked by some summits like in 1997 during which the Kyoto protocol was signed with first greenhouse gas reduction targets, but with different commitments from one country to another. More recently in 2015, the Paris agreement was signed to go further on the reduction of GHG emissions and includes all the countries.

For the past 30 years, despite the adoption of these two international protocols or agreements, energy consumption has increased by more than 54 % since the Rio Summit in 1992. Fossil fuel consumption (coal, oil, gas) has increased by 53 %, during the same period and the coal consumption has increased even more to 64 % [14]. Following this increase in energy consumption, there has still been no reduction in GHG emissions, with the exception of the COVID period (Fig. 2), which led to a reduction of 2.2 Gt CO₂ of the fossil fuel and industrial processes [16]. CO₂ fossil fuel emissions now account for about 85 % of total CO₂ emissions from human activities (excluding the other GHG). If other GHG are considered, all the human activities generated 59.6 ± 6.6 GtCO₂eq in 2019 [16].

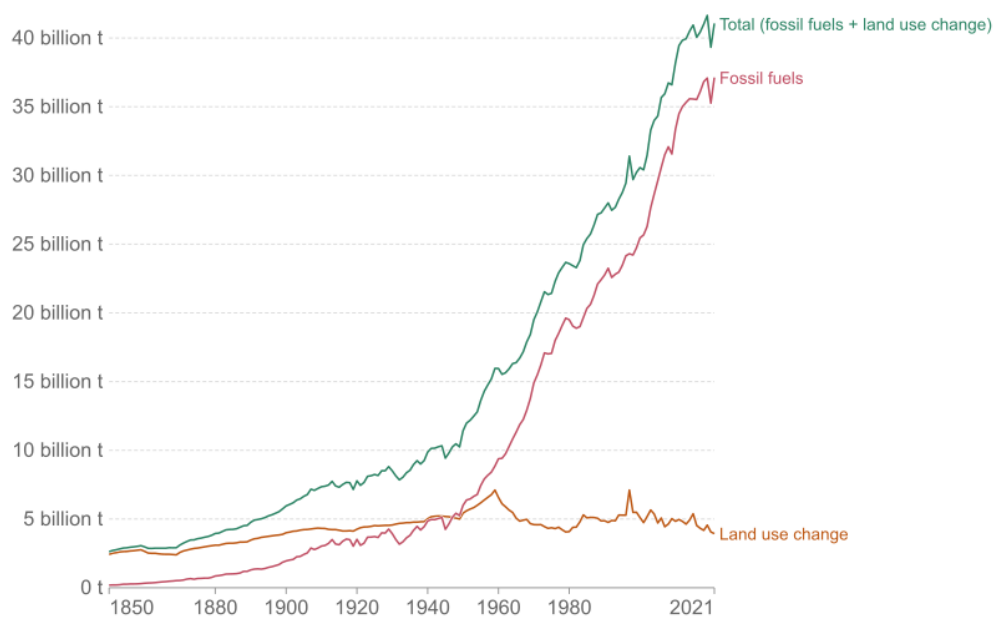


Fig. 2 - Global CO₂ emissions from fossil fuels and land use change, from [17]

The Intergovernmental Panel on Climate Change (IPCC), synthesised 2105 climate modelling scenarios² to make global warming projections [16]; the trends presented in Fig. 3 for the targets 1.5 °C and 2 °C in relation to the pre-industrial era are compared to the projected emissions with the current policies planned and implemented, resulting in a mean warming value of about 3.2 °C.

¹ <https://www.un.org/en/conferences/environment>

² Data available on : <https://data.ene.iiasa.ac.at/ar6>

There is therefore still a huge gap between the political will, e.g. to limit warming to below 2 °C as voted in the Paris Agreement [18], and the policies put in place to combat this temperature rise. For the scenarios, which limit global warming to below 2 °C, emissions of CO₂ are expected to fall before 2025 and to reach a zero-net value (not considering the other GHG) in 2050 for 1.5 °C and 2070 for 2 °C. Swift decarbonization of human activities is crucial in order to limit global warming to less than 2 °C. This would make it possible to limit the severe, irreversible and large-scale consequences for all the systems, be they physical, biological or human as highlighted by the 5 five global reasons for concern of IPCC reports.

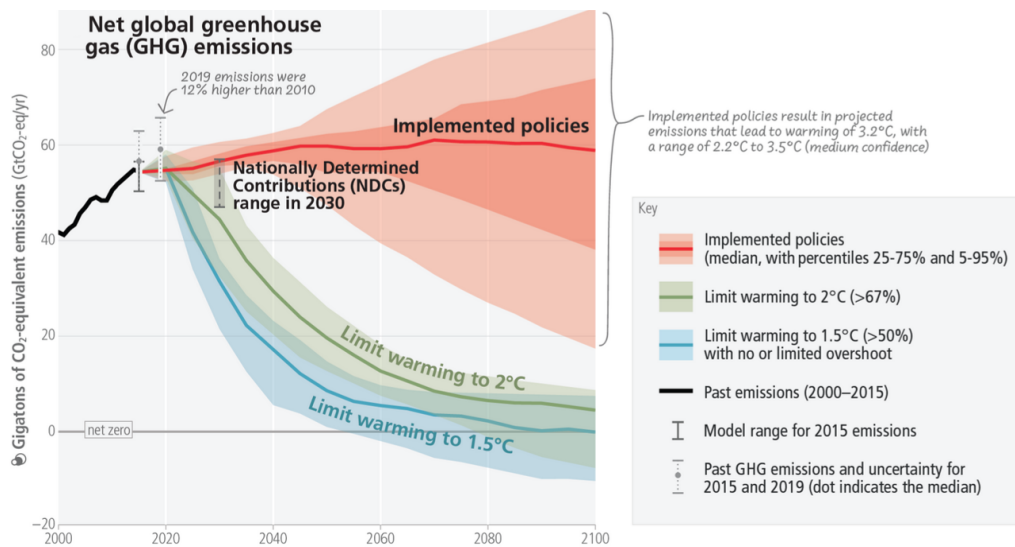


Fig. 3 - Historical data of net global GHG emissions and projections to 2100, from IPCC AR6 [16]

All human activities are concerned by the reduction of GHG emissions, but certain sectors can wield a significant impact. Among them, the industry sector is the largest emitter of GHGs, accounting for 24.2 % of total emissions, and 1/3 of the energy portion (Fig. 4), ahead of energy consumption in buildings (17.5 %) and transport (16.2 %).

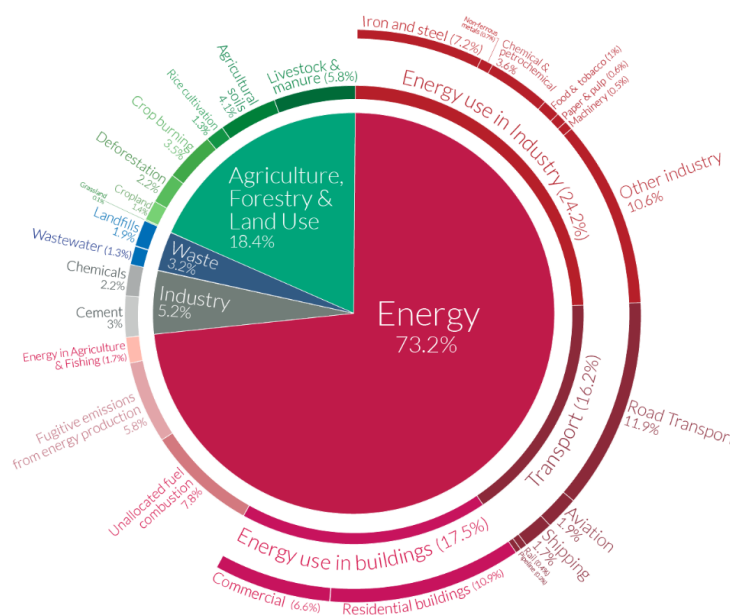


Fig. 4 - Global greenhouse gas emissions by sector in 2016, figure from [17]

Limiting current environmental problems to climate change alone is absolutely reductive when it comes to addressing global change linked to human activities. This is why the Stockholm Resilience Centre has developed an analysis framework called "planetary boundaries", which defines sustainable limits for 9 criteria broken down into 12 sub-criteria, beyond which equilibrium is threatened. Exceeding these limits drift the earth system towards another equilibrium and does not allow to return to the initial state (Fig. 5).

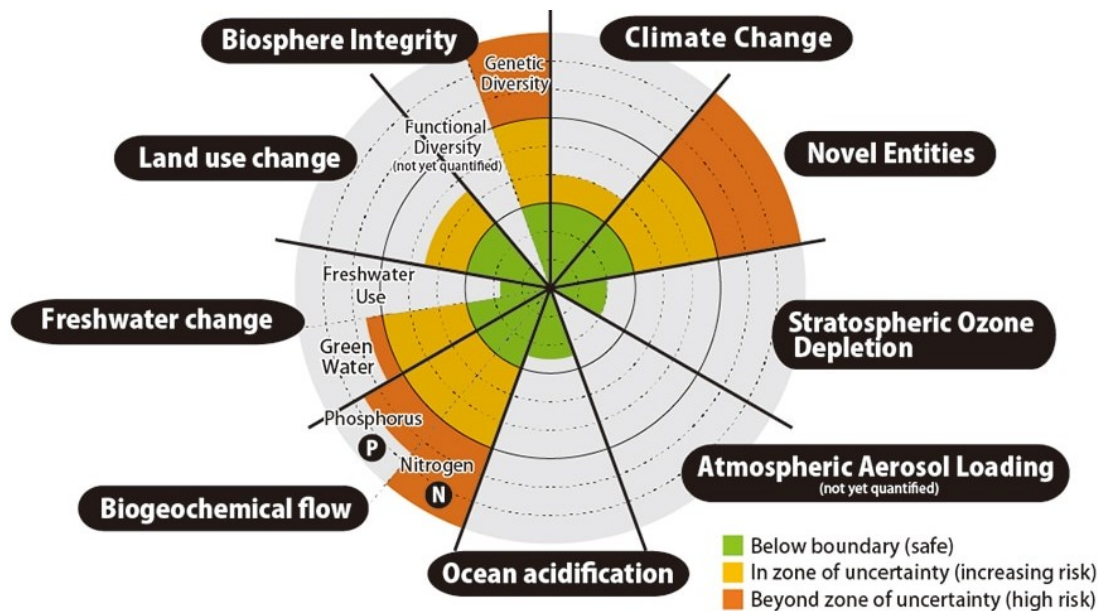


Fig. 5 - Current state of planetary boundaries from [11], [19]

These thresholds are subject to a high level of uncertainty due to the complexity of the phenomena involved and the feedback loops. It has therefore been decided to define 3 zones: (i) the first is a zone considered to be safe, where the current level enables the current equilibrium to be maintained; (ii) the second zone, called uncertainty, corresponds to a level within the margin of error, where any increase entails an additional risk of permanently altering the current equilibrium; (iii) the last zone corresponds to the overshoot of the sustainable threshold for the limit in question. The 9 criteria are as follows:

1. Climate change, linked to the concentration of GHG in the atmosphere, which is responsible for the greenhouse effect and therefore the energy balance between earth and space.
2. Atmospheric aerosol loading, linked to the quantity of atmospheric pollutants.
3. Stratospheric ozone depletion, linked to the concentration of ozone in the stratosphere, which shields the earth's surface from extreme ultraviolet (UV) radiation, UVC and some UVB rays.
4. Ocean acidification, linked to the balance of the different forms of inorganic carbon dissolved in ocean water, which is modified by the absorption of CO₂ by the ocean.
5. Freshwater change, linked to the amount of water available for human consumption and biodiversity.
6. Land use change, linked to the size of preserved natural areas and forests.

7. Biosphere integrity, linked to the mortality of species and their ability to conserve genetic diversity.
8. Biogeochemical flows, linked to the use of fertilizers (nitrogen and phosphorus).
9. Novel entities, linked to pollution by anthropogenic products (i.e. plastics).

Of these 9 categories, 2 are in a zone of uncertainty (climate change and land use change), 4 are already beyond the zone of uncertainty for at least some of their criteria (Freshwater change, Biosphere integrity, Biogeochemical flows, Novel entities) and 1 has not yet been quantified at this stage. Although climate change will have an even greater impact on biodiversity and human living as temperature rises, it is not currently the only threat to maintaining the equilibrium that sustains life on earth. Conversely, it is imperative that actions taken to address climate change exert minimal influence on other planetary limits.

I.1.2 Global industrial final energy consumption for heat production

The evolution of the global final energy demand - excluding non-energy use of fossil fuels - is presented in Fig. 6 for all human activities. Buildings, industry and transport sectors are equivalent and represent the major parts of the final energy consumption. The final energy demand of industry was equal to 33600 TWh in 2019.

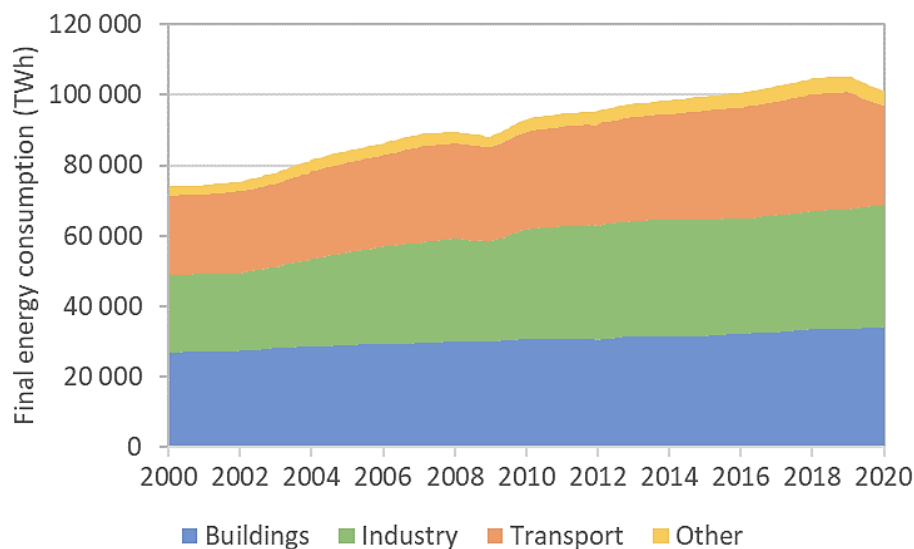


Fig. 6 - Final global energy consumption by sector, from González-Torres et al. [20]. Other covers residential, commercial and public services agriculture/forestry, fishing and non-specified consumption.

Industrial heat production accounts for two-thirds of industrial energy demand as estimated by IEA [21]. Unfortunately, as for many other relevant information, the details concerning this production are not in open access on their website. In the absence of such data, it is nonetheless interesting to assess the share of each energy source in the various industrial processes, separating electricity from other energy sources. As the open data of IEA are often incomplete, we have to consider two different sources for year 2019 [22] and for year 2020 [10] to assess these parameters (Table 1). In this table, the values in bold are raw data from IEA and the other are calculated from

these data¹. The share of each source of energy in industry, excluding non-energy use in 2020 is presented in Fig. 7.

Table 1 - Share of each energy in industry separating energy use and non-energy use in 2019 and 2020; values in bold are from the IEA, others are calculated

		electricity	coal	oil	gas	other	total
2019	Energy (TWh)		9048	3409	7139	14010	33605
	Non-energy (TWh)		576	7911	2264	0	10751
	Share of Energy		94 %	30 %	76 %	100 %	76 %
2020	Total (TWh)	9505	13069	8956	8186	4624	44569
	Energy (TWh)	9505	12287	2697	6215	4624	33766
	Non-energy (TWh)	0	782	6259	1971	0	10802
	Share of Energy	100 %	94 %	30 %	76 %	100 %	76 %

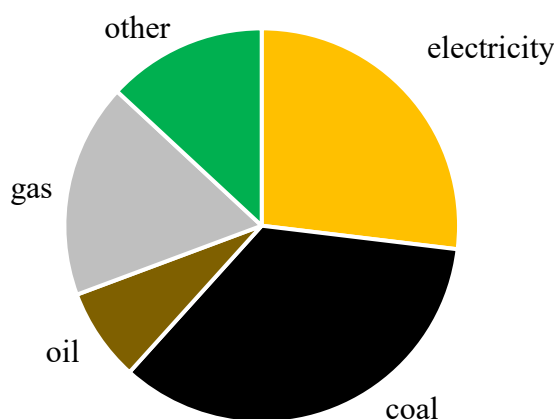


Fig. 7 - Share of each source of energy in final consumption for industry in 2020

At global level, coal consumption is still the main contributor of energy consumption. Therefore, a switch to gas could already be beneficial in terms of GHG emissions, even if other, more carbon-free options, have also to be deployed where possible. Non-energy use (Table 1, 2019) consists mainly of oil, followed by gas and, to a much lesser extent, coal. On the contrary oil contribution to energy is small and lower than other types of energy (bioenergy, waste, other gases, etc.).

Heat production for industrial applications can be achieved by a variety of technologies, depending on the temperature level required for the industrial process in question. This makes the study of heat production complex, since it is necessary to distinguish between these different temperature levels in order to carry out a detailed analysis. Fig. 8 presents the global share of final energy consumption depending on the temperature level of the industrial processes. Half of the energy is consumed by processes requiring temperatures higher than 400 °C, 25 % for temperature lower than 100 °C, 20 % in the range 100-200 °C and a few processes in the range 200-400 °C.

¹ The 2019 data distinguish between non-energy use and energy - which is important to estimate the share of energy dedicated to the production of heat -, but unfortunately the share of electricity is not given explicitly, but added to the energy mix through the different source of energy converted in electricity. On the contrary, the data of 2020 separates electricity from the other sources of energy but do not separate non-energy use from energy. Nevertheless, from 2019 data it is possible to estimate the share of non-energy use in the total energy consumption. Assuming that this share is similar in 2020, it is possible to assess the share of each source of energy in industry, excluding non-energy use in 2020.

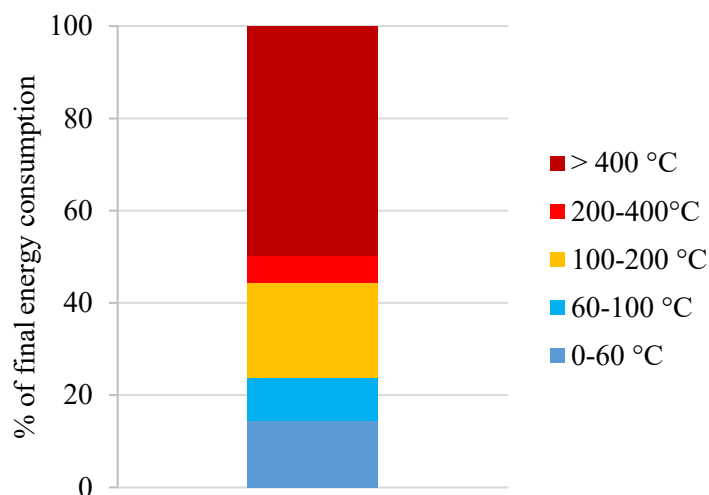


Fig. 8 - Share of final energy consumption for heat production by temperature levels [22], [23]

As highlighted in this section, global information on the characteristics of industrial production in terms of industry, process temperature level or share of each energy source is not readily available, making a worldwide study difficult. On the other hand, there is a lot of information available in Europe, which is therefore chosen as the geographical area for this thesis.

I.1.3 Heat consumption in Europe

In Europe, total consumption of the industrial sector was around 3,700 TWh in 2012, of which almost 2,000 TWh was for heat production [24]. As shown on Fig. 9, the first source of energy is gas, used at different temperature levels, while coal has a smaller contribution than in the rest of the world and is mostly used for high temperature processes ($T > 500$ °C). The challenge is therefore to find alternatives to both coal and gas for high temperature levels (> 500 °C) and to replace gas with decarbonised technologies for temperature levels in the range 100-200 °C. As highlighted in Fig. 9, the range 200-500 °C represents a small part of the total energy consumption for heat production in the European industry, as it is the case at world scale (Fig. 8).

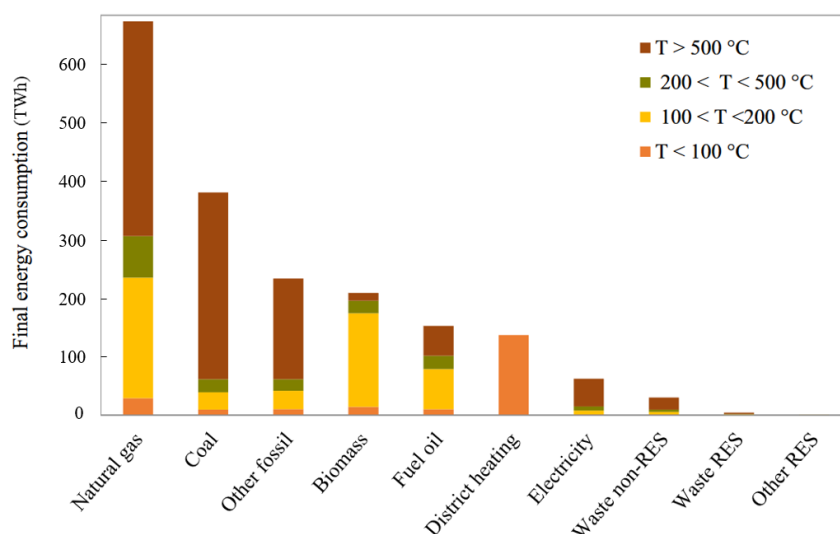


Fig. 9 - Final energy consumption for process heat in industry by energy carrier and temperature level for EU28 in 2012, figure from Malico et al. [25]

The breakdown of heat consumption is shown in Fig. 10 for the major industrial sectors. For the three most energy intensive industries (metallic, chemical and non-metallic processes), two thirds of the energy is used by processes requiring temperatures in the range 200-500 °C. Furthermore, the distribution is equivalent for the ranges 500-1000 °C and 1000-1500 °C, which represent the largest consumption, the demand in the range 200-500 °C being low except for chemical processes. In terms of total energy consumption, these temperature ranges are followed by demand in the range 100-150 °C, most of which is required by the food and tobacco industry, and then demand between 150 and 200 °C, mainly related to the paper process. The temperature levels are therefore varied, as is the type of heat required by the industry. Conventional process heating technologies are based on one or a combination of the basic heat transfer mechanisms (generally conduction and convection heat transfer for low-temperature processes and radiative heat transfer for higher temperatures). They can be classified into four general categories according to the type of energy carrier used: steam, fuel, electric and hybrid, which is a combination of the first three [26].

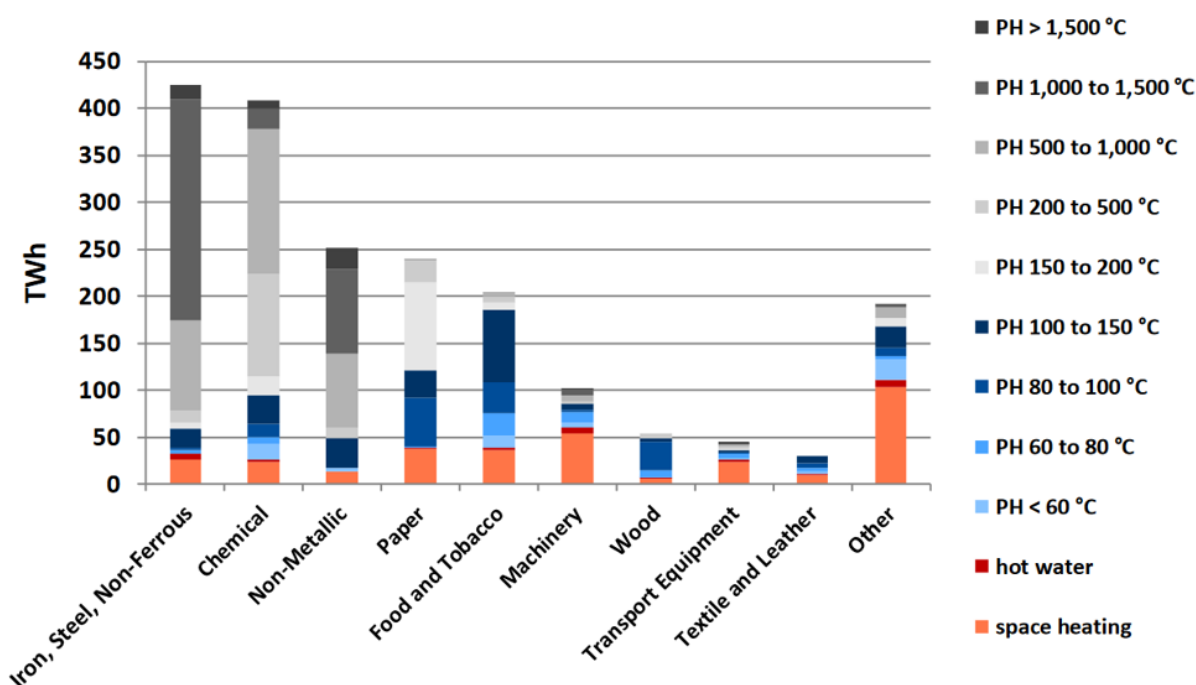


Fig. 10 - Process Heat demand across different industrial sector of European countries decomposed by temperature level, from [24]

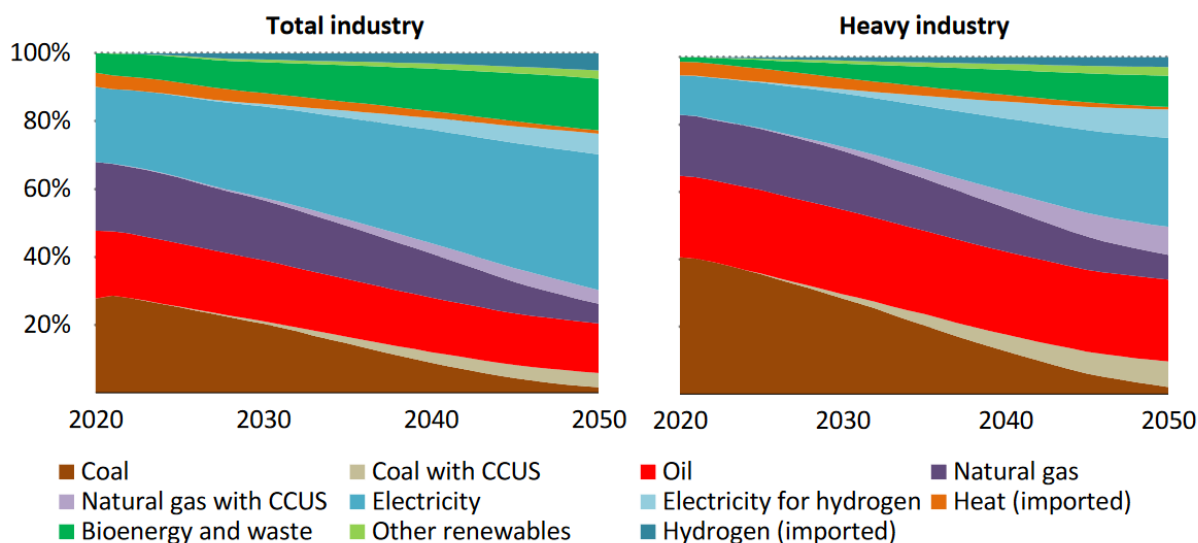
I.2 Outlook of heat production as part of energy transition

I.2.1 Transition scenario from IEA and European roadmap

In the transition scenario of the International Energy Agency (IEA) [10] [27], the trend tends to double the share of electricity in the mix at the expense of fossil fuel consumption (Fig. 11).

At the same time, this scenario anticipates the development of hydrogen-based solutions and carbon capture and storage (CCS) technology. More than 75 % of fossil fuels remaining in the mix in 2050 are not combined with CCS. At the same time, bioenergy is playing an increasingly important role in the industrial mix, reaching a share of 17 % by 2050. In terms of total demand, IEA forecasts an increase in the sector's final energy consumption until 2030, followed by a slight decrease of 4 % between 2030 and 2040 and 6 % between 2040 and 2050. This reduction is

explained by a reduction in demand and an increase in the energy efficiency of industrial processes.



IEA. All rights reserved.

Fig. 11 - Total final consumption by source in the net zero emission scenario including non-energy use, 2010-2050, from IEA [27]

This trend is also reflected in the European roadmap, which also calls for the electrification of industrial processes as a lever for decarbonisation [28]. However, as this roadmap shows, electrification presents a number of technological and economic bottlenecks that need to be resolved if the energy transition is to succeed.

I.2.2 Technologies for the energy transition

The energy transition needs to be accompanied by technological transformations. For industry, decarbonisation is based on 3 main pillars which can be found in numerous reports such as the IEA report [27] (Fig. 12) or in the European Union's industry decarbonisation scenarios [28]:

- Replacing fossil fuels with alternative energy sources. As presented in section I.1.3, most industrial demand can be broken down into demand for very high temperatures ($> 500\text{ }^{\circ}\text{C}$) and for temperatures lower than $200\text{ }^{\circ}\text{C}$, that are developed in part I.2.3 and I.2.4, respectively. These alternative energy sources may require heat storage systems, presented in part I.2.5, to cope with their intermittency or with technological or economic constraints.
- Development of Carbon Capture Utilisation and Storage (CCUS), presented in part I.2.6, which represents an important contribution to the GHG emission mitigation strategy.
- Improving efficiency (materials and energy), which is not a new pillar, but a process that has been ongoing since the industrial revolution.

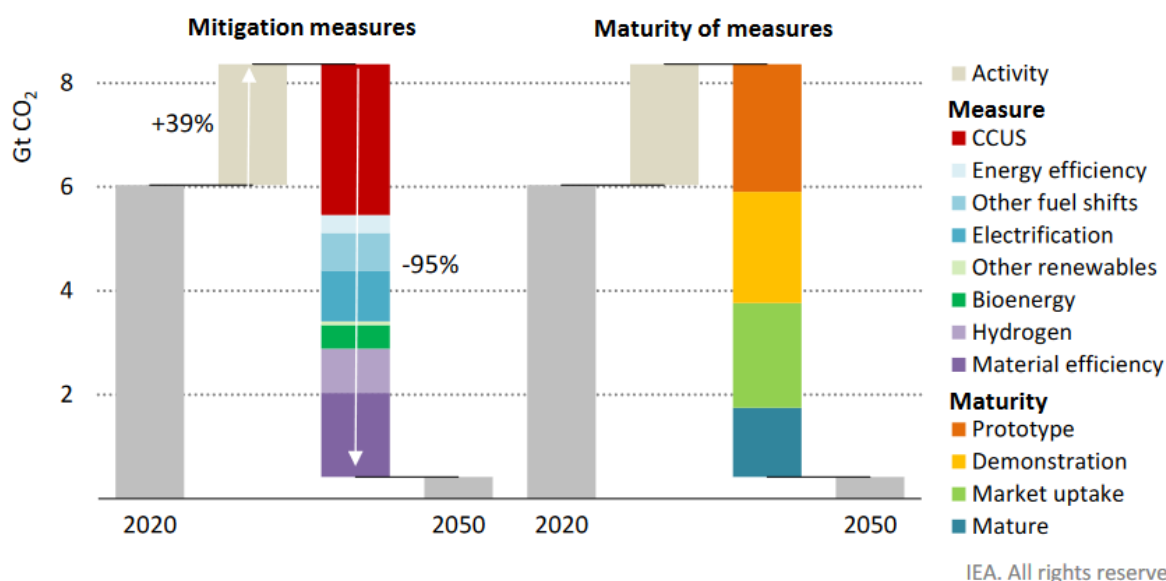


Fig. 12 - Global CO₂ emissions from heavy industry, mitigation measures and technology maturity, from the net zero roadmap of IEA [27]

I.2.3 Alternative technologies to decarbonise high temperature processes

Decarbonisation of high-temperature industrial processes (> 500 °C) faces challenges that are highly specific to the processes themselves.

IEA has proposed an analysis of over 500 technologies across different energy sectors (industry, buildings, transport) that contribute to the goal of net-zero emissions [23]. Among these technologies, those best suited to meeting the challenges of decarbonising the high-temperature process are presented in Table 2. There are currently 4 technologies with a Technology Readiness Level (TRL) of more than 8, i.e. with a first level of industrialisation. There are also many technologies that have been identified as contributing to decarbonisation, but which are not yet ready for development within industry. The development of these technologies is therefore a major challenge if the industry is to achieve large-scale decarbonisation.

Table 2 - a) Technology Readiness Level (TRL) for different technologies identified as promising to replace fossil fuels in heat production systems [23] and b) TRL definition

a)

Technology	TRL
Induction	10
Radio wave	3
Microwave	5
Infrared	3
Ultra-violet	3
Electric arc	3
Fluidised bed boilers fuelled with biomass	2
Torrefaction	9
Pyrolysis	9
Concentrated solar power-generated heat for industrial process	8
Hydrogen boiler	9
Biomass boiler	10

b)

1	INITIAL IDEA <i>Basic principles have been defined</i>	7	PRE-COMMERCIAL DEMONSTRATION <i>Solution working in expected conditions</i>
2	APPLICATION FORMULATED <i>Concept and application of solution have been formulated</i>	8	FIRST OF A KIND COMMERCIAL <i>Commercial demonstration, full scale deployment initial form</i>
3	CONCEPTS NEEDS VALIDATION <i>Solution needs to be prototyped and applied</i>	9	COMMERCIAL OPERATION IN RELEVANT ENVIRONMENT <i>Solution is commercially available, needs evolutionary improvement to stay competitive</i>
4	EARLY PROTOTYPE <i>Prototype proven in test conditions</i>		
5	LARGE PROTOTYPE <i>Components proven in conditions to be deployed</i>	10	INTEGRATION NEEDED AT SCALE <i>Solution is commercial and competitive but needs further integration efforts</i>
6	FULL PROTOTYPE AT SCALE <i>Prototype prove at scale in conditions to be deployed</i>	11	PROOF OF STABILITY REACHED <i>Predictable growth</i>

I.2.4 Alternative technologies to decarbonise low temperature processes

In Europe, industrial processes with a temperature level in the range 100-200 °C, are currently mostly fuelled by gas, oil and biomass (Fig. 9). To replace fossil fuels, the heat production at this temperature level is facilitated by several technologies whose TRL is already high, such as electric boiler, biomass boiler and mechanical heat pump (MHP). There are also other technologies, such as hydrogen boilers as an alternative to gas or the recovery of waste heat either on site or for the production of electricity using technologies such as organic Ranking cycle.

Heat can also be produced externally and transported by a heating network fuelled by decarbonised energies or waste incineration. For these temperature levels, the current level of technological development means that all the solutions are already operational and commercialised, with the exception of two technologies, which have certain limitations:

- For hydrogen boilers, the current level of development supports the possibility of an industrial installation, the limit being the availability of low carbon H₂.
- For mechanical heat pumps, the TRL is highly dependent on the targeted temperature level (Fig. 13). In 2018, Arpagaus et al [29] proposed a decomposition of TRL as a function of 4 different process temperature ranges: (i) below 80°C, for which the technology is already widely developed in industry with a TLR of 11, (ii) between 80 °C and 100 °C, for which the technology is marketed but there is not yet widespread installation with a TRL of 10, (iii) between 100 °C and 140 °C, for which MHP are developed in laboratory and there are completed prototypes, with a TRL of 8-9, (iv) for temperatures above 140 °C, for which several prototypes are being developed and the TRL is between 4 and 6 depending on the temperature levels targeted. However, MHP development has evolved rapidly in recent years, and the thresholds proposed by Arpagaus et al [29] are already outdated. Technologies reaching temperatures of 160-165 °C are starting to be marketed, with 2 references at 160 and 165 °C [30]. Another example is the SuPrHeat project that aims to develop a prototype capable of reaching 200 °C [31].

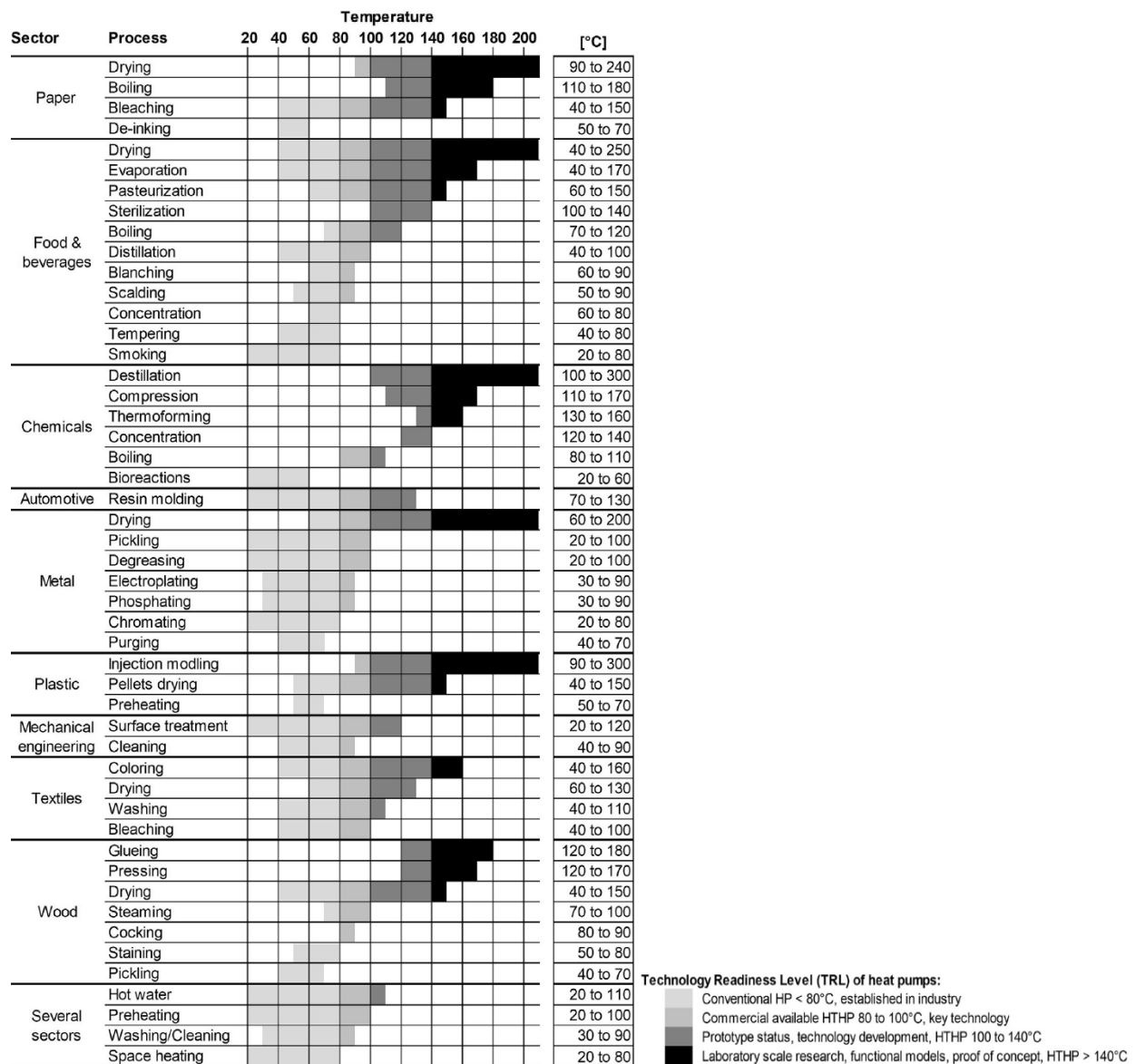


Fig. 13 - Overview of process temperature for different industrial sectors by temperature level and Technology Readiness Level from Arpagaus et al. [29]

I.2.5 Heat Storage

In addition to the improvements described above, research is being carried out into heat storage solutions for industrial sites, with the aim of making the most of waste heat recovery for industrial sites, to increase the flexibility of heat generators (e.g. integration of power-to-heat scheme based on intermittent renewable sources). On this work, the focus is put on short-term storage, the medium and long term thermal storages interest in the frame of constant heat demand needing to be explored further. There are currently many options for Thermal Energy Storage (TES) as reviewed by Sarbu et al [32]; three technologies used for this purpose are shown in Table 3. Sensible heat storage, also known as Tank Thermal Energy Storages (TTES), is the most mature and competitive technology, but it has a small energy density compared to the other systems and therefore requires more space. Phase Change Materials (PCM) are also sufficiently mature to be considered for industrial development. This technology is currently limited to low temperatures because prices rise sharply above 150 °C [33]. Overall, latent technologies are underdeveloped in

industry due to the high level of investment required, and current developments are taking place more in the building sector than in industry [33]. Lastly, solutions based on chemical reactions are an interesting option, but are not yet at a TRL level high enough to be considered by industry.

Table 3 - Typical parameters of TES systems, from [32] and TRL from [33]

TES system	Capacity (kWh/t)	Power (MW)	Efficiency (%)	Storage period	Cost (€/kWh)	TRL
Sensible (hot water)	10 – 50	0.001 – 10	50 – 90	Day / Month	0.1 – 10	8 - 9
Phase change materials	50 – 150	0.001 – 1	75 – 90	Hours / Day	10 - 50	5 - 9
Chemical reactions	120 – 250	0.01 – 1	75 – 100	Hours / Day	8 - 100	< 4

I.2.6 Carbon Capture and Storage

The other topic raised in numerous reports on decarbonisation strategies for industry is the development of Carbon Capture and Storage (CCS). This strategy enables the decarbonisation of both fossil fuels or biomass fired based electricity generation and on-site industrial production. Rubin et al. [34] have carried out a review of the various CO₂ capture techniques. It is possible to divide the technologies into three groups:

1. Post combustion capture methods, decomposed with different operating principles:
 - Amine-based capture such as MEA
 - Ammonia-based capture
 - Calcium-based capture
 - Membrane-based
2. Pre-combustion capture methods, decomposed with different operating principles:
 - Solvent-based capture
 - Sorbent-based capture
 - Membrane-based
3. Oxy-combustion systems

The first group includes all the technologies that enable capture after combustion (Fig. 14). This technology is the most advanced of the three in terms of commercialisation, particularly the technology based on amine-based solvents. This process currently works via a chemical reaction with solvent.

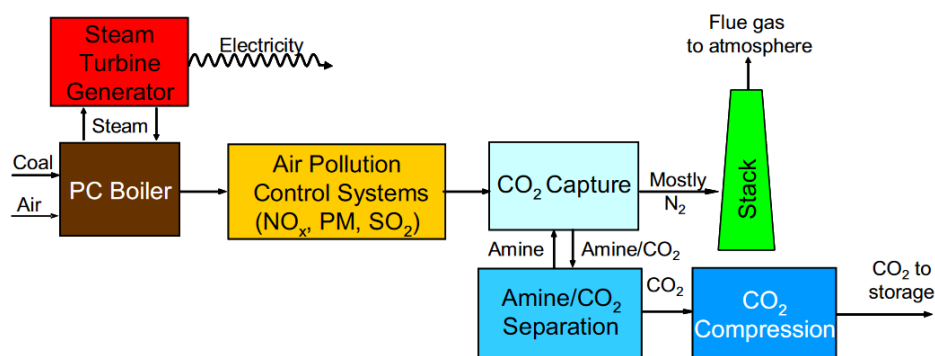


Fig. 14 - Simplified schematic of a coal-fired power plant with post-combustion CO₂, from [34]

The second group is suitable for configurations based mainly on coal. The aim is to inject steam and oxygen into the fuel to obtain a mixture of carbon monoxide and hydrogen, known as synthesis gas or syngas. By injecting water, it is then possible to obtain a CO₂/H₂ mix. The first is recovered and stored, while the second is used for combustion (Fig. 15).

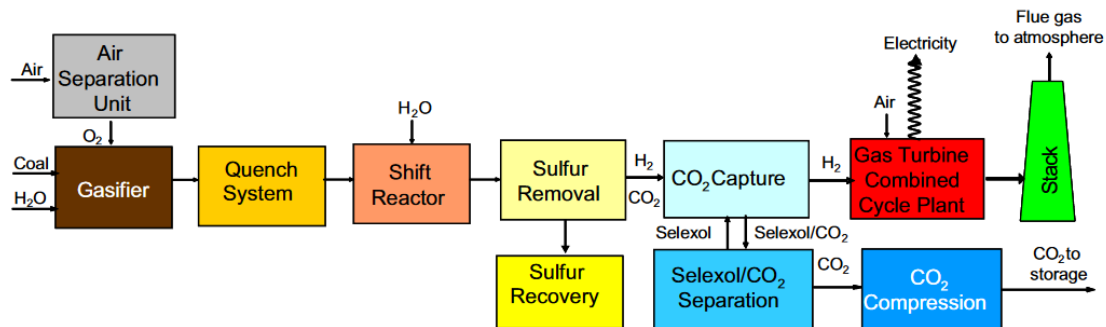


Fig. 15 - Simplified schematic of an integrated gasification combined cycle (IGCC) coal power plant, with pre-combustion CO₂ capture, from [34]

The last group is currently at the prototype stage, and also the least developed. The principle is based on injecting pure oxygen instead of air into the boiler, which produces a flue gas composed only of water vapour, CO₂, and pollutants (SO₂, NO_x). After condensation of the water vapour and filtration of the pollutants, CO₂ can be sent directly to storage.

It should be pointed out, however, that there are still many uncertainties surrounding the development of CCS, and the latest ‘EU Reference Scenario 2020’ report [35] revised upwards the price of CCS for certain technologies because of the lack of development projects.

I.3 Energy and environmental analysis methods

In addition to the development of the new technologies described in the previous section, optimisation of existing processes themselves is also an important pillar of the technological transformation aimed at achieving greenhouse gas emission reduction targets. It is common for industries to upgrade or change their energy systems. For example, transformations have been implemented with the banning of ozone-depleting potential (ODP) refrigerants in the Montreal Protocol [36], followed by the banning of HCFC refrigerants. More recently, a gradual banning of HFC refrigerants with a high Global Warming Potential (GWP) is in progress to reduce GHG emissions (F-gas regulation) [37]. These transformations are also driven by the increase in requirements on discharges of industrial pollutants into air and water through the industrial emission directive from European commission [38].

I.3.1 Optimising existing production systems

It is possible to improve the efficiency of existing systems using different approaches including:

- the reduction of energy used to generate heat by optimising the combustion process itself, the extraction and/or recuperation of energy from exhaust gases, and the reduction of the amount of energy lost to the environment. An example for gas boiler is the addition of a condensing economizer in which the flue gas temperature is lowered below the dew point, condensing the moisture, and recovering latent heat as well as a greater amount of sensible heat than would be possible with a simple economizer.

- the reduction of the consumption and losses of the auxiliaries, by optimising operating regimes and the design and ensuring maintenance to limit the degradation of performance over time.

The current integration of these different measures depends very much on the level of management of the industry's production system. Some industries have already made most of the possible optimisations, while others are starting to embark on the transformation process. Wang et al. [39] present the potential optimisation of three industries (iron and steel, cement and coal fired power plants) for China and identify several optimisation measures, such as modernising the structure of production equipment and promoting cleaner production technologies. They also point out that, depending on the sector, these efforts are not based on the same lines of action. Zuberi et al. [40] identify different improvement actions and quantify the associated gains in terms of energy, economic and CO₂ emission indicators. The three most effective measures identified for reducing CO₂ emissions from Swiss industry are heat recovery for steam generation with an abatement of 300 ktCO₂/year followed by the process heat integration with an abatement of 250 ktCO₂/year and the load pre-heating with an abatement of 100 ktCO₂/year.

Multi-criteria analysis methods known as 3E (Energy, Exergy, Economy) and 4E (Energy, Exergy, Economy and Environment) studies are used to assess the relevance of these solutions. These methods are not really standardised, but what they do have in common is that they integrate several or all these approaches, cross-referencing the different criteria to assess the various trade-offs between advantages and drawbacks. A brief overview of these methods is presented in the next section, to highlight recent developments.

I.3.2 Multi-criteria optimisation methods 3E/4E

Research into the optimisation of means of production, as well as the transformation of these means of production, is very dynamic. A non-exhaustive list of studies published since 2016 dealing with these subjects is presented in Table 4, breaking down the fields of research according to the areas covered. 3E optimisation studies were the first to appear in the literature and still account for a large number of optimisation studies published in recent years. The aim of these studies is to minimise the irreversibility of systems in order to maximise the efficiency while offering reduced costs. This can translate into benefits for industrial processes through reduced energy consumption and therefore cost savings. Most of the references in Table 4 use this type of assessment.

With the growing awareness of the major consequences of global change, 4E studies are increasingly being carried out to include environmental impact assessment. However, most environmental assessments focus solely on reducing greenhouse gas (GHG) emissions, although some go further and assess the environmental burden across a wider range of impact categories (for example, impacts that affect human health or resource consumption). A study realised by Chen et al. [41] presents the optimisation of an industrial cascade heat pump based on waste heat recovery to achieve energy savings of 33 % combined with a reduction in CO₂ emissions of 44 % compared with the initial configuration. Adding the environmental assessment highlights the environmental benefits and drawbacks of energy optimisation. Blanco et al. [42] study the environmental impact of different GHG reduction scenarios and clearly identify that reduction in impact on *climate change*¹ is always combined with an increase in impact on *human toxicity* and

¹ The LCA impact categories presented later in Table 22 are written in italic in all the manuscript.

natural land transformation for the industrial sector. This type of study highlights the environmental consequences of any energy transition and is therefore essential when the transformation of an energy system is envisaged. These studies ensure that the environmental burden of greenhouse gases is not transferred excessively to other environmental impacts.

Table 4 - State of the art of studies on process optimisation coupling Energy (En), Exergy (Ex), Economy (Eco), Environment (En) or only Greenhouse gases (GHG)

	Reference	En	Ex	Eco	GHG	Env
Combustion process optimisation	[43]	x	x	x	x	x
Recovery of waste heat	[44]	x	x	x	x	
	[45]	x	x	x		x
Transformation of processes for heat production	[46], [47]	x	x	x		
	[48], [49]	x	x	x	x	
	[42]	x	x	x	x	x
Others (refrigerant, TES, CCS)	[50], [51]	x	x	x		
	[52], [53]	x		x	x	
	[54]	x	x	x	x	x
	[55]					x

An increasing number of studies incorporate environmental considerations, with very different analytical frameworks from one study to another, sometimes using a simple emission factor per unit of energy consumed, and other more advanced studies incorporating a more comprehensive LCA framework. An approach based on LCA is used in this thesis and is detailed in the next section.

I.3.3 Life cycle assessment

As mentioned above, environmental constraints are increasingly present in short- and medium-term political and industrial strategies. The development of analytical tools - called Life Cycle Assessment (LCA), for assessing environmental performance - began in the 1990s. In 1997, the first version of ISO 14040 [56] (subsequently updated as ISO 2006a) was published with the aim of harmonising the framework and principles of LCA and increasing the transparency and comparability of LCA studies. This framework is broken down into 4 stages described in Fig. 16, (i) the goal definition stage, (ii) the scope definition stage, (iii) the inventory analysis stage which consists of recovering and validating the data used for the LCA and (iv) the impact assessment stage which enables the inventory to be converted into an impact. As steps (i) and (ii) are self-explanatory and highly dependent on the case study, they will not be detailed here.

Step (iii), Life Cycle Inventory (LCI), consists of producing the dataset, which must take into account geographical and temporal constraints and define the type of modelling used. Modelling is specific to each process and depends on the previous steps, such as the scope definition. There are two main LCI modelling frameworks: the attributional and the consequential [57]. Each of these two frameworks provides a different way of analysing the impacts. The attributional LCI aims to assess how much of the impacts can be attributed to the process under study, while consequential LCI is defined by Hauschild et al. [57] as “the changes to the economy caused by the introduction of the studied product system, i.e. the product system's consequence”. For the proposed application - namely the heat production in industry, which represents a significant contribution of the energy market - the electrification of processes is likely to lead to an increase

of electricity production to satisfy this new demand. The consequential method assesses the impacts that will result from the new process, i.e. the consequences that the impacts will have.

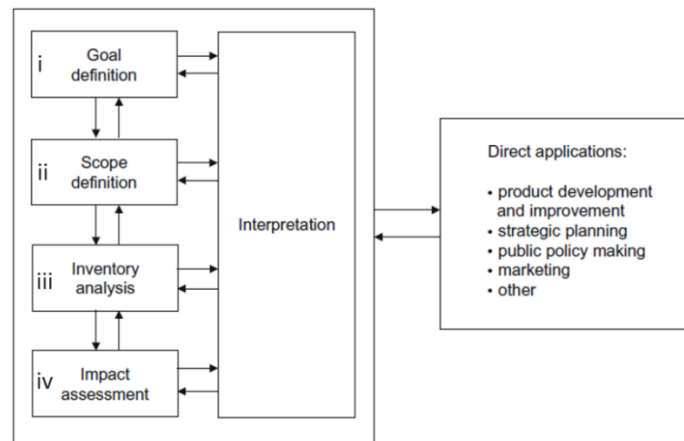


Fig. 16 - Framework of LCA modified from the ISO 14040 standard, from [57]

Fig. 17 shows an example with a power generation made from two different sources S1 and S2. In the initial configuration, heat is produced only from gas and after electrification, heat production is done using both gas and electricity. For this example, it is assumed that the electricity production required to meet this new demand comes from the source S1, which is increased compared to the initial electricity mix by a value S'1. Therefore, the consequence on the electrical network of the electrification of this industrial process is the addition of S'1 to the initial electricity mix S1+S2.

- For the consequential framework, the LCI considers only the impact coming 100 % from the new production S'1.
- For the attributional framework, the LCI considers the impact of the same amount of electrical energy, but with a distribution corresponding to the proportion of each source in the new energy mix made up of S1+S'1+S2.

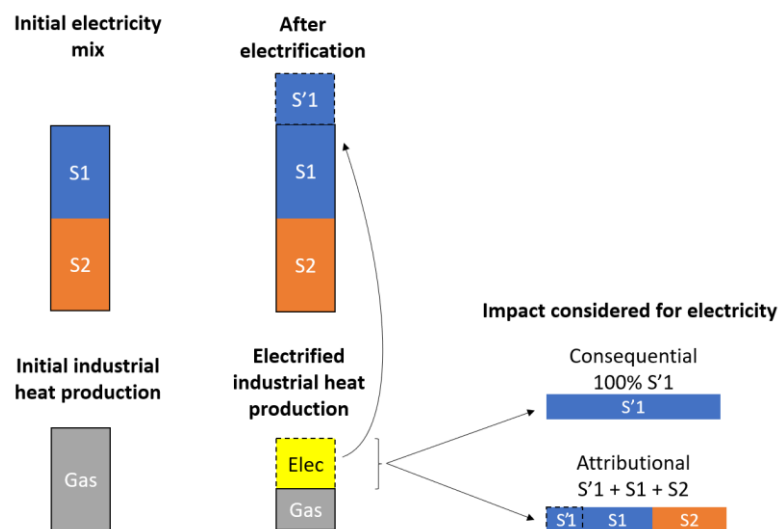


Fig. 17 - Principles of the two main LCI modelling frameworks, for a production of heat from gas in initial situation and from both gas and electricity after electrification. S1 and S2 are two energy sources to produce electricity and S'1 the new installed capacity from S1 to meet the new demand.

The last step, (iv) Life Cycle Impact Assessment, aims to translate the elementary emissions into impacts. The development of various impact assessment methods following the first ISO 14040 version is presented in Fig. 18 from the early 2000s. Each of these methods has its own specific features, namely (i) geographical specificity by integrating impacts specific to geographical areas, (ii) types of impact studied with different levels of assessment. They can be classified in three families:

- Methods to assess very specific impacts, such as the method AWARE¹ to assess water consumption or USEtox² to assess human and biodiversity toxicity due to chemical use.
- Methods focusing on midpoint impacts such as Environmental footprint³ or ReCiPe⁴,
- Methods focusing on endpoint impacts such as IMPACT World+⁵ or ReCiPe

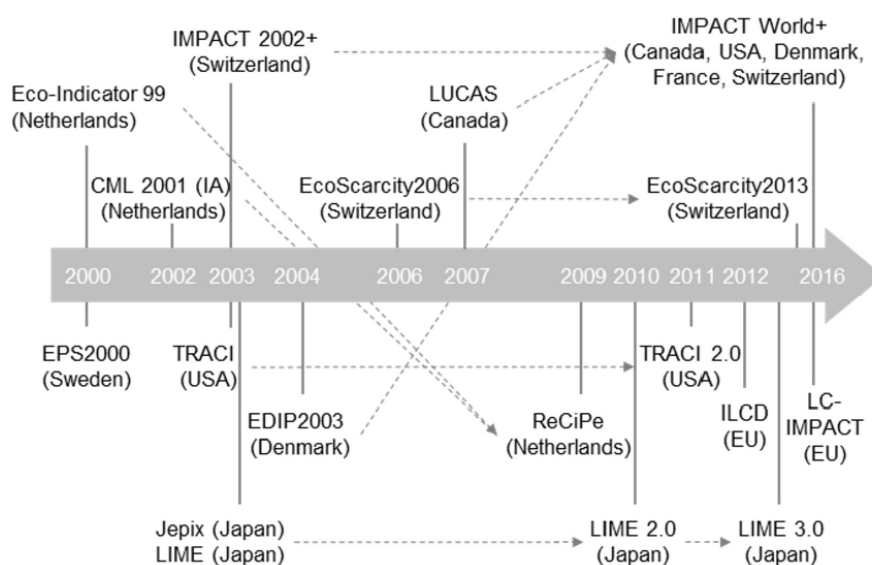


Fig. 18 - Publication date of the main LCA analysis methods, from [58]

A midpoint impact corresponds to a grouping of elementary flows that contribute to the same environmental impact; for example, GHG emissions are grouped together to assess the impact on midpoint indicator *climate change*. In the chain of cause-effect, the midpoint categories therefore lie between emissions and environmental damage, as shown in Fig. 19. For the previous example of *climate change*, it is possible to have different midpoint categories, for example *radiative forcing increase* or *atmospheric temperature increase*.

An endpoint impact, also known as damage, is defined by Hauschild et al. [57] as “Endpoint indicators are representative of different topics or Areas of Protection that “defend” our interests as a society with regards to human health, ecosystems or planetary life support functions”. These categories are often divided into 3: (i) Human health (ii) Ecosystem quality or natural environment (iii) Natural resources and ecosystem services as shown in Fig. 19.

¹ <https://wulca-waterlca.org/aware/>

² <https://usetox.org/>

³ <https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml>

⁴ <https://www.rivm.nl/bibliotheek/rapporten/2016-0104.pdf>

⁵ <https://www.impactworldplus.org/en/>

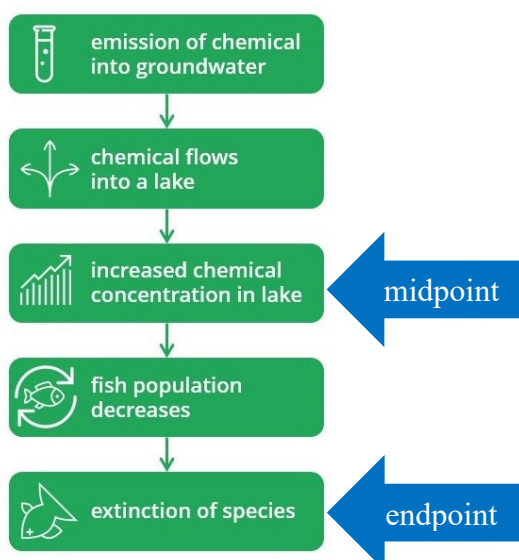


Fig. 19 - Example of a cause-effect chain, from [59]

An example of the link between midpoint and endpoint categories is shown in Fig. 20. Each endpoint category is impacted by a number of midpoint categories, all of which contribute in different ways. This step corresponds to a so-called normalisation step, which is defined by ISO 14040 as an optional step because it introduces greater uncertainty into the results. This stage involves converting all the midpoint impact categories into a contribution to the endpoint category and assigning a weighting to each midpoint category based on their contribution to the endpoint impact. When the impact category considered is close to emission, uncertainties are lower, but interpretation is more difficult because it is difficult to assess the impact on human health or biodiversity. The midpoint categories therefore have a lower level of uncertainty than the endpoint categories, for which assumptions are made to convert the contribution of each type of impact into damage.

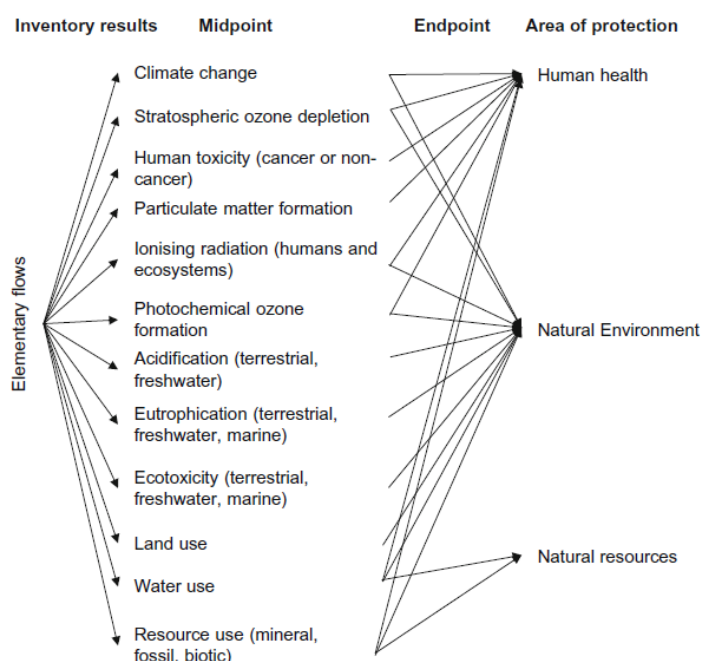


Fig. 20 - Framework of the International Reference Life Cycle Data System characterisation linking elementary flows from the inventory results to indicator results at midpoint level and endpoint level for 15 midpoint impact categories and 3 areas of protection from [57]

LCA studies are originally intended either to compare two products with each other, or to evaluate the gain in relation to an initial situation. More recently, a new branch of LCA research is being developed, focusing on methods for comparing LCA results with a sustainable level. Bjørn [60] show that it is necessary to move on from comparing systems with each other to comparing systems with respect to a sustainable level. Indeed, as the author points out, a better solution is not necessarily good enough to be aligned with sustainable level. This new type of analysis involves addressing one of the environmental impacts, by defining for that impact the level which is acceptable for a process, an industry or a sector. There are different ways of defining what proportion is attributable to a process [61], [62], for example:

- Economic value added, for which the share is based on the economic value added as a reflect of where society is ready to invest.
- Physical production output, for which the share is based on physical flows (e.g., final energy consumption or exergy destruction).
- Equal per capita¹, for which the share is identical for all individuals.

I.3.4 Integrating environmental impacts in energy studies

As presented in section I.3.2, an increasing number of energy studies are incorporating environmental constraints. As mentioned by Blanco et al. [42], Energy System Modelling (ESM) and LCA are complementary. ESM makes it possible to provide reliable data integrating efficiency or changes over time in systems, e.g. losses due to partial load or seasonality. Concurrently, LCA studies provide a methodology to integrate the production and end-of-life phases, which are often not considered in ESM. While powerful and meaningful, the implementation of a full LCA approach increases the complexity of the problem to be solved with potential issues to be addressed as highlighted by Blanco et al. [42], in particular with the inclusion of system boundaries extension.

Most of ESM studies integrating environmental impacts are relatively recent and mainly focus on the potential reduction of GHG emissions [63]–[67]. As shown by da Costa et al. [68], the transformation of an energy system can have benefits in terms of reducing greenhouse gas emissions but at the same time can increase impacts on other environmental indicators. Therefore, studies that focus solely on global warming may have blind spots and partial conclusions, ultimately leading to potential risk of environmental burden-shifting [69], [70]. Energy systems are a major contributor to the overall environmental impact of human activity, as shown in Table 5.

The contribution to *climate change* represents more than 2/3 of the emissions related to human activity, which justifies the inclusion of this parameter in the ESM studies, but this is also the case for other impacts such as *ocean acidification* or *fossil resource scarcity*, for which the energy sector has an even greater contribution. The current distribution of impact categories could be significantly altered by the changes linked to the energy and environmental transition. Therefore, the current share of impacts from the energy systems may not be suitable for assessing the importance of these criteria in the future.

¹ This type of analysis needs to be supplemented with another principle to obtain the process level contribution.

Table 5 - Contribution of energy systems (i.e. production, distribution, consumption) to total global impacts from Gebara et al.[71].

Impact category	Impact share from energy systems
Global Warming	73 %
Ocean Acidification	82 %
Stratospheric Ozone Depletion	37 %
Human Ozone Formation	71 %
Ecosystem Ozone Formation	63 %
Particulate Matter Formation	58 %
Terrestrial Acidification	51 %
Freshwater Eutrophication	1 %
Marine Eutrophication	22 %
Land Occupation	2 %
Water Consumption	6 %
Material Resource Scarcity	12 %
Fossil Resource Scarcity	90 %

I.3.5 Life cycle simplification in the case of electrification of industrial heat

While powerful and meaningful, the implementation of a full LCA approach increases the complexity of the problem to be solved. To reduce complexity, one of the options used today is to study some of the environmental indicators to simplify the message without affecting the results of the study [72]–[74]. Hence, methods for simplifying LCA analyses have been widely proposed over the past 20 years [73], [75], [76]. From a systematic review of the LCA simplification state of the art, Beemsterboe et al. [73] identified five simplifying strategies: exclusion, inventory data substitution, qualitative expert judgment standardisation and automation. For each of these strategies, the author outlines the main concerns linked to these simplifications. Simplification methods based on the exclusion of certain impact categories are among the most common approaches [75], [76]. Many studies have examined the effectiveness of a limited number of indicators to best reflect the environmental impact of a product or process [72], [74], [77]–[80]. The most radical of these approaches consists in adopting only one environmental indicator such as the carbon footprint [74], [81] or an energy indicator like Cumulative Energy Demand (CED) or Cumulative Exergy Demand (CExD) [77], [78], [82], [83].

Using cumulative energy demand as a single proxy for environmental performance was the title of one of the first papers related to LCA simplification [77], which is still widely cited in the literature today. Indeed, most of the current processes - especially industrial heat production as outlined previously - are driven by fossil fuels as shown by Huijbregts et al. [77], with a correlation between fossil fuel consumption, global warming and resource depletion indicators. Therefore, as concluded by the authors, “the use of fossil fuels is an important driver of several environmental impacts and thereby indicative for many environmental problems. It may therefore serve as a screening indicator for environmental performance”. However, these conclusions - which are still valid today for fossil fuel energy intensive process as the energy transition is still struggling to get off the ground - could change abruptly if ambitious transition scenarios are put in place. Therefore, the consequences in terms of environmental impacts of a massive electrification of industrial heat production are relevant and deserve to be analysed and quantified.

In a dedicated work - under review at the time of this writing, whose pre-prints are available in Appendix 7- we show that the use of a single indicator introduces severe biases for electrical mix not fully based on fossil fuels. One of the findings, is the wide disparities between different electricity production sources in terms of many environmental indicators. Some energy sources behave in a similar way, i.e. it is possible to approximate the environmental impact of electricity production by using an energy-based indicator (cumulative exergy demand or cumulative energy demand) as for gas/hydro or hydro/wind. However, the results show that no general correlation can be found between the 16 studied environmental impacts and most of the energy indicators when shifting from one source of energy to another. One of the conclusions of this work is the importance of maintaining an environmental approach as comprehensive as possible to assess properly the environmental impact of energy transition. Indeed, the environmental issues and impacts associated with a decarbonised mix are very different from those we face today.

I.4 Objectives and scope of the thesis

I.4.1 Challenges to decarbonising industry

Alternative solutions to fossil fuels exist today for a number of configurations, both for industry and for power generation. However, the transition in the energy mix is progressing at a slow pace, as presented in section I.1.2. This lack of progress can be explained by a number of obstacles and challenges. A major limit to the development of new technologies stem from the many uncertainties facing the industry. These limits include those identified in the reports of the United Nations Economic and Social Council [84]:

1. Uncertainties about energy prices and their evolution over time.
2. Uncertainties linked to the development of technologies, the reliability of new solutions and the ability of companies to integrate them.
3. The absence of a legislative framework to encourage the development of the most virtuous technologies.

Henderson et al. report [85] also suggests other reasons:

4. Difficulties in obtaining funding for innovative projects because of the greater risk involved.
5. The need to reconsider and adapt the current economic model, with higher initial investments and more fluctuating energy prices.

These technical and economic uncertainties are compounded by the inability to properly assess the environmental consequences of energy use. Numerous "net zero" plans have been published at national and international level e.g., European Green deal¹ by the European commission, the Net zero by 2050 by the IEA [27]. There are also strategies developed at company or sector level, e.g., 2050 Net Zero Roadmap Accelerator Program² by Global Cement and Concrete Association or Nestle's net zero roadmap³. These plans present general roadmaps for the reduction of

¹ https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

² <https://gccassociation.org/netzeroaccelerator/>

³ <https://www.nestle.com/sites/default/files/2020-12/nestle-net-zero-roadmap-en.pdf>

greenhouse gas emissions, but do not clearly allocate the efforts to be made by sector or sub-sector, nor do they detail the best strategies for achieving these objectives, not to mention the other environmental consequences of the transformation of the current fossil fuel-based energy paradigm. Some of these roadmaps may even seem like mere incantations, devoid of concrete measures. It is therefore difficult today to have a coherent long-term strategy align with these roadmaps for industry.

This thesis intends to provide some answers to these questions using an analytical framework that combines energy and economic approaches with an environmental assessment. This approach is expected to provide a better understanding of the limitations of each strategy, making it easier to implement them in the most appropriate configurations.

I.4.2 Scope of the thesis

The methodology developed in this thesis could be applied to any sector of human activity, but we have chosen to apply it to the industrial sector, for which - as we saw in the introduction there is a lack of assessment at sector level. More precisely, it has been shown in section I.2 that heat production represents an essential part of the energy use by the industrial sector and that it is intimately linked to the temperature of the process studied. We have therefore limited our study to heat production and chosen the 100-200 °C temperature range, which accounts for a significant proportion of current GHG emissions, although it is not the main one, which, as we saw in section I.2 is dominated by processes with temperatures above 500 °C.

The 100-200 °C is linked to many processes i.e. drying, boiling or distillation with numerous applications in food industry, paper and board and chemistry [29], [86]. From a methodological point of view, this temperature range is interesting because it allows us to study two different electrical solutions: MHP fuelled by waste heat and electrical boiler, as well as other heat production systems like gas or biomass boilers coupled or not with heat storage solutions. Some heat production solutions are however not considered, like heat supplied by a heating network or geothermal energy, because they are too specific of the industrial site location. Hydrogen boilers are also excluded from this study because of the huge uncertainty on the future means of production of this energy vector, and therefore the difficulty of carrying out 4E analyses with this solution.

Despite these restrictions to this particular temperature range and to some available technologies for heat production, the goal of this work is to remain as broad as possible, without considering solely the transformation of a particular industrial process, by analysing how to produce industrial heat from a known demand while minimising the environmental and economic costs. Furthermore, all the environmental impacts are considered, not just those linked to climate change, by adopting an LCA approach in a multicriteria analysis. In addition, a better insight of the relevance of deploying a technology is proposed through the estimation of its impact on the planetary boundary exceedance after downscaling to the sector allocated contribution.

In order to be as realistic as possible, the study is temporal and considers dynamic variations in energy supply and demand, particularly for electricity. In addition, as electricity production varies greatly from one country to another, it is necessary to consider a geographical area for this study. As we explained in section I.2, it is very difficult to find data on a global scale, which is why our field of study will be Europe, where the availability of data is relatively good. In addition, different time periods are considered in order to study the impact of the reduction in carbon emissions

targeted in the future for a 2 °C scenario, but also the possibility of increasing use of carbon capture and storage, which appears in many energy transition scenarios.

The following chapter presents the methodology developed and all the assumptions and data used to meet the objectives described in this section.

Chapter II

II. Methodology

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II.1 Assessment framework

This work assesses the heat production for an industrial process at a defined temperature $T(t)$, for a variable hourly demand $E_{out}(t)$. The aim is to define the best configuration (design and planification) to meet the heat demand considering environmental and economic criteria by combining different possible technologies like electric, gas and biomass boilers, heat pumps fed with waste heat or thermal storage. All the energy sources used to cover this need (including those used to produce electricity) are studied at hourly time-steps, including their environmental impacts and costs. The analysis being multicriteria, it is possible to find a set of feasible and non-dominated solutions answering the optimisation problem; this set of solution is also called Pareto front [87]. Non-dominated solutions are, by definition, never worse than any other solution on all criteria.

The general assessment framework used to calculate and rank the non-dominated solutions is presented in Fig. 21. Environmental, technological, energy, process and economic inputs are integrated into the economic, energy and environmental models used by the optimisation algorithm. Based on these inputs, a multi-criteria optimisation model is used to bring out the set of non-dominated solutions. Finally, different ranking methods of these non-dominated solutions are proposed based on environmental or economic weighting criteria in order to provide insight for industries and policy makers in the perspective of industrial energy transition considering their contribution to global environmental impact and exceedance of environmentally sustainable limits. The different steps of this analysis are detailed in the following sections.

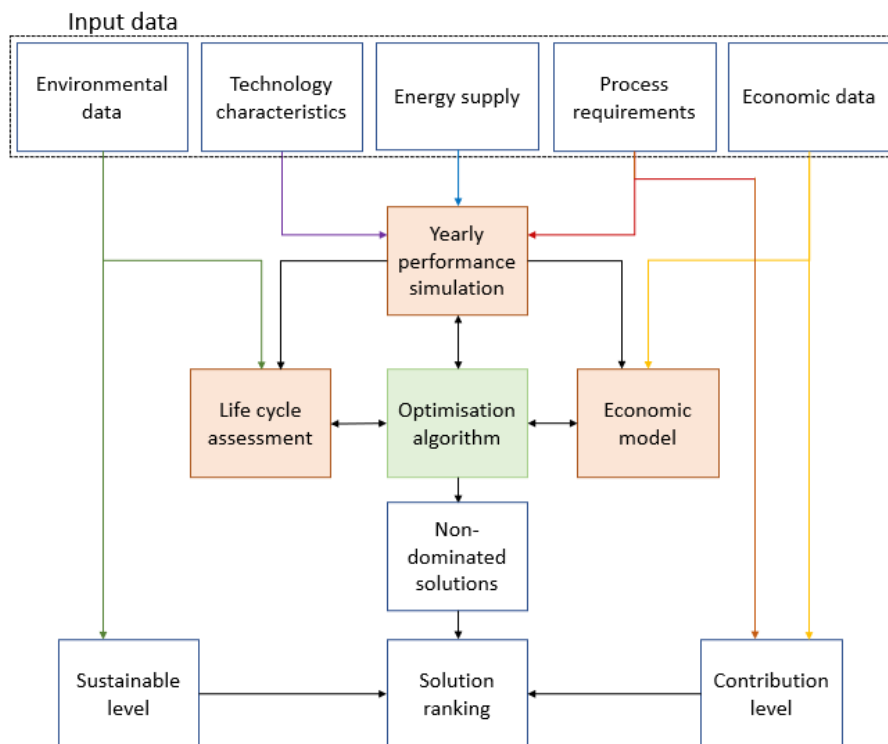


Fig. 21 - Assessment framework

II.2 Definition of modelling assumptions and input data

This section presents the different case studies that are selected to highlight the relevance of the assessment method. These selected case studies attempt to provide a diversity of situations, both

geographically (five representative European countries) and in temporal terms (3 time periods of 25 years, typical of industrial plant lifetime: 2015-2040, 2040-2065 and 2065-2090). However, it is important to stress that a large number of assumptions have to be made, due to a lack of accurate data. Therefore, for each type of input data, the hypotheses are discussed to highlight the limitations of the results. Nevertheless, the scope of the proposed assessment method is in no way tied to these assumptions: it could also be applied to other case studies with more specific data.

II.2.1 Environmental data

The environmental data are derived from Ecoinvent 3.7.1 Life Cycle Inventory (LCI) database [88]. As described in chapter I, there are two main LCI modelling frameworks: the attributional and the consequential [57]. For the proposed application - namely industrial heat production, which represents a significant share of the energy market - the electrification of processes will result in an increase of electricity production to satisfy this new demand [27], [35], [89]. Therefore, a consequential approach is more appropriate. The environmental data used are as much as possible those of the country studied except for the limitations presented in Table 6. The LCA methodology following ISO standard and Life Cycle Inventory Analysis information can be found in Appendix 4.

Table 6 - Limitations of environmental data

	Limitations	Potential for improvement and consequences
Geographic	Generic data are used for a number of processes (boiler, boiler fuels, storage tank).	Ongoing development of data from industry will increase the choice of data available in the future. For the time being it is not possible to differentiate between countries or industries that are implementing efficient techniques.
Temporal	Use of historical data: potential energy optimisation of processes is not considered, while a change can be expected with environmental transition.	Idem geographic limitation: the study presents conservative results with a possible gain on some impact categories (toxicity, material consumption, etc.).
Technological	Only technologies with a sufficient level of development are present in the database, which limits the potential for future technologies.	The integration of new technology is not yet possible and is an area for improvement in the coming years.

II.2.2 Heat generators and storage characteristics

The generic equation II-1 is used to calculate the energy consumption E_{in} of a generator supplying the process with an amount of heat E_{out} . All variables are time-dependent, so that performance can be assessed on a dynamic basis.

$$E_{in}(t) = \frac{E_{out}(t)}{\eta_x(t) \cdot (1 - \varepsilon_{x,T}(t))} \quad \text{II-1}$$

Where E_{out} is the final energy demand, i.e. heat, of the industry for a specific process at temperature T , η the efficiency of the heat production technology x , that may differ at nominal and partial loads, and $\varepsilon_{x,T}$ a correction factor that enables to roughly estimate the heat losses to the environment linked to the temperature of the process, following the approach of Bülher et al. [90]. Note that this approach could be improved in the future with more specific correlations for the different systems studied.

The system efficiencies at nominal and partial loads are detailed in the following sections for each considered technology. The value of $\varepsilon_{x,T}$ used by Bülher et al. [90] is presented in Table 7 for three different temperature ranges. To solve the discontinuity issue, the correction factor is assumed to follow a linear evolution between 120 °C and 380 °C. MHP are assumed to have the same losses to the environment as “direct electric heating” and biomass boiler the same as “other fuels”.

Table 7 - Share of energy losses within the system ($\varepsilon_{x,T}$) by technology and temperature level [90]

Range [°C]	Direct electric heating [%]	Other fuels (gas, oil or coal) [%]
≤ 120	0	0
120 - 380	10	15
≥ 380	25	30

II.2.2.1 Mechanical heat pump

For the design COP of the MHP, it is chosen to use the correlation provided by Schlosser et al. [91], which is obtained from a regression on the basis of MHPs currently available on the market (equation II-2).

$$COP_d = 1.9118 \times (T_{up,d} - T_{rec,d} + 0.088378)^{-0.89094} \times (T_{up,d} + 0.044189)^{0.67895} \quad \text{II-2}$$

where T_{up} is the industrial process temperature in K. The index d stands for the design value, i.e. the nominal load of the MHP. This equation was obtained for a temperature of waste heat T_{rec} between 80 °C and 160 °C and a temperature lift, $\Delta T_{lift} = T_{up} - T_{rec}$, between 25 K and 95 K.

As technologies can have also to operate at part-load, either because demand is variable or because they are coupled with other technologies, it is necessary to appropriately consider the consequences on the performances (e.g. change in efficiency). To the best of our knowledge, there is no generalised relationship for evaluating the efficiency of MHPs at part load for high power and high temperature levels. To determine the COP for a partial load, i.e. the efficiency η_{MHP} used in equation II-1, the approach of Pieper et al. [92] is chosen (equation II-3).

$$\eta_{MHP} = COP_d + 0.0273 + 0.0097 \cdot (T_{up} - T_{up,d}) + 0.0216 \cdot (T_{rec} - T_{rec,d}) + 0.14443 \cdot (1 - PL) \quad \text{II-3}$$

where COP_d is calculated with equation II-2, and PL is the partial load factor in % of design value. As this study is not based on a real MHP system with known characteristics, we assume in this work, that T_{up} and T_{rec} are at design level, which eliminates two terms in this equation.

Equation II-3 is chosen to estimate the efficiency η_{MHP} because it allows the parameter to be modelled simply for a power level compatible with industrial process temperature; this is the best approximation found in the literature for high-temperature modelling. The results are consistent with the relationship from Ommen et al. [93], which is made for a 2 stage heat pump of 800 kW for an output temperature of 70 °C. Both studies proposed an efficiency of 100 % at design level and for a partial load ratio of 50 % the efficiency drop to 98 % for Pieper et al. [92] and to 97 % for Ommen et al. [93].

II.2.2.2 Electric and gas boilers

For both electric and gas boilers, no loss of efficiency due to partial load is considered in accordance with [94], [95] ; only the heat losses to the environment ($\epsilon_{x,T}$), presented in part II.2.2, are considered. For gas boilers, with condensing economizer presented in part I.3.1, the efficiency based on lower calorific value is set at $\eta = 97\%$ with an efficiency improvement expected to reach 98 % in 2050 [95]. For electric boiler, an efficiency $\eta = 100\%$ is assumed.

II.2.2.3 Biomass boiler

The efficiency of the biomass boiler is based on the parameters reported by Veyron et al. [96] as described in equation II-4:

$$\eta_{\text{biomass}} = 0.7922 + 0.0703 \cdot y_{PL} \quad \text{II-4}$$

where y_{PL} is the load ratio and the efficiency at design level is obtained for $y_{PL} = 1$.

Applying this case to a biomass boiler feeding a district heating network [96], which is studied in the case of a thermal capacity of 3 MW, the load ratio can be calculated according to the equation II-5.

$$y_{PL} = \frac{-0.7922 + \sqrt{0.6276 + 0.2425 \cdot PL}}{0.1406} \quad \text{II-5}$$

Where PL is the partial load factor. The efficiency obtained with this method is consistent with experimental measurements; the calculated design load efficiency is equal to 86.2 % while a value of 85.4 % was found experimentally by Świerzewski et al. [97]. Mermoud et al. show an average efficiency of 82.6 % on a 120-hour measurement campaign with variation of the load factor [98].

II.2.2.4 Thermal energy storage

A standard Tank Thermal Energy Storage (TTES) using sensible heat is considered. Storage losses are assumed to be proportional to the amount of energy stored. Storage losses are estimated at 5 % of the stored energy for a charge cycle of 8 hours and a discharge cycle of 16 hours [33].

II.2.2.5 Limitations and area for improvement

The main limitations of part II.2.2 are presented in Table 8.

Table 8 - Limitations of technologies and efficiencies

	Limitations	Potential for improvement and consequences
Geographic	No distinction between countries on average efficiency for the new installations	Applying the method on a more limited geographical scale would allow for an additional level of detail.
Temporal	Performance improvement is not considered, which limits the potential gain of some technologies, i.e. MHP and biomass boiler.	The method could also be used to test the viability of a technology improvement pathway to look at the potential gains and drawbacks of an evolution (e.g. for refrigerants).
Technological	Only technologies with a high TRL are considered.	As for the limitations of the environmental part, some technologies could be integrated for a specific process application but it is not possible to generalise it at the moment.

II.2.3 Energy supply

II.2.3.1 Representative electricity mix at EU level

The main objective of this section is to propose a number of varied but credible energy mix at European scale. Hence, it is possible to assess their impact on the optimal configurations found by the optimisation model. As a reminder, the study follows a consequential approach, so the energy sources considered here are only the new energy sources installed.

The energy scenario considered are based on electric mix planned by EU country in 2050. Each country has different scenarios developed by governments, Transmission System Operator (TSO), from the Heat Roadmap Europe [99] or from the trends to 2050 report by the EU (TRENDS2050) [35]. A total of 96 scenarios are considered across the 27 European countries. Among these countries, 39 scenarios come from Heat Roadmap Europe, 27 from the TRENDS2050 and 30 are from scenarios developed by the government or TSO of the country (Fig. 22). Heat Roadmap Europe is decomposed in three different scenarios named BL 2050 for the Base Line scenario for 2050, CD 2050 for the Conventionally Decarbonised scenario and HRE 2050 for the Heat Roadmap Europe scenario for 2050. In order to reduce the number of study cases, a clustering model was implemented to group the scenarios according to typical electricity mix.

Clustering becomes necessary because combining the 96 scenarios with the 3 industrial demand profiles (described in section II.2.4) and the 3 time periods considered, we obtain 864 configurations which would require too much calculation time. The chosen method identifies different possible electricity mix which are both representative of European strategies and the most diverse from one another. The k-means method [100] is chosen as clustering algorithm, considering the widespread use of this method in the energy sector [101]–[104].

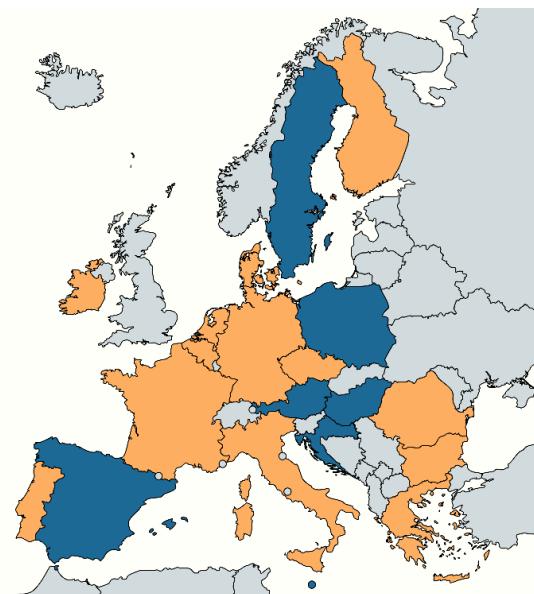


Fig. 22 - Additional scenarios to TRENDS2050 by country, in orange countries with TSO and Heat Roadmap Europe scenarios and in blue countries with Heat Roadmap Europe scenarios¹.

This method treats each input data as an object with a location in a multi-dimensional space. The function finds iteratively a distribution in which the objects in each cluster minimise the distance to each other and maximise the distance from the objects in the other clusters as illustrated in Fig. 23. Each cluster in a k-means clustering consists of member objects from the input data and a centroid that is created and evolves at each iteration. For each cluster, the sum of the distances between the centroid and all member objects of the cluster is minimised.

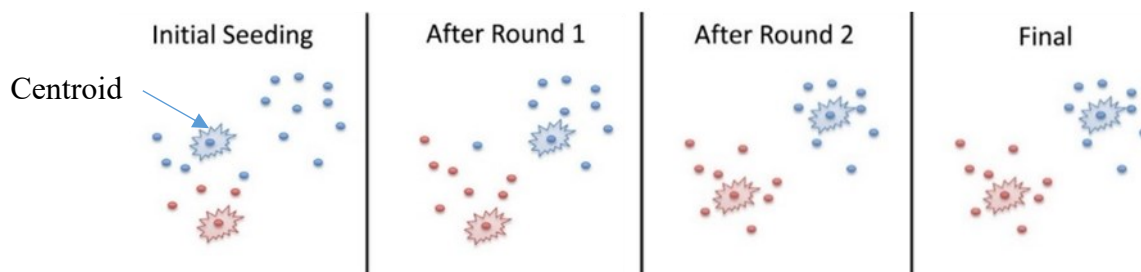


Fig. 23 - k-means optimisation algorithm diagram from Page et al. [105]

The share of the various electricity production technologies in the 2050 mix is used as input data for clustering: dammed hydro, geothermal, offshore wind, onshore wind, solar, river hydro, wave and tidal, nuclear, Combined Heat and Power (CHP) and condensing powerplants. Furthermore, the last two are broken down as a function of: gas, petroleum, solids (coal and lignite) and biomass.

The number of clusters is determined by optimisation using Caliński-Harabasz scoring method [106] with a minimum number of 2, to have a minimum diversity of electricity mix and a maximum number of 10 to have a usable number of cases afterwards. Fig. 24 shows that the optimal number of clusters is 5 for this configuration but the difference in criterion values is small in the range 3-8. By limiting the number of clusters, the distance between their means increases, which guarantees a greater diversity. Therefore, in this work, we have chosen to limit the number of clusters to an intermediate value of 5.

¹ Map created with mapchart.net.

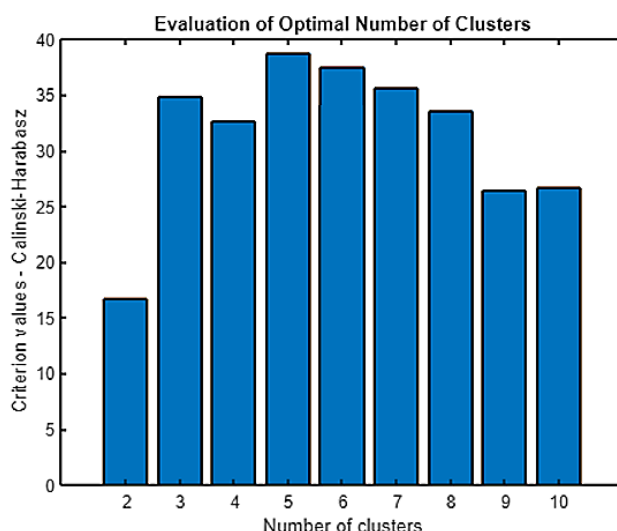


Fig. 24 - Caliński-Harabasz values for a number of clusters ranging from 2 to 10

Among the five selected clusters, Table 9a identifies five different types of electric mix produced by the new installations:

- (i) Cluster C1 mix is composed of renewable energies at 90 % with a dominant share of offshore wind at 46 % of the electricity. This renewable mix is combined with 10 % production from new thermal power plants. This cluster includes 27 of the 96 mix studied. This scenario is called **C1-offshore**.
- (ii) Cluster C2 mix is composed of renewable energies at 47 %, nuclear at 42 % and new thermal power plants at 11 %. Cluster C2 is the mix that presents the most significant share of nuclear. This cluster includes 8 of the 96 studied mix. This scenario is called **C2-nuclear**.
- (iii) Cluster C3 mix is dominated by the installation of new thermal power plants at 48 %, of which 38 % of gas, 1 % of solids and 9 % of biomass and a renewable energy mix for a total of 50 %. This cluster includes 14 of the 96 studied mix. This scenario is also called **C3-thermal power**.
- (iv) Cluster C4 mix shows similar trends to cluster C1 but with a renewable part coming mainly from onshore wind development. This cluster includes 37 of the 96 studied mix. This scenario is called **C4-onshore**.
- (v) Cluster C5 mix also shows similar trends to cluster C1 but with a renewable share dominated by photovoltaic production. This cluster includes 10 of the 96 studied mix. This scenario is called **C5-solar**.

The number of clusters enables to study five trends of transformation of the European electricity mix with different strategies that reflect both the will of each state but also the technical feasibility. This has the interest to highlight the correlations between the choices of electrical production for a country and the economic and environmental interest of industrial process electrification.

Another scoring method - the Davies-Boulding [107] - was tested and the results are consistent with Caliński-Harabasz method (Table 9b), with small mix differences in C4 and C5. The deviations between the centroids are always less than 2 % except for the photovoltaic rate in the C5 scenario. This deviation is explained by a different number of electricity mix within the cluster

C5 and therefore a centroid position that varies due to the low number of mix considered for C5 case of the Davies-Boulding method.

The values presented in Table 9 are rounded up to the nearest unit. There are three energies with values close to zero, namely, (i) waves and tidal are never present at more than 0.4 % of the energy sources and (ii) oil thermal production is never present at more than 0.25 % and finally (iii) river hydro with a maximum of 1.1 %. The last value may seem low, but the European potential of the hydro river in consequential approach is already almost fully exploited according to TRENDS2050.

Table 9 - Centroid of the clustering method using a) Caliński-Harabasz scoring method and b) Davies-Boulding scoring method

a)

Caliński-Harabasz		C1	C2	C3	C4	C5
RES*	Dammed hydro	2 %	8 %	4 %	4 %	2 %
	Geothermal plants	2 %	2 %	1 %	3 %	5 %
	Offshore wind	46 %	3 %	5 %	3 %	4 %
	Onshore wind	22 %	21 %	12 %	47 %	22 %
	Photovoltaic	16 %	13 %	25 %	23 %	58 %
	River hydro	1 %	0 %	0 %	1 %	0 %
	Wave & tidal	0 %	0 %	0 %	0 %	0 %
	Concentrated solar power	0 %	0 %	4 %	0 %	0 %
Condensing or CHP	Biomass	4 %	3 %	9 %	7 %	1 %
	Solid	0 %	0 %	1 %	0 %	0 %
	Petroleum	0 %	0 %	0 %	0 %	0 %
	Gas	5 %	7 %	38 %	8 %	4 %
	Nuclear	2 %	42 %	0 %	1 %	0 %

*excluding biomass

b)

Davies-Boulding		C1	C2	C3	C4	C5
RES*	Dammed hydro	2 %	8 %	4 %	4 %	1 %
	Geothermal plants	2 %	2 %	1 %	4 %	3 %
	Offshore wind	46 %	3 %	5 %	3 %	4 %
	Onshore wind	22 %	21 %	12 %	45 %	18 %
	Photovoltaic	16 %	13 %	25 %	24 %	66 %
	River hydro	1 %	0 %	0 %	1 %	1 %
	Wave & tidal	0 %	0 %	0 %	0 %	0 %
	Concentrated solar power	0 %	0 %	4 %	0 %	0 %
Condensing or CHP	Biomass	4 %	3 %	9 %	6 %	1 %
	Solid	0 %	0 %	1 %	0 %	0 %
	Petroleum	0 %	0 %	0 %	0 %	0 %
	Gas	5 %	7 %	38 %	8 %	2 %
	Nuclear	2 %	42 %	0 %	1 %	0 %

It is possible to see in Table 10 that, depending on the country, the different scenarios are located in 1, 2 or 3 clusters. Four of the studied countries (AT, CY, IR and NE) have all their scenarios in the same cluster despite the availability of several scenarios; this reflects a low variation across all national projected scenarios. On the other hand, the 14 other countries cover a larger spectrum of possible future evolution for their energy system. It is possible to notice that the C2 and C3

scenarios are never considered as the only possibility and are always associated with a C1, C4 or C5 scenario. This can be explained by the development of at least one scenario with a high share of renewable energies for all countries. The details of the scenarios are presented in the Appendix 1.

For the rest of the study, each cluster is represented by the scenario the closest to the cluster mean using Euclidean distance, which is also the criterion used by the clustering algorithm. The representatives of each group are highlighted in bold in Table 10. Estonia TRENDS2050 is the closest to C1 means but the absence in offshore wind in the current mix makes the approximation of the load factor too high; we have therefore decided to use the 2nd closest scenario, which is a scenario made by the German environmental protection agency [108] for the cluster C1. A scenario named “N3” from RTE [109], the French TSO, is the closest to C2. Two different scenarios from Italy are used for C3 with the scenario BL2050 form heat roadmap and C5 with the scenario TRENDS2050 and finally the scenario TRENDS2050 for Croatia for the cluster C4.

Table 10 - Clusters representing the electricity mix scenarios of each studied country, the values in bold are the representative mix of the cluster.

Country tag	Country name	Cluster representative of at least one national electricity mix scenario		
AT	Austria	C4		
BE	Belgium	C1	C3	
BG	Bulgaria	C4	C5	
CY	Cyprus	C5		
CZ	Czechia	C2	C4	
DE	Germany	C1	C3	
DK	Denmark	C1	C4	
EE	Estonia	C1		
EL	Greece	C4		
ES	Spain	C3	C4	
FI	Finland	C1	C2	C4
FR	France	C1	C2	C4
HR	Croatia	C4	C5	
HU	Hungary	C2	C4	C5
IE	Ireland	C1		
IT	Italy	C3	C4	C5
LT	Lithuania	C4		
LU	Luxembourg	C5		
LV	Latvia	C1		
MT	Malta	C3		
NL	Netherlands	C1		
PL	Poland	C1	C2	C4
PT	Portugal	C4		
RO	Romania	C2	C3	C4
SE	Sweden	C1	C4	
SI	Slovenia	C3		
SK	Slovakia	C4		

II.2.3.2 Choice in energy supply input

The energy input for electricity is based on the result of the clustering. To figure out the hourly environmental impact and cost, an hourly profile is created for each representative country, considering a load factor for each of the present energy sources equivalent to the one achieved in 2019. This load factor is applied to the new installed capacities for each technology. For example,

if in 2019 for a particular day and time of the year, the load factor of offshore wind power is equal to 20 % for 1 GW installed capacity, the assumed wind power in 2050 at the same day and time will be 400 kW if the new installed capacity of offshore wind power reaches 2 GW in 2050. The only exception is for Croatia for which some information are not available in the current electricity mix and two assumptions on minor electricity production sources have to be done, i.e. (i) a constant production from geothermal over the year, (ii) a load factor for offshore equivalent to the onshore. This last uncertainty has a limited impact because the share of energy from offshore wind is small, and this approximation only affects the hourly distribution, not the share of the mix coming from offshore wind.

These assumptions do not consider potential technological improvements and changes in the process, but they do allow for the creation of hourly power demand profiles for each energy source over the year, while having an annual electricity production from each source in line with the projections. The hourly profiles of these five mix are presented in Appendix 1 and the profile for cluster C1 is presented in Fig. 25 as an illustration.

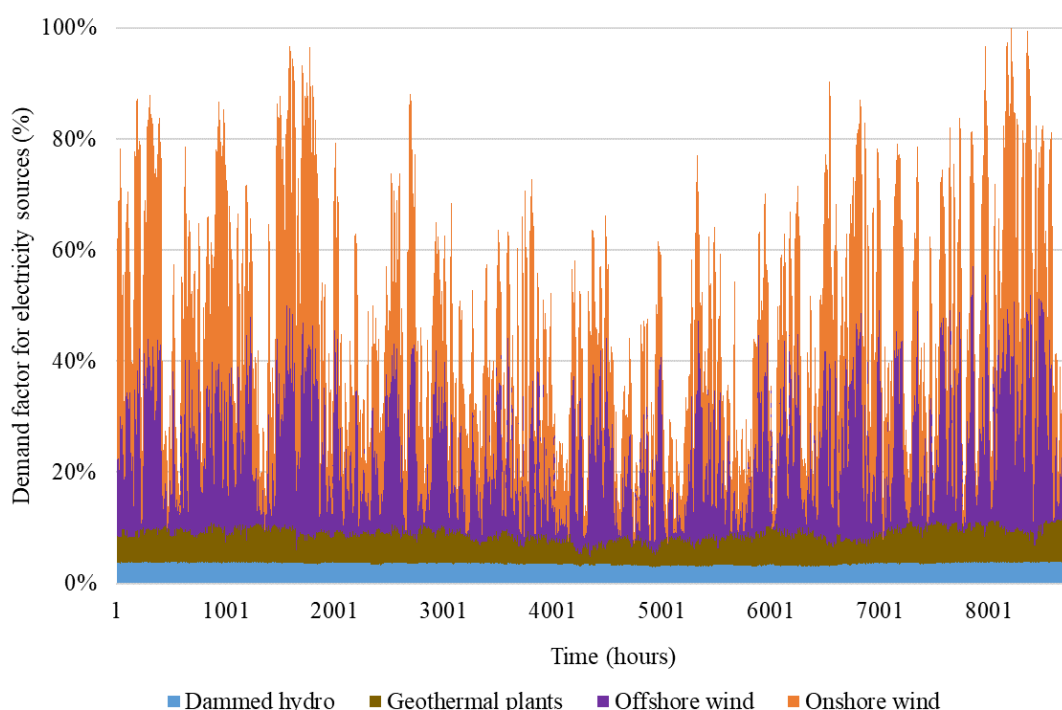


Fig. 25 - Demand factor for year 2019 for the representative electricity mix of cluster C1.

II.2.3.3 Carbon Capture and Storage (CCS)

The proportion of CCS in the power generation mix as well as for on-site industrial CCS is derived from the scenario AIM/CGE 2.2 published by Riahi et al. [110] from IPCC AR6 [16] and can be found in Table 11 for the 3 periods of 25 years that are considered in this work: 2015-2040, 2040-2065 and 2065-2090.

Table 11 - Average CCS share in electricity production and industrial heat production system

	2015-2040	2040-2065	2065-2090
Electricity production	8 %	32 %	71 %
On-site industrial CCS	0 %	2 %	39 %

The CCS efficiency, which is defined as the share of CO₂ not rejected by the CCS, is set at 88 % according to García-Freites et al. [111]. The environmental impact of CCS is based on the LCA carried out by Bisinella et al. [112]. The efficiency degradation of CCS, which is defined as the relative change in energy output for the same energy input with and without CCS, is set at 15 % for gas [113] which is consistent with the data from the IPCC report giving a range between 11 and 22 % [114] and 22.6 % for BioEnergy with Carbon Capture and Storage (BECCS) for oxy-fuel combustion [115]. For the gas boiler, only natural gas is considered (no shale gas or biogas). For biomass and gas boilers, industries are assumed to use fuels with national average characteristics, i.e. prices, supply distance, source of production.

II.2.3.4 Limitations and area for improvement

The main limitations of the assumptions made in this section are presented in Table 12.

Table 12 - Limitations of energy supply

	Limitations	Potential for improvement and consequences
Geographic	No local distinction within a country and use of average values (for biomass boiler especially)	This limitation could be addressed by dealing with a specific process and by identifying potential sources of supply.
Temporal	Energy supply is based on current trends and the transformation of the European energy system could change some European energy trading strategies.	A sensitivity analysis could be conducted to assess the differences in impact and cost under different types of scenarios.
Technological	No consideration for improvement in the load factor of energy production sources	Potential error in the hourly distribution of each energy, but the annual production is in line with the scenarios used.

II.2.4 Process requirements

Three typical consumption profiles are used as reference cases (Fig. 26). These weekly scenarios are repeated over a year with no shut down for maintenance and servicing for the sake of simplicity. A thermal heat demand of the order of 1 MW is considered but a change of scale is possible without overestimating the impact, as the data are given for a large range (from 1 MW to 30 MW in most cases). Three types of processes are considered:

- The process in Fig. 26a has a very small temporal variation [116]; it is referred as **continuous process** and enables to assess the impact of the dynamic aspects of the source of energy for a process with little variation.
- The process presented in Fig. 26b is a process with a constant power during the week and a shutdown during the weekend [116]; this process, referred as **weekly process**, enables to assess the ability of the heat production system to achieve rapid ramp-up after the weekend and to be able to maintain a constant operating demand during the week.
- The last process, described in Fig. 26c, is a **batch process** with short heat demand of one hour every 8 hours [117]. This process enables to study the capacity of the heat production system to respond to very short demands.

It can be noted that the demand over the year is different between the different processes with an annual demand of 6.80 TWh for the continuous process, 5.44 TWh for the weekly process and 1.09 TWh for the batch process.

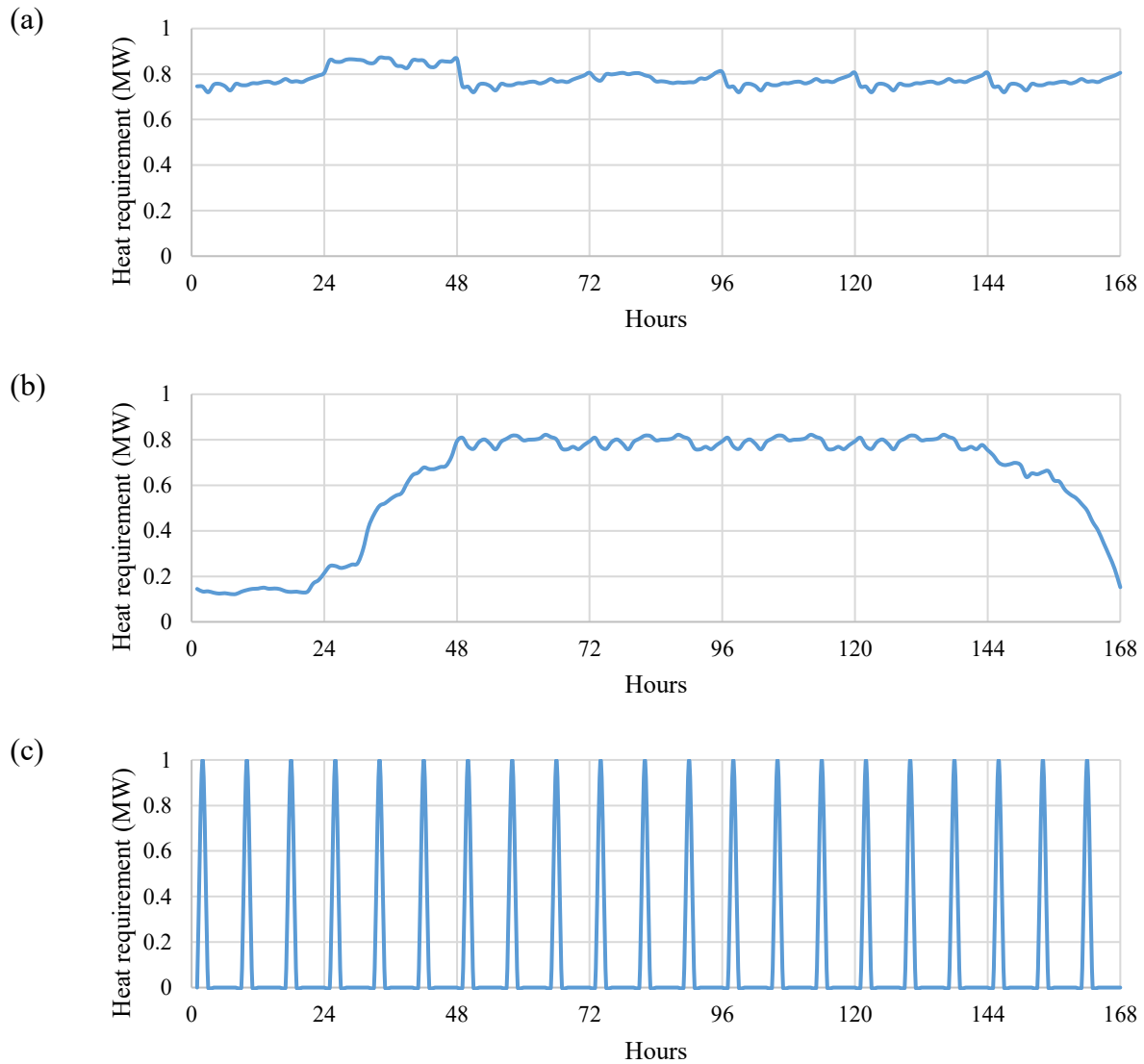


Fig. 26 - Hourly heat requirement profile over a week for (a) food continuous process [116], (b) paper continuous process and (c) food batch process

The temperature level considered as a reference for the study is set at 130 °C [86] which is representative of many processes as described in part I.1.3. The main limitations of process requirements are described in Table 13.

Table 13 - Limitations of process requirements

	Limitations	Potential for improvement and consequences
Geographic	Not concerned	Not concerned
Temporal	No changes in process output are included in the study	This limitation can be addressed by studying a specific process.
Technological	No process optimisation considered	

II.2.5 Economic data

II.2.5.1 CAPEX and OPEX data

The economic model is broken down into CAPEX and OPEX for the production system and the energy costs (Table 14). The on-site cost of integration, i.e., integrating the production technologies into the process, is not considered in this study. The CAPEX assumed for the calculations is split into two time periods: before 2050 and after 2050, i.e. no degressive value is considered. This assumption only affects biomass since there is no price evolution expected by 2050 as the CAPEX remain the same for other technologies. The proposed methodology considers the total costs over a year, and the CAPEX are considered on a pro-rata basis of their lifetime. For the OPEX, the cost is calculated in proportion of the number of years before 2050 and after 2050. The data validity range is from 0.5 MWth to 20 MWth for MHP, from 1 MWth to 30 MWth for electric and gas boilers and from 20 MWth to 250 MWth for the biomass and gas boilers. The economic data for biomass boilers is only available for large power plants and may lead to an underestimation of the CAPEX and OPEX for smaller power plants. The change in size from 1 – 30 MW to 20 – 250 MW for the gas boiler leads to a change of around 10 % in CAPEX and a greater reduction in OPEX of around 30 %. To bring the biomass boiler to the same power level as the other technology, i.e. 1 - 30 MW, the same tariff evolution is applied, as proposed in the Table 14. Concerning the sensible heat storage, there is a range depending on parameters like the localisation or the storage capacity. For this work, the average value is considered because the model applies to a great diversity of configurations.

Table 14 - Economic data for studied technologies and expected evolution from 2020 to 2050

Technology	CAPEX (M€ ₂₀₁₆ /MWth)		Fix OPEX (k€/MWth/year)		Variable OPEX (€/MWth)		Lifetime		Source
	2020	2050	2020	2050	2020	2050	2020	2050	
MHP	1	1	3	2	1.8	1.6	20	25	[95]
Gas Boiler 1–30 MW	0.11	0.11	3	2	0.5	0.5	25	25	[95]
Gas Boiler 20–250 MW	0.1	0.1	2	1.8	0.2	0.2	30	40	[95]
Electric Boiler	0.12	0.12	0.5	0.5	0.2	0.2	20	20	[95]
Biomass Boiler 1–30 MW	0.33	0.29	7.5	4.4	0.5	0.5	25	35	This work
Biomass Boiler 20–250 MW	0.3	0.26	5	4	0.2	0.2	25	35	[95]
TTES	0.12	-	-	-	-	-	20	-	[118], [119]

II.2.5.2 Electricity and fuel costs

The cost of fuels from TIMES model [95] is presented in Table 15 except for electricity, which has a cost calculated on an hourly basis and which is further detailed below. The cost calculation is based on the average price over the lifetime of the installation. The temporal evolution is based on an annual price inflation of 2 %, which is consistent with the values proposed by the TIMES model. This value applies to all prices (gas, biomass and electricity). This approximation of not dissociating the evolution between the different energy sources is based on the strong uncertainty that exists on the evolution of energy prices; in particular, as it is possible to see it today, with a significant evolution of the prices of all energy sources following the war in Ukraine.

Table 15 - Fuel prices from 2015 to 2050 based on JRC EU TIMES model [95]

€/MWh	2015	2020	2025	2030	2035	2040	2045	2050
Natural Gas	24.48	26.60	29.34	32.04	33.73	35.42	36.04	36.65
Inflation equivalent		1.7 %	2.0 %	1.8 %	1.0 %	1.0 %	0.3 %	0.3 %
Wood energy	12.96	14.18	15.48	16.96	18.54	20.27	22.14	24.19
Inflation equivalent		1.8 %	1.8 %	1.8 %	1.8 %	1.8 %	1.8 %	1.8 %
Wood residue	5.33	5.87	6.48	7.16	7.92	8.75	9.65	10.66
Inflation equivalent		1.9 %	2.0 %	2.0 %	2.0 %	2.0 %	2.0 %	2.0 %

The electricity price is calculated using a regression based on the hourly price of the year 2019 estimated for each of the five electricity scenarios presented in part II.2.3.1 and corrected using the inflation rate of 2 % as for the other fuel. The aim is to be able to calculate the price of electricity at each time-step as a function of the electricity mix production sources in operation. This provides a means of estimating the cost of production associated with new electricity generation technologies to align the method of calculating the environmental impact and the calculation of the cost. The cost of electricity induced by the electrification of industry is therefore considered.

The regression model is based on a machine learning algorithm named Gaussian Process Regression (GPR) [120]. The cost calculation C_{el} is based on the share of each source of electricity generation in the mix and the total demand (equation II-6). This regression method has multiple applications in the literature on energy applications and especially on renewable energy to predict the electricity production and efficiency.

$$C_{el} = f(\%_{\text{onshore wind}}, \%_{\text{offshore wind}}, \dots, \text{demand}) \quad \text{II-6}$$

The validation of the method is made with the French electricity production over the year 2019 to test the ability of the model to predict a value from the input criteria and with the 2018 values to validate the reproducibility on a new data set. The validation is based on two indicators: Root-Mean-Square Error (RMSE) defined in equation II-7 and Relative Root-Mean-Square Error (RRMSE) defined in equation II-8.

$$\text{RMSE} = \sqrt{\frac{\sum(\hat{p} - p)^2}{h}} \quad \text{II-7}$$

$$\text{RRMSE} = \frac{\sqrt{\frac{\sum(\hat{p} - p)^2}{h}}}{\bar{p}} \quad \text{II-8}$$

where \hat{p} is the regression price value in €/MWh, p the real price in €/MWh, \bar{p} the average price over the year and h the numbers of hours over the year tested.

The real electricity price and the price calculated by the regression model are presented in Fig. 27. A focus on the first 100 hours of the year shows that the regression is able to accurately predict the price of electricity. The root-mean-square error (RMSE) defined in equation II-7 for the GPR over the year has a value of 3.45 €/MWh, which can be seen as the average prediction errors. One of the limitations of this model is that it is not able to consider elements other than the energy parameters that are considered in the forecasting model, e.g., war or pandemic. A test of the model

trained with 2019 data on the year 2022 for France leads to an RMSE of 301 €/MWh. This very high value shows the inability of the model to integrate parameters independent of energy sources. For the French electricity, the average electricity price is of 293 €/MWh in 2022 compared to 40 €/MWh in 2019 without any significant transformation on the share of production sources (except for a decrease in nuclear production of approximately 10 % linked to the shutdown of some reactors for repairs).

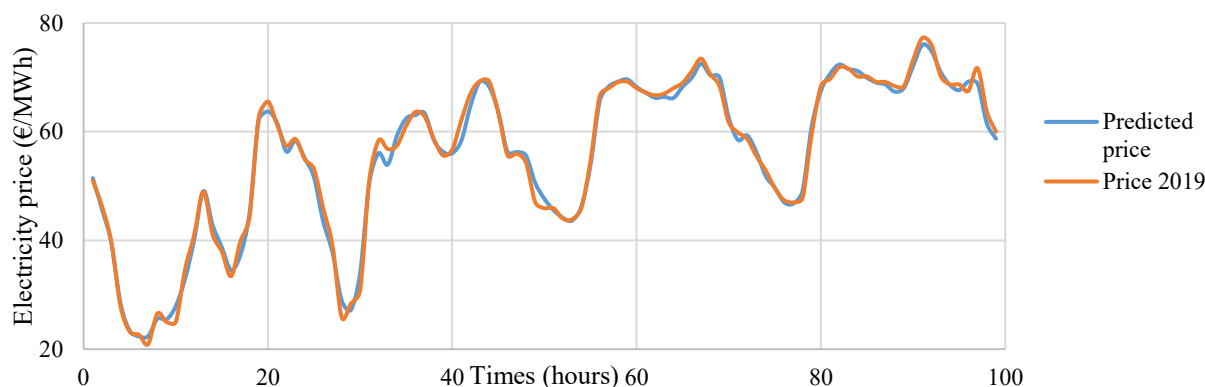


Fig. 27 - Electricity price evolution for the first 100 hours of the tested year 2019 in France

The regression is performed for each mix C1 to C5 selected as reference case. For each configuration, the RMSE and RRMSE are given in Table 16. This regression tends to underestimate the variability of the energy price and therefore limits the use of storage in the model to cope with the price fluctuation depending on the energy sources used. The table shows that the regression model with the parameters used effectively predicts the price on the data set (year 2019) with a response close to what is expected. Contrary to the year 2022 presented previously, the validation with the data from year 2018 presents results close to the real prices with an RMSE between 10 and 13 €/MWh, i.e. a RRMSE between 20 and 30 %. The presence of negative prices tends to penalise this indicator, i.e. the more hours with negative prices, the lower the average price.

Table 16 - RMSE et RRMSE for the price of the five electricity representative scenarios using GPR regression for 2018 and 2019 data

	C1 - GE	C2 - FR	C3 - IT	C4 - HR	C5 - IT
RMSE 2019 (€/MWh)	3.64	3.45	3.72	9.71	3.72
RRMSE 2019 (%)	10 %	9 %	7 %	20 %	7 %
RMSE 2018 (€/MWh)	11.76	10.11	12.69	No data available	12.69
RRMSE 2018 (%)	28 %	26 %	21 %		21 %

II.2.5.3 Flexibility added costs

The French TSO has carried out scenarios including the storage required to balance the French electricity grid [109]. As consequential evaluation is considered here for the LCA, the main contributor to electricity storage is the battery, in the absence of a significant increase in pumping station storage in the scenarios. The other changes are the increase in demand flexibility, interconnection between countries, the addition of new decarbonised thermal installations and storage in electric cars. Only the impact of batteries (except car batteries) is considered in this work because (i) electricity storage using battery is the main type of storage in the scenarios and the environmental impact of other regulation source e.g., demand flexibility or electricity import are already accounted. (ii) Even if grid management using electric car batteries is an important

factor of regulation, it is not considered because the primary use of the vehicle is mobility and it is still open to debate which share of impact can be assigned to the complementary use. Therefore, we assume here that the use of the vehicle is not intended to regulate the network.

In this work, the amount of battery needed to regulate the electrical network is specified for each scenario. It is possible to determine the battery power per amount of electricity consumed (called battery power to electricity consumption ratio) and the share of controllable electricity generation sources for each scenario. A regression based on the scenarios from the French TSO [109] is proposed to estimate the battery rate (b_r) needed to regulate the electricity mix as a function of the controllable energy rate in Fig. 28. The controllable energy considered here are thermal production, nuclear, dammed hydro, and geothermal production, while hydro river, solar and wind energy are supposed to be not controllable.

	Battery power capacity (GW)	Battery power to electricity consumption ratio ($\text{GW}_{\text{bat}}/\text{GWh}_{\text{grid}}$)	Controllable electricity rate
Sc. N03	1	$1.5 \cdot 10^{-6}$	62 %
Sc. N2	2	$3.0 \cdot 10^{-6}$	42 %
Sc. N1	9	$1.3 \cdot 10^{-5}$	38 %
Sc. M1	21	$3.0 \cdot 10^{-5}$	24 %
Sc. M0	26	$3.6 \cdot 10^{-5}$	11 %

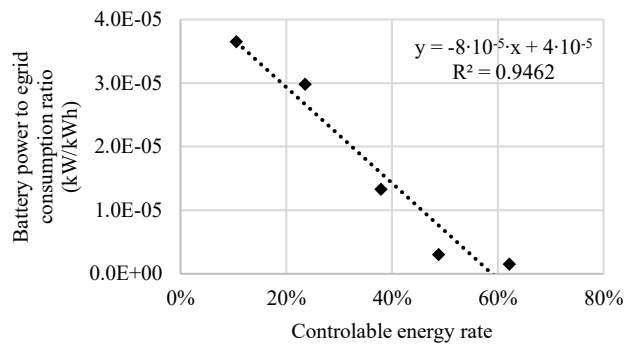


Fig. 28 - Electricity storage assumptions for batteries in France with the regression used to estimate the battery power needed to regulate the grid from 5 electricity mix scenarios [109]

The environmental battery requirement in $\text{kg}_{\text{bat}}/\text{GWh}_{\text{grid}}$ is calculated using equation II-9 and the extra costs of electricity is calculated using equation II-10; the results for each electricity mix are presented in Table 17.

$$B_r = b_r \cdot \frac{\text{EtP}}{E_d} \tag{II-9}$$

$$B_c = b_r \cdot \frac{c_{\text{bat}}}{\text{LT}} \tag{II-10}$$

Where b_r is the battery power to grid consumption ratio described in Fig. 28 in kW/kWh, EtP the energy-to-power ratio using a value of 5 kWh/kW for a daily storage cycle and a discharge time of a few hours (from the typical range 1 to 10 hours [121]), E_d the battery energy density set at 0.2 kWh/kg [121], c_{bat} the cost of battery per unit of power set at 484 €/kW_e from a Lithium-ion battery installation in Denmark for a power of 19 MWe [122], LT the battery life time set at 10 years [121].

Table 17 - Battery data for the five representative scenarios based on their controllable rate

	Controllable rate	Battery requirement (Br) ($\text{kg}_{\text{bat}}/\text{GWh}_{\text{grid}}$)	Extra electricity costs due to batteries (Bc) (€/MWh _{grid})
C1 - offshore	16 %	809.3	1.57
C2 - nuclear	63 %	-	-
C3 - thermal	53 %	104.1	0.20
C4 - onshore	26 %	604.5	1.17

C5 - solar	16 %	800.3	1.55
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II.2.5.4 Carbon Capture and Storage

The additional cost of implementing CCS can be estimated in two main ways, either per ton avoided or per kWh of electricity produced. Regarding the cost of electricity per kWh, several sources, including a study by the IPCC, estimate a range cost between 16 and 27 \$/MWh (14 to 25 €/MWh) depending on the type of technology used [114]. On the other hand, a review made by Van der Speck et al. [123] of the various studies using a Monte Carlo uncertainty distribution shows that the most likely incremental cost (50 % probability) is estimated to be 24.5 \$/MWh. A value of 23 €/MWh is retained in this study for electricity production systems.

As for the cost per ton of CO₂, the same sources give the range 20 - 49 \$/tCO₂ (18 - 45 €/tCO₂) for the IPCC and an estimated value in the range 16 - 35 €/tCO₂ for Van der Speck's review. A value of 30 €/tCO₂ is considered for on-site integration of CCS in industrial processes. With these assumptions, the cost for each technology is presented in Table 18.

Table 18 - Cost for on-site CCS installation for heat production with gas or biomass boilers

Technology	CO ₂ emissions at the boiler outlet (tCO ₂ /MWh)	CCS cost (€/MWh)
Gas boiler	0.17	5.2
Biomass boiler	0.41	12.4

II.2.5.5 Carbon tax

A carbon price is incorporated in the model using values from the PRIMES model [35]. The values used are shown in Table 19. After 2050, the value is set at 150 €/tCO_{2eq}.

Table 19 - Carbon price from 2015 to 2050

	2015	2020	2025	2030	2035	2040	2045	2050
Carbon price (€/tCO _{2eq})	7.5	25	26.5	30	50	80	120	150

II.2.5.6 Limitations and area for improvement

The limitations of the economic model are presented in Table 20. The electrical calculation model has two main limitations, (i) the cost calculation must be based on past data. The 2019 year is chosen because it is the last year with complete data before the events related to COVID and the war in Ukraine which induced important variations linked to the reduction of consumption for the first and the very important increase of energy prices for the second. The model is therefore unable to reproduce specific elements in its operation and it is not possible to consider external events that are not directly linked to energy production modes. (ii) The second limitation comes from the fact that the model does not consider the change in scale linked to the development of certain technologies. This assumption is acceptable when looking at the evolution of the costs of renewable technologies between 2020 and 2050 [124], which are reduced by a maximum of 13 %, with the exception of solar for which the cost is still subject to strong variations.

Table 20 - Limitations of economic data

	Limitations	Potential for improvement and consequences
Geographic	No differentiation of CAPEX and OPEX between the different European countries and no consideration of a specific tax level for each country	This is a limitation of conducting a macro study, which does not use country and process specific data. Uncertainties could be reduced by narrowing the scope of the study.
Temporal	OPEX and CAPEX are divided into two periods before and after 2050 with no change. A constant cost inflation rate of 2 % is considered for fuel cost and no actualisation.	
Technological	The cost of batteries and CCS is based on current estimates and may decrease if massive expansion of the use of these technologies is achieved.	

II.3 Process energy balance

The role of the energy model is to create solutions that verify all the operating conditions of the technologies to meet the process demand. For that matter, the model verifies the condition presented, which gives the heat produced by each source of energy at each time-step as described in equation II-11.

$$\sum_x P_{out,x}(t) = D(t) + \frac{\Delta S(t) + S(t) \cdot (1 - \epsilon_{sto})}{\Delta t} \quad \text{II-11}$$

where $P_{out,x}$ is the heat production from technology x in MW, D the process demand in MW, S the amount of energy in thermal storage at time-step t in MWh and $\Delta S(t) = S(t) - S(t - 1)$, the variation in energy stored. The storage efficiency named ϵ_{sto} , is the share of energy stored at each time-step. As detailed in Appendix 3 the hourly storage efficiency is set at $\epsilon_{sto} = 0.996$ considering the heat losses defined in part II.2.2.

Some additional constraints are added in the energy model in the following sections.

II.3.1 Definition of the admissible power

The operating power ranges of some technologies may be constrained by technological operating limits. A minimum operating power is considered for all technologies with a limit set at 20 % of the full load power except for biomass for which the minimum is set at 30 %. The operating conditions are described in Fig. 29 and can be broken down into three categories (displayed with numbers 1 to 3 in the figure).

(1) Power ramp-up

For all technologies except biomass there is no ramp-up power. The power demand must be higher than P_{min} , but the technologies are assumed to be able to respond instantly to the demand.

For biomass, the power ramp-up is forced to the maximal admissible level shown in orange in the figure, until the technology's minimum permissible power P_{min} is reached. Limitation in capacity ramp-up is considered and assumed linear with a maximum increase of 4.2 % per hour extrapolated from Table 21. The turn off time is not considered in the model, as it is assumed that it is possible not to inject heat into the process.

Table 21 - Biomass boiler operational constraints from [96]

Minimum run time	72 h
Minimum down time	12 h
Start-up time	24 h
Turn-off time	2 h

(2) Admissible power zone

Once in the admissible power zone, the behaviour is no longer constrained and the power can increase, decrease or stabilise while staying in admissible power zone. The only exception is for the power increase of biomass, which remains constrained by the gradient that cannot exceed the maximum admissible value shown in orange in Fig. 29.

(3) Power decrease

The decrease in power is not restricted and it is assumed that it is possible to decrease it at any rate, or just instantly shut-down the power supplied by an energy source to the process.

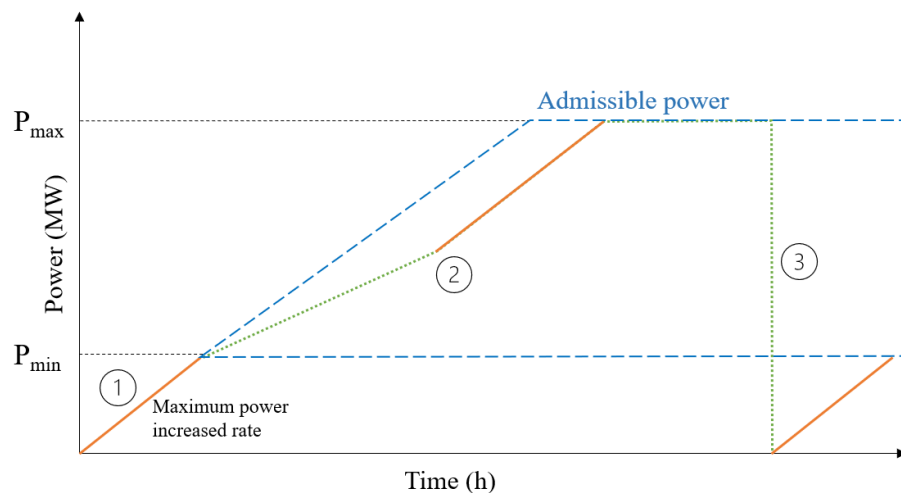


Fig. 29 - Operating range modelling for the heat production technologies, with a maximum power increase rate in orange, an admissible power in blue dotted line and a feasible power evolution in green.

II.3.2 Available waste heat

The operation of the heat pump is modelled using fatal heat recovery for an open system, i.e. the power of the MHP at time-step t is limited by the amount of energy rejected by the industrial process at time-step $t-1$. For each time-step, the maximum available power is limited by the

maximum design heat output of the MHP and the maximum admissible heat output that the MHP can generate with the available waste heat as described in equation II-12 and Fig. 30. Therefore, the heat production is limited when the process does not have access to enough waste heat. This configuration based on MHP upgrading waste heat provides a best-case scenario with a high efficiency compared to MHP upgrading geothermal energy or air-source heat pump.

$$P_{\text{out,MHP}}(t) \leq \sum_x P_{\text{out},x}(t-1) \cdot \delta(t-1) \cdot \frac{\text{COP}(t)}{\text{COP}(t) - 1} \quad \text{II-12}$$

where P_{out} is the heat flux output and δ is the share of energy that can be recovered from the open cycle, which is specific to each process and site. The impact of this value is assessed later in this work.

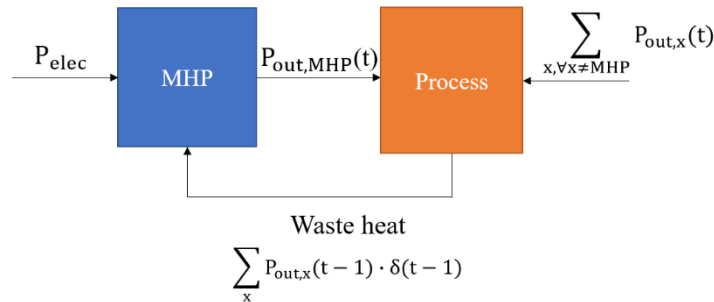


Fig. 30 - Schematic representation of waste heat recovery from MHP

II.4 Environmental model description

II.4.1 Life cycle assessment methodology

The environmental model was developed during a residency at DTU Quantitative Sustainable Assessment in collaboration with Pr. Alexis Laurent.

The following methodology is based on ISO 14040/14044 standards [56], [125]. All assumptions and information that are required to follow the ISO standards of the LCA are detailed in Appendix 4. For the sake of simplification, this section presents only the main information.

LCA is used in the optimisation model to highlight the set of environmentally non-dominated solutions. LCA is calculated at each time-step considering the share of each energy sources, the load factor of the electricity grid, the variation of the electricity mix, etc. For this matter, the functional unit used is the heat production to meet the demand of the industrial processes described in part II.2.4, with an hourly discretisation over 1 year in the five countries selected as representative in part II.2.3.1 and for the three different period of time 2015-2040, 2040-2065 and 2065-2090.

The system boundary for the environmental assessment is presented in Fig. 31, with the detail of every considered and excluded processes from the LCA. The two main processes not considered in the study are (i) the connection with the process due to this high level of specificity and minor environmental impact compared to the process itself and its energy consumption and (ii) the process requirement in material, chemical, consumable. The last element not considered in this study is the benefit from potential energy avoided by the new system compared to the current one (which is mainly gas-based). This choice is made to assess the level of impact of a technical

solution against an acceptable level of impact, defined in the following sections rather than comparing the benefit of a new technical solution compared to current energy system.

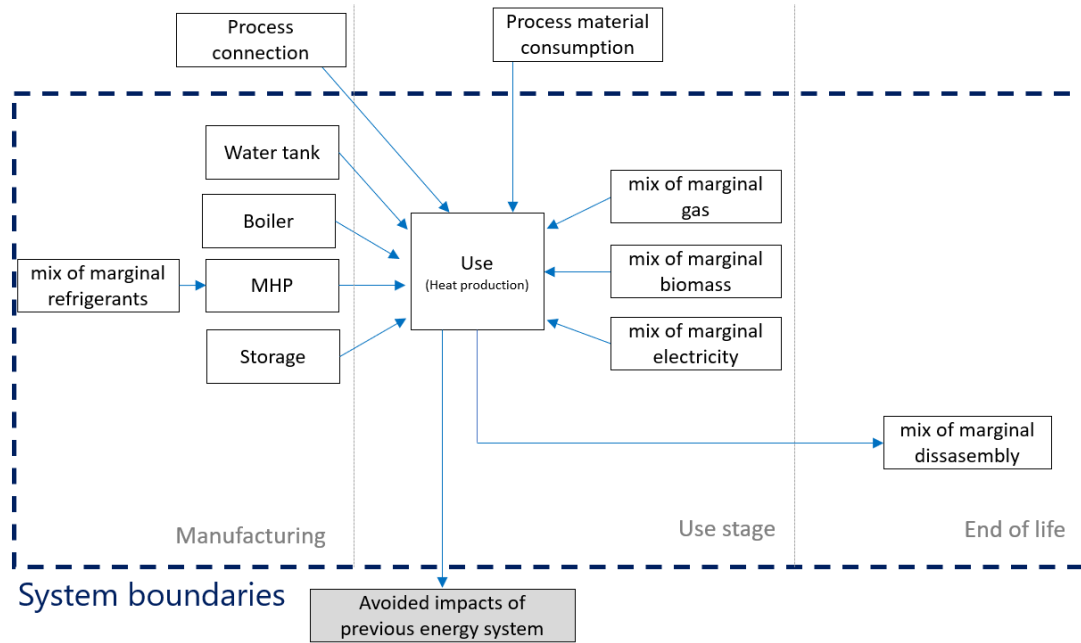


Fig. 31 - Flow diagram. The blue dotted line indicates the system boundaries; all processes outside of the line are not considered in this study. The grey box represents the avoided energy consumption due to the change of the heat production system.

The environmental impact calculation of each technology (I_x) over one year is broken down into two contributions:

- (i) The impact of the life cycle of the system itself ($I_{x,syst}$), which is scaled down to one year pro rata to its useful life.
- (ii) The impact related to the sum of energy used at each time-step for heat production which is calculated from the impact per unit of energy ($i_{x,en}$) as described in equation II-13. The total impact due to each technology for the industrial sector studied I_s is presented in equation II-14.

$$I_x = \frac{I_{x,syst}}{LT} + \sum_t i_{x,en}(t) \cdot E_{in,x}(t) \quad \text{II-13}$$

$$I_s = \sum_x I_x \quad \text{II-14}$$

Selection of impact categories, classification and characterisation are done using EF 3.0 methodology developed for the Joint Research Center from European commission [126] for the environmental analyses and the method named cumulative energy demand (CED) [127] and cumulative exergy demand (CExD) [127]. Each considered impact category y with its description is presented in Table 22. In the following, $I_{s,y}$ refers to impact of industrial sector “s” for impact category “y”. As explained in footnote of section I.3.2, to make the reading easier, the impact categories are written in italic in this manuscript, e.g., *climate change*.

Table 22 - Environmental and energy impact categories y with description from SIMAPRO software

Source	Impact category y	Units	Description
EF 3.0	Climate change	kgCO _{2eq}	Radiative forcing as Global Warming Potential GWP100 Baseline model of the IPCC 2013 with some factors adapted from EF guidance
	Ozone depletion	kgCFC-11 _{eq}	Ozone Depletion Potential calculating the destructive effects on the stratospheric ozone layer over a time horizon of 100 years.
	Ionising radiation	kBq U-235 _{eq}	Ionizing Radiation Potentials: Quantification of the impact of ionizing radiation on the population, in comparison to Uranium 235.
	Photochemical ozone formation	kg NMVOC _{eq}	Expression of the potential contribution to photochemical ozone formation.
	Particulate matter	disease incidence	Disease incidence due to kg of PM2.5 emitted. The indicator is calculated applying the average slope between the Emission Response Function (ERF) working point and the theoretical minimum-risk level. Exposure model based on archetypes that include urban environments, rural environments, and indoor environments within urban and rural areas.
	Human toxicity, non-cancer	CTUh	Comparative Toxic Unit for human. Using USEtox consensus multimedia model. It spans two spatial scales: continental scale consisting of six compartments (urban air, rural air, agricultural soil, natural soil, freshwater and costal marine water), and the global scale with the same structure but without the urban air.
	Human toxicity, cancer	CTUh	
	Acidification	mol H ⁺ _{eq}	Accumulated Exceedance characterizing the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit.
	Eutrophication, freshwater	kg P _{eq}	
	Eutrophication, marine	kg N _{eq}	Nitrogen equivalents: Expression of the degree to which the emitted nutrients reach the marine end compartment (nitrogen considered as limiting factor in marine water).
	Eutrophication, terrestrial	mol N _{eq}	Accumulated Exceedance characterizing the change in critical load exceedance of the sensitive area, to which eutrophying substances deposit.
	Ecotoxicity, freshwater	CTU _e	Comparative Toxic Unit for ecosystems. Using USEtox consensus multimedia model. It spans two spatial scales: continental scale consisting of six compartments (urban air, rural air, agricultural soil, natural soil, freshwater and costal marine water), and the global scale with the same structure but without the urban air.
Land use	Pt	Soil quality index	

			Calculated by JRC starting from LANCA® v 2.2 as baseline model.
	Water use	m ³ deprivation	User deprivation potential (deprivation-weighted water consumption) Relative Available Water REMaining (AWARE) per area in a watershed, after the demand of humans and aquatic ecosystems has been met. Blue water consumption only is considered, where consumption is defined as the difference between withdrawal and release of blue water. Green water, fossil water, sea water and rainwater are not to be characterised with this methodology.
	Resource use, fossils	MJ	Abiotic resource depletion fossil fuels; based on lower heating value ADP for energy carriers, based on Van Oers et al. 2002 as implemented in CML, v. 4.8 (2016).
	Resource use, minerals and metals	kg Sb _{eq}	Abiotic resource depletion (ADP ultimate reserve) ADP for mineral and metal resources, based on Van Oers et al. 2002 as implemented in CML, v. 4.8 (2016).
Ecoinvent	Cumulative energy demand	MJ	Method to calculate Cumulative Energy Demand (CED), based on the method published by Ecoinvent version 2.0 and expanded by PRé Consultants for raw materials available in the SimaPro 7 database. The method is based on higher heating values (HHV)
	Cumulative exergy demand	MJ	In this method exergy is used as a measure of the potential loss of "useful" energy resources.

II.4.2 Specific process modelling

II.4.2.1 Environmental impact of battery

The electric storage by battery is modelled using the data of the so called "*Battery cell, Li-ion {GLO} | Conseq, U*" and is calculated based on the controllable energy rate in each mix as described in section II.2.3. The following additional assumptions are considered in the modelling:

- (i) The impact is smoothed over the entire lifespan of the battery, regardless of the operating mode. This means that the impact of the battery is not only attributed to operating hours but to all hours considered in the study.
- (ii) The impact is calculated for a lifespan of 10 years.

II.4.2.2 Environmental impact of CCS

The calculation of the environmental impact of CCS is based on the data of the so-called "*Electricity, high voltage {XX} | electricity production, natural gas, combined cycle power plant | Conseq, U*" for the gas with CCS and "*Electricity, high voltage {XX} | electricity production, hard coal | Conseq, U*" for the part combining coal and CCS. The data is calculated for each country, with the notation XX representing the country tag for each of the five representative mix. The CCS modelling is then added by integrating the modelling done by Bisinella [112].

The main assumptions, in addition to adding the part needed for carbon transport and storage, are:

- (i) CO₂ captured efficiency : 88 %
- (ii) 4 kg of monoethanolamine (MEA) is used per tonne of CO₂ [112]
- (iii) Releasing around 0.1 kg NH₃ per tonne CO₂ captured [112]
- (iv) NaOH is added in the stripping step at an amount of 0.1 kg per tonne CO₂ captured [112]
- (v) Around 4 kg of solid waste is generated per ton of CO₂ captured [112]
- (vi) A distance between the process and the storage of 400 km with pipeline [112]

II.4.2.3 Refrigerant

Concerning the refrigerant used in MHP, the parameters are presented in Table 23. For the refrigerant recovered, an end-of life recycling treatment is considered. There is a lot of different available refrigerants with different properties [29] able to operate at different temperature levels. By default the refrigerant considered is R744 (CO₂) from the work of Elmegaard et al. [128]. This refrigerant presents some limitation but remains one of the best options in the incoming years with no toxicity and limited environmental impact. A parametric study is realised later in this work to assess the impact of the refrigerant choice.

Table 23 - Refrigerant assumptions

Parameters		Ref.
Refrigerant load by power unit, m_{wf}	2 kg/kW	[129]
Annual leakage rate, La	5 %	[129]
End of life leakage rate, Le	15 %	[53]

II.5 Economic model description

The economic model is extremely simplified with many limitations, but it does allow us to integrate some economic aspects into the method. It is based on the assumptions described in section II.2.5. The calculation is based on the final energy consumption E_{in} and the maximum power demand of technology x over the whole year. Two indicators are considered, (i) the annual cost of the system described in equation II-15, which is selected for the optimisation process and (ii) the PayBack Period (PBP) described in equation II-16.

$$C_s = \sum_x \frac{CAPEX_x}{LT_x} + \sum_x OPEX_x + \sum_t \sum_x E_{in,x}(t) \cdot c_x(t) \quad \text{II-15}$$

where C_s is the annualised cost of heat production for the industrial sector s and c_x the cost per unit of energy for technology x .

$$PBP = \frac{CAPEX}{\text{savings}} = \frac{\sum_x \frac{CAPEX_x}{LT_x}}{(\sum_t E_{in,ng} \cdot c_{ng}(t) - \sum_t \sum_x E_{in,x}(t) \cdot c_x(t) - \sum_x OPEX_x)} \quad \text{II-16}$$

Where the reference is supposed to be natural gas (ng) boiler for the calculation of savings. For the PBP in the industry, a return time of 5 years is chosen as the maximum acceptable to investors,

but the common return time is often even more demanding with a value between 2 and 3 years [130] [131]. The PBP indicator is not used in the optimisation model for the generation of non-dominated solutions but is used to analyse the solutions from an economic point of view. The 5-year threshold defined for the PBP is a convention linked to economic wills and cannot be equated with the requirements on environmental limits which are defined by physical limits and not human conventions. This limit is studied separately to evaluate the potential for development but is not considered on the same level as the environmental limits.

II.6 Optimisation and classification methods

II.6.1 Optimisation algorithm

A genetic optimisation algorithm is used to generate the set of non-dominated solutions. The operation of this algorithm is described in more detail in Chapter IV. A non-dominated solution - also known as a Pareto-efficient solution - is a solution in a multi-objective optimisation problem that is not dominated by any other possible solution. In our configuration, this implies that a non-dominated solution is never less efficient than another solution on all environmental, economic and energy criteria. As presented in Fig. 32 in a two-dimension configuration of a multi-objective optimisation problem, there can be multiple solutions that are non-dominated. These solutions are typically represented graphically by a Pareto front which is the green dotted line in the figure. The optimisation model therefore eliminates all the less efficient solutions on all aspects, represented in blue in the figure, so as to conserve only the best options. Note that all the non-dominated solutions are necessarily more efficient on certain indicators and less efficient on others.

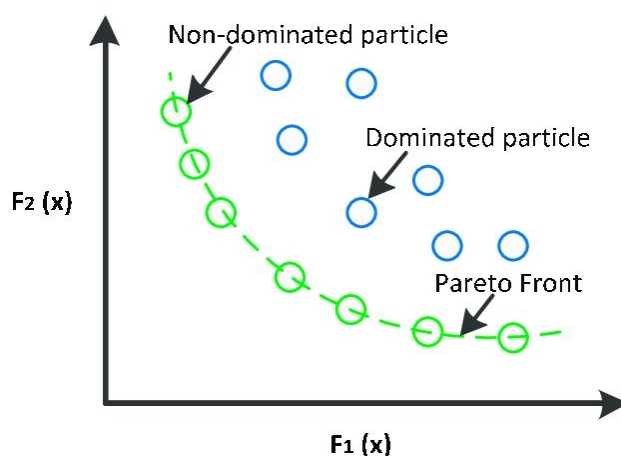


Fig. 32 - Dominated, non-dominated and Pareto-front solution set, figure from [132]

In this work, the optimisation package from Matlab [133] is used to solve the problem (minimisation of objective function with constraints). This algorithm works by combining initial solutions and introducing mutations to efficiently explore the solution space. This method has been extensively studied in the literature [134], [135] and is already applied for energy optimisation [136], [137]. It is well suited to our case as each initial solution with one single energy source can be combined to make any possible solution. The initial solutions are therefore easy to generate.

II.6.2 Fitness function and constraints

The fitness function $F(X)$ to minimise with the optimisation algorithm is presented in equation II-17. This equation is a vector composed of the functions $I_{s,y}$ calculated with equation II-14 for each impact category y and the economic indicator C_s from equation II-15.

$$F(X) = \begin{bmatrix} I_{s,1} \\ I_{s,2} \\ I_{s,3} \\ I_{s,4} \\ \vdots \\ C_s \end{bmatrix} \quad \text{II-17}$$

Where $I_{s,1}$ is the impact of the industrial sector over one year for the 1st impact category e.g., climate change, $I_{s,2}$ the impact for the 2nd impact category, e.g. cumulative exergy demand and so on. Only the PBP indicator presented in equation II-16 will be studied retrospectively and is therefore not present in the vector $F(X)$.

The constraints applied to the fitness function are decomposed in three categories:

- (i) The first one is the linear constraint imposed by the energy balance presented in equation II-11 in part II.3.
- (ii) The second one is composed of three non-linear constraints presented in part II.3.1. It contains (i) the power ramp-up limit for biomass boiler, (ii) the limits imposed by the operating range of each heat production technology and (iii) the limit of available waste heat potential for the production of MHP.
- (iii) The last constraint is the variable boundaries, which is used to restrict the search in a predefined area. The lower boundary is set at 0 to avoid negative values, which are not physical, and the upper boundaries of heat production system is set at 3 times the maximal demand over the year (D_{\max}) to allow overproduction to be able to charge the storage while meeting the industrial demand. This value is deliberately very permissive to leave the model enough room to evolve. Finally, the upper boundary of storage is set at 100 times the maximal demand over the year (D_{\max}) to allow storage equivalent to at least 4 days for a continuous process, the limit is also deliberately high to allow the model to explore storage and not eliminate solutions that could be beneficial.

II.6.3 Sustainable and contribution level definition

The optimisation model generates a set of non-dominated technical solutions to meet industrial demand. Each of these solutions presents better results in certain impact categories and worse results in others. Given that this work does not seek to eliminate certain impact categories in order to maintain a holistic environmental approach, a methodology is proposed to help ranking all the non-dominated solutions according to criteria of least possible impact on the environment. This methodology is based on two indicators, which are described in the following sections (i) the deviation from environmental sustainability level and (ii) the contribution of the considered industrial sector to the total impacts of the global economy.

II.6.3.1 Environmental sustainability level

The life cycle assessment is expanded to include the environmental sustainability assessments of the non-dominated solutions. To simplify the discussion, we will henceforth refer to the environmentally sustainable limit as the 'sustainable limit'. Sustainable limits are based on the carrying capacities of the whole Earth system in the face of various anthropogenic pressures based on planetary boundaries and extended with human health [57]. Global sustainable levels for all human activities are defined using equation II-18 on the basis of the current impact, which is corrected with a reduction factor derived from Vargas et al. [138], except for marine eutrophication, which is based on Willett et al. [139] and climate change which is based on the scenario AIM/CGE 2.2 published by Riahi et al. [110] and used in IPCC AR6 as one of the reference scenario to limit warming to 2 °C without overshoot [16].

$$Sl_{tot,y} = \frac{I_{tot,y}}{Rf_y} \quad \text{II-18}$$

Where $Sl_{tot,y}$ is the global environmental sustainability threshold for environmental impact “y”. $I_{tot,y}$ is the total impact of the human activities over a year for environmental impact y using the base year 2010, which is the closest year to the studies on sustainable levels provided by the EF 3.0 method. $I_{tot,y}$ units depend on each impact category “y”. Rf_y is the reduction factor to reach a sustainable level for environmental impact y presented in Table 24. A value Rf_y below 1 indicates that the current level is below the sustainable level, while a value greater than 1 indicates that the sustainable level is exceeded. A sustainable level of less than 1 means that the impact is within the threshold (planetary boundary or human health damage threshold) and therefore is considered sustainable.

Table 24 - Reduction factors used for the 16 impact categories from EF 3.0

Impact category	Units	Reduction factor	Source
Climate change (steady state)	kg CO2 eq	9.36	Vargas et al. [138]
Climate change (budgeting 2015- 2040)	kg CO2 eq	1.23	Riahi et al. [110]
Climate change (budgeting 2040- 2065)	kg CO2 eq	2.22	Riahi et al. [110]
Climate change (budgeting 2065- 2090)	kg CO2 eq	16.08	Riahi et al. [110]
Ozone depletion	kg CFC11 eq	0.28	Vargas et al. [138]
Ionising radiation	kBq U-235 eq	0.01	Vargas et al. [138]
Photochemical ozone formation	kg NMVOC eq	0.54	Vargas et al. [138]
Particulate matter	disease incidence	5.97	Vargas et al. [138]
Human toxicity, non-cancer	CTUh	0.9	Vargas et al. [138]
Human toxicity, cancer	CTUh	0.26	Vargas et al. [138]
Acidification	mol H+ eq	0.3	Vargas et al. [138]
Eutrophication, freshwater	kg P eq	3.22	Vargas et al. [138]
Eutrophication, marine	kg N eq	8.2	Willett et al. [139]
Eutrophication, terrestrial	mol N eq	0.3	Vargas et al. [138]
Ecotoxicity, freshwater	CTUe	0.85	Vargas et al. [138]
Land use	Pt	9.33	Vargas et al. [138]
Water use	m3 deprivation	0.51	Vargas et al. [138]
Resource use, fossils	MJ	4.08	Vargas et al. [138]
Resource use, minerals and metals	kg Sb eq	4.08	Vargas et al. [138]

At the level of a particular human activity or an industrial sector, the sustainable level is derived from $Sl_{tot,y}$ following equation II.19.

$$Sl_{s,y} = Sl_{tot,y} \cdot \tau_{s,y} \quad \text{II.19}$$

Where $\tau_{s,y}$ represents the share of environmental impact y authorised for the considered sector, which depends on the importance of this sector in relation to all human activities. The sum of $\tau_{s,y}$ for all human activities must be lower or equal to 1 in order not to exceed the sustainable limit for impact category “ y ”. Allocating $\tau_{s,y}$ to each sector of human activity is definitely open to discussion; it may be based on economic considerations, prioritising basic human needs, etc. These questions are a thesis topic in themselves and go well beyond the initial objectives of the present thesis. This is why we have chosen two simple approaches in this thesis:

- i) The simplest approach is to use the share of the current environmental impact of the sector in relation to the total environmental impact, i.e. $\tau_{s,y} = \frac{I_{s,y}}{I_{tot,y}}$.

In this thesis, $I_{s,y}$ is the contribution of the heat production over one year calculated from equation II-14 for impact category “ y ”.

- ii) The second approach is based on the economic importance of the sector considered in relation to all human activities. It is calculated using the economic added value of the process compared to the global added value: $\tau_s = \frac{EVA_s}{EVA_{tot}}$.

The difference between these two methods is shown graphically in Fig. 33. This graph represents the share of four processes in global GHG emissions on the one hand and GVA emissions on the other. The first method (i) corresponds to the value on the x axis and the second method (ii) the value on the y axis. The choice of method leads to different consequences depending on the sector. For example, the “Agriculture, forestry and fishing” sector has a share almost twice as large with method (ii) compared to method (i). For the sector “Food products, beverages and tobacco” on the other hand, method (i) implies a larger share than method (ii). The “Paper products and printing” sector has a relatively equivalent impact and is not greatly affected by the choice of method.

These two approaches are examined in Chapter III, in the context of a preliminary example relating to the agri-food sector. In Chapter V, which presents the final results of this work, the second approach is retained.

The sustainability ratio ($Sr_{s,y}$) defined in equation II-20 is used to assess the gap between the process and the sustainable level for each impact category.

$$Sr_{s,y} = \frac{I_{s,y}}{Sl_{s,y}} \quad \text{II-20}$$

A value below 1 implies that the level of the evaluated solution is sustainable and the lower the value, the greater the margin. Conversely, a value greater than 1 implies a level higher than the level defined as sustainable.

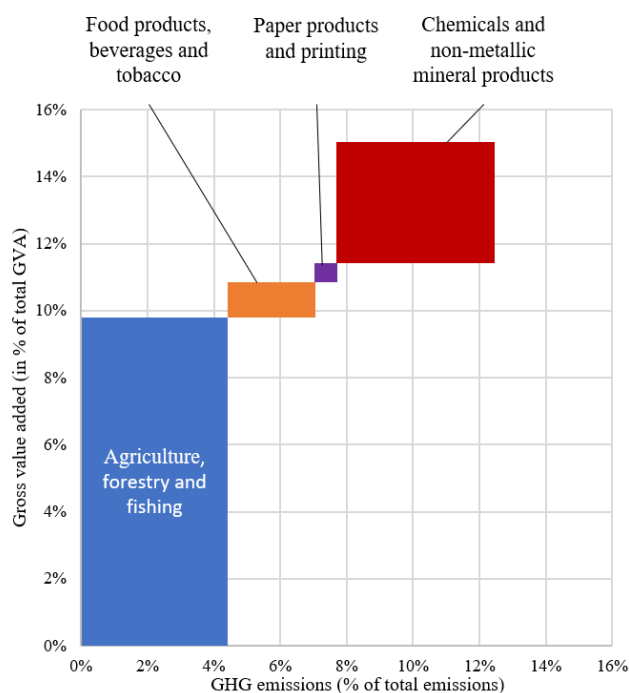


Fig. 33 - Breakdown of share of GVA and GHG emissions for four processes compare to all human activities

Two approaches can be used to determine the reduction factor for each impact category: the first one is the steady-state approach and the second one is the budgeting. The first approach is relevant for all non-time-dependent indicators. It is used to assess the impact categories that have the capacity to regenerate, for example, the use of water according to the regenerative capacity of the water cycle. The second approach is time-dependent and is relevant to impacts that increase over time, like CO₂ footprint, where there is a maximum emission level to be reached by 2100 to limit the temperature below a certain threshold.

The reduction factors (Rf) used in this work are presented in Table 24. The environmental sustainability thresholds are defined using the steady state approach proposed by Vargas et al. [138] with the exception of climate change and marine eutrophication which are further detailed in the following sections. We are aware that these values remain approximate and depend on numerous assumptions. However, they allow us to test the methodology developed in this work which could be improved with more precise values in the future.

II.6.3.1.1 Climate change

For the climate change category there is a lot of different studies and approaches to define this threshold. Vargas et al. [138] propose a reduction factor of 9.4 with a steady state approach. This value can be compared to the work by Bjørn and Hauschild [140] who estimated the steady-state emissions of greenhouse gases to stay below 2 °C at 6.8 Gt-CO₂eq/yr, hence a reduction factor of 8.2 compared to the EF 3.0 current reference value [126]. A comparative analysis of several methods from Gebara et al. [71] shows a threshold between -0.7 and 17 Gt-CO₂eq/yr (depending on the approach and the thresholds used). The steady state approach is not retained in this work because there is no long-term sustainable rate of emissions from fossil fuels. Indeed, any fossil fuel combustion will increase the amount of CO₂ present in the carbon cycle and part of it will contribute to long term increase of the CO₂ concentration in the atmosphere. In this work, the

budgeting values is extracted from the scenario proposed by Riahi et al. [110] to limit the temperature increase to 2 °C compared to the pre-industrial time without overshoot. The reduction factor is derived from the carbon budget for each studied period, as presented in Table 24. Therefore, the emission level decreases from now to the end of the century when it is expected that efficient technologies will be more developed e.g. decarbonisation of electricity, electrification or CCS.

II.6.3.1.2 Eutrophication, marine

The other impact category not coming from Vargas' work is the eutrophication due to the absence of threshold in his work. Bjørn et al [141] realised a review of different methods for considering this impact category. The initial Planetary Boundary (PB) for nitrogen (N) was set at 25 % of contemporary total human fixation of N₂, corresponding to approximately 35 Tg N/year [11]. More recently de Vries et al. [142] improved the scientific foundation by basing the PB on critical concentrations of N compounds in different environmental compartments. Their most precautionary PB estimate, equal to 62 Tg N/year of intentional anthropogenic fixation, was subsequently adopted in the revision of the PBs in Steffen et al. [143]. Lastly, Willett et al. [139] proposed to adjust the PB to 65 Tg N/year which is used in this study and which correspond to a reduction factor of 8.2.

II.6.3.1.3 Resource use, minerals and metals

The indicator proposed by Vargas has several limitations, as suggested by Gebara et al. [71]. The main limitations are that it only considers geological resources and does not consider resources already taken from the environment. On the other hand, Gebara's synthesis work shows that there is currently no better method, so the value proposed by Vargas is retained in this study.

II.6.3.2 Share of the contribution in the global economy

To put the environmental impacts of a specific industrial sector into perspective in relation to the global impacts of human activities, a downscaling methodology is used. There are many principles of downscaling, i.e. moving from global to process level impacts [61], [62]. The sharing principle used in this work is the Economic Value Added (EVA), which has been the most used sharing principle until now [61]. Although many biases may distort this coupling, this approximation allows the share of environmental impacts for each industry to be roughly estimated. As these data are readily available, it makes the study reproducible and transferable to any sector. To define whether an industrial sector has a significant impact within an impact category y , we use equation II-21. The economic share of Global Value Added (GVA) of this sector is compared to its share of environmental impact y relative to total impacts for this impact category. The higher the share of environmental impact in relation to the share of GVA, the more significant the contribution of the studied sector to this impact category. On the contrary, when the value is low, it means that the sector is not a big contributor to the global impact.

$$Cl_{s,y} = \frac{I_{s,y}}{I_{tot,y}} \cdot \frac{1}{\tau_s} \quad \text{with } \tau_s = \frac{EVA_s}{EVA_{tot}} \quad \text{II-21}$$

Where $Cl_{s,y}$ is the contribution level of the studied sector for the environmental impact y , $I_{s,y}/I_{tot,y}$ the share of impact of the sector for environmental impact y in relation to total emissions, τ_s is the share of economic value added of the studied perimeter in relation to total economic value

added (%). EVA_s is calculated using equation II-22. A contribution level of 1 represents a share of emissions equivalent to the share of GVA created, implying a contribution to GVA aligned with the process impact. On the contrary, a low or high value implies an environmental contribution that is not aligned with the value created, which leads to an insignificant or predominant environmental contribution of the process on the impact category respectively.

$$EVA_s = EVA_{tot} \cdot \frac{EVA_{indu}}{EVA_{tot}} \cdot \frac{EVA_s}{EVA_{indu}} \quad \text{with} \quad \frac{EVA_s}{EVA_{indu}} \approx \frac{E_{in,s}}{E_{in,indu}} \quad \text{II-22}$$

where EVA_{indu} is the gross added value all industrial sectors and EVA_{indu}/EVA_{tot} is the share of GVA from all industrial sectors in the global economy, $E_{in,s}$ is the final energy consumption from the studied industrial sector and $E_{in,indu}$ is the final energy consumption of all industrial sectors. We assume here that the ratio of process value added to total GVA in industry is close to the ratio of final process energy consumption to total industry consumption, as evaluated by Kasperowicz et al. [144]. As a result, there is no need to use economic data specific to the process which are often difficult to obtain. The contribution level can be reformulated by combining equations II-21 and II-22 to obtain equation II-23.

$$Cl_{s,y} \approx \frac{I_{s,y}}{I_{tot,y}} \cdot \frac{EVA_{tot} \cdot E_{in,indu}}{EVA_{indu} \cdot E_{in,s}} \quad \text{II-23}$$

This criterion puts the importance of the sustainability ratio into perspective. Indeed, if the sustainability ratio is high, but the contribution level is low, reducing the environmental impact of this process may not have a significant impact on the global sustainability but remains a needed target. On the contrary, reducing the environmental impact of a process having a high contribution level can have a significant effect on the impact category even if the impact level of this process is below the threshold.

II.6.4 Ranking

Each non-dominated solution identified by the optimisation algorithm is never less efficient than another solution on all environmental, economic and energy criteria. Therefore, in order to go further in the analysis, we need to find criteria for classifying these different solutions based on sustainable ratio and contribution level on each impact category. Various methods can be used for that purpose. Three of them will be presented and used in chapter V.

II.7 Conclusions

This chapter presented the general methodology used in this thesis to analyse different industrial heat production systems dynamically, seeking to optimise environmental, energy and economic indicators.

One of the major contributions of this method is to define sustainable levels for an industrial sector based on current global emissions, which are scaled down by a reduction factor to determine the "acceptable" level of impact of human activities to ensure that environmentally sustainable limits are not exceeded. From this "acceptable" value, a downscaling principle based on added value is used to assign a "right to impact" to each process, in order to give each process its own roadmap.

An optimisation algorithm developed in greater detail in Chapter IV is used to obtain a pareto front of non-dominated solutions on all the criteria considered. Before presenting this algorithm, we propose in the following chapter some applications of this methodology which do not require the use of the optimisation algorithm and enable to highlight the various concepts developed in Chapter II.

Chapter III

III. Simplified applications of the methodology to the electrification of heat production

Contents

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In this chapter, two applications of the methodology developed in Chapter II are presented, using a simplified approach compared with the general one. Indeed, in these two examples, the use of an optimisation algorithm is not necessary, as the aim is not to compare several options for industrial heat production, but to assess the suitability of certain solutions in simplified contexts. Assessments combining, energy, economic and environmental methods (3E) are used to obtain some general information on the impact of electrification on process heat production. This helps to illustrate certain parts of the methodology.

The first application was published in Applied Energy [145] in 2022; the reader can refer to it for further information. It is a simplified 3E analysis, considering only the “*climate change*” criterion as environmental indicator. The goal is to find the environmental and economic conditions enabling industrial heat production tanks to MHP fed with waste heat and electricity, to comply with the targets from the Paris Agreement. Several industrial sectors for 24 EU countries are taken as use-cases with 2030 and 2050 as reference years.

The second application was presented at the ECOS (Efficiency, Cost, Optimisation, Simulation and Environmental Impact of Energy Systems) 2022 congress in Copenhagen. The full set of environmental impacts is considered in the energy model to assess the electrification of food industry in Denmark and in France. This work was carried out in collaboration with DTU's Department of Mechanical Engineering laboratory, which is working on the electrification of the Danish agri-food sector. More information on their work on the electrification of industry can be found in the Elforsk project report [128]. This second part illustrates how the different indicators of sustainability developed in chapter II (sustainability ratio, contribution level, etc.) can be used to assess the sustainability of a heat production system.

III.1 Combined energetic, economic and climate change assessment of heat pumps for industrial waste heat recovery [150]

In this section, a simplified version of the methodology is proposed to assess the minimum energy performance of a MHP fed with waste heat and national electricity grid to stay below the environmental thresholds defined by Europe GHG emission reduction targets for 2030 and 2050. The reduction factors are aligned with the scenario of a 2 °C rise in temperature compared to the pre-industrial era as presented in chapter II.6.3.1. A 100 % efficient gas boiler is considered as the current reference for heat production. This study considers the *climate change* impact of the electricity mix of each European country.

The simplified methodology is presented in Fig. 34. For the environmental assessment, the scope of the study is reduced to data concerning the *climate change* indicator. For the technologies, only MHP and gas boiler are considered, and a perfectly continuous process over the whole year is taken into account. On the other hand, energy data from the various European countries are considered, and the economic study considers the different assumptions described in chapter II.

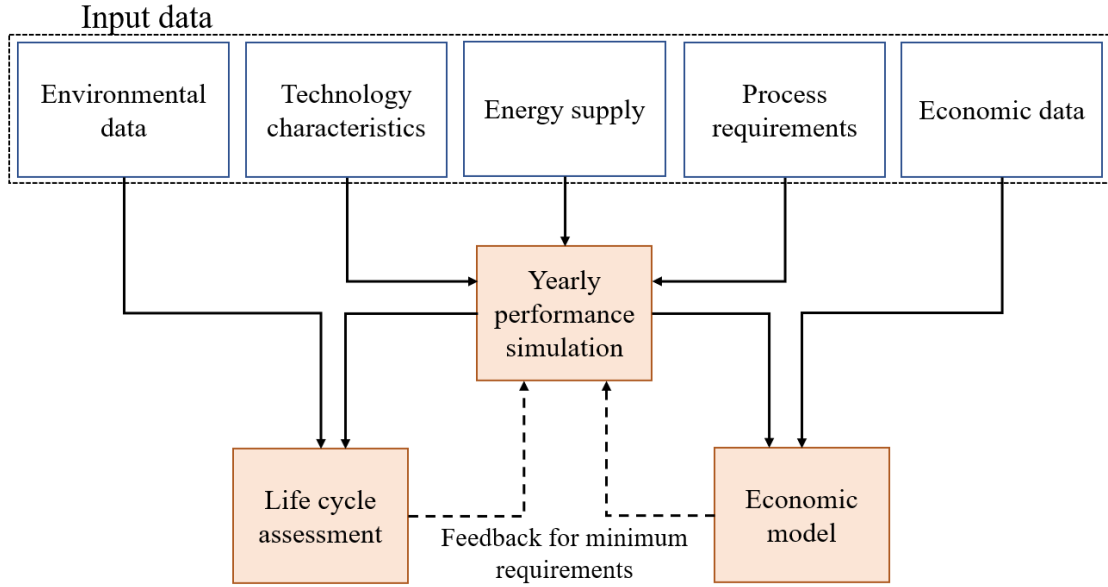


Fig. 34 - Proposed assessment framework to add carbon footprint and economic constraints within the energy model

III.1.1 Maximum carbon footprint assessment of MHP-based solutions

III.1.1.1 Definition of the maximum electricity carbon content to meet GHG emission targets

The GHG emissions of the reference configuration over one year are based on gas combustion in a 100 % efficient gas boiler as described in equation III-1.

$$I_{CC,ng} = E_{in,ng} \cdot i_{CC,ng} \quad \text{III-1}$$

Where ng refers to natural gas, E_{in} is the final energy consumption of the industrial process over one year, i_{cc} the *climate change* impact per unit of energy in $\text{kgCO}_{2\text{eq}}/\text{MWh}$ and I_{CC} the *climate change* impact over one year. These emissions are compared to the emissions of a MHP fed with waste heat and electricity, which produces the same energy demand over one year. These emissions can be split in three terms linked to (i) energy consumption over one year presented in equation III-2, (ii) MHP manufacturing life cycle spread over the system's lifetime (equation III-3) and (iii) impact of working fluid spread over the system's lifetime (equation III-4).

$$I_{CC,el} = E_{in,el} \cdot i_{CC,el} \quad \text{III-2}$$

$$I_{CC,MHP} = \dot{W}_{el,max} \cdot i_{CC,MHP} \cdot \frac{1}{LT_{MHP}} = \frac{D_{max}}{COP} \cdot i_{CC,MHP} \cdot \frac{1}{LT_{MHP}} \quad \text{III-3}$$

$$I_{CC,wf} = m_{wf} \cdot \left(i_{CC,wf} \cdot (La \cdot LT_{MHP} + Le) - i_{CC,wf,EoL} \cdot (1 - Le) \right) \cdot \frac{1}{LT_{MHP}} \quad \text{III-4}$$

where el refers to electricity. $i_{cc,MHP}$ is the *climate change* impact per unit of nominal electrical energy for the production and disposal of MHP in $\text{kgCO}_{2\text{eq}}/\text{MW}_{el}$; the MHP nominal electrical energy is sized according to its maximal thermal demand D_{max} in MW. $i_{cc,wf}$ is the *climate change*

impact per kg of working fluid in kgCO_{2eq}/kg, with m_{wf} the refrigerant charge in kg. Eol refers to the end-of-life treatment of the working fluid, L_a is the annual leakage rate in percentage of total refrigerant mass, L_e the end-of-life leakage rate in percentage of total refrigerant mass, LT_{MHP} is the lifetime of the MHP.

To determine the conditions under which the use of a MHP is beneficial for the *climate change* indicator, we compare its emissions with those of the current reference system (gas boiler), corrected by the factor necessary to achieve the desired decarbonisation targets. This gives the maximum carbon content of the electricity needed to achieve these objectives. The balance to calculate the benefit with a given impact factor reduction for climate change (Rf_{CC}) compared with the current configuration is presented in the equation III-5.

$$\frac{I_{CC,ng}}{Rf_{CC}} - (I_{CC,el} + I_{CC,MHP} + I_{CC,wf}) > 0 \quad \text{III-5}$$

For a given COP, equation III-6 together with equations III.1 to III.4 provide the maximum electricity carbon content ($I_{cc,el,max}$) to respect the reduction target of GHG emissions. It should be noted that the carbon footprint impact of the auxiliaries related to the operating of the MHP is not included in both the environmental and energy models.

$$I_{cc,el,max} = \frac{I_{CC,ng}}{Rf_{CC}} - I_{CC,MHP} - I_{CC,wf} \quad \text{III-6}$$

Compared to the Total Equivalent Warming Impact also called TEWI indicator, which is widely used in assessing the CO₂ impact of mechanical heat pumps [146], the proposed methodology goes further by integrating imported emissions from the refrigerant manufacturing and end of life.

The data used in this configuration are presented in Table 25. The current carbon content of electricity for each country is based on data from the European Environmental Agency [147], and the evolution of the carbon content is estimated for 2050 from the scenarios proposed by European Commission in ref. [35]. The case study focuses on two working fluids, based on the work of Arpagaus et al [29]. The choice was made to compare fluids used in high temperature MHPs. The reference considered is R134a¹ which is currently widely used and has a high GWP (i.e. 1300 kgCO_{2eq}/kg [148]). R1336mzz(Z) is considered as a very low GWP alternative fluid (2 kgCO_{2eq}/kg [148]).

Two scenarios are considered, including or excluding the imported emissions. When imported emissions are considered, all emissions across the life cycle are included. For the configuration without imported emissions, only emissions during operation are considered: CO₂ content of consumed electricity and refrigerant direct emission for MHP, and natural gas combustion for the reference boiler. These choices were made based on heat pump process from the Ecoinvent life cycle inventory database [88]. The electricity carbon intensity values were extrapolated from the expected sources of electricity [147] and the current value of the GHG intensity of each generation source for all countries studied from Ecoinvent database [88].

¹ Note that this fluid is different from the one used in the rest of the thesis (II.4.2.3) because the paper [145] was written at the beginning of the thesis

Table 25 - Carbon footprint data

Parameters	Impact value	Units	Ref.
Heat pump production and disposal, $i_{CC,MHP}$	14.6	kgCO _{2eq} /kW _{el} ^a	[88]
Electricity 2018, $i_{CC,el}$	varies by country ^b	kgCO _{2eq} /kWh _{el}	[147]
Electricity 2030 to 2050, $i_{CC,el}$	varies by country ^c	kgCO _{2eq} /kWh _{el}	[35]
Heat from gas life cycle, $i_{CC,ng}$	247	kgCO _{2eq} /kWh	[88]
Including operation	213	kgCO _{2eq} /kWh	[88]
R134a life cycle, $i_{CC,wf}$	2361	kgCO _{2eq} /kg	[88]
Including operation stage	1300	kgCO _{2eq} /kg	[148]
Including end of life	776	kgCO _{2eq} /kg	[88]
R1336mzz(Z) life cycle, $i_{CC,wf}$	12.1	kgCO _{2eq} /kg	[88]
Including operation stage	2	kgCO _{2eq} /kg	[148]
Including end of life	1.4	kgCO _{2eq} /kg	[88]
Operation hours, h	8000	Hours	[149]
MHP Lifetime, LT	20	years	[150]
Refrigerant load by power unit	2	kg/kW	[129]
Annual leakage rate, La	5 %	-	[129]
End of life leakage rate, Le	15 %	-	[53]

^a Impact intensity for the heat pump does not consider the operation stage since it is already considered with electricity consumption entries

^b Ranging from 9 to 922 kgCO_{2eq}/kWh for 24 EU countries

^c Ranging from 21 gCO₂/kWh (Luxembourg) to 663 gCO₂/kWh (Poland) in 2030 and from 7 gCO₂/kWh (Portugal) to 191 gCO₂/kWh (Belgium) in 2050

III.1.1.2 Threshold of the maximum *climate change* impact of electricity versus COP

The long-term viability of MHP's *climate change* impact is a major issue to be addressed. Indeed, because of its lifespan of approximately 25 years, the installed MHP should be able to comply with EU GHG reduction targets for both 2030 and 2050. The blue and red curves of Fig. 35 show the maximum *climate change* impact of electricity enabling alignment with the European targets of 2030 and 2050 as a function of the MHP COP. The blue and red areas capture the range of carbon footprints of the electricity grid mix of all considered EU countries for 2030 (21-663 gCO_{2eq}/kWh and 17-704 gCO_{2eq}/kWh without and with imported emissions, respectively) and 2050 (7-191 gCO_{2eq}/kWh and 26-263 gCO_{2eq}/kWh without and with imported emissions, respectively). Fig. 35a and Fig. 35b present the result without and with imported emissions respectively.

As the European GHG emission reduction targets for 2030 and 2050 do not include imported emissions, it is fair to compare this target with the configuration without imported emissions. It can be observed from the comparison between Fig. 35a and Fig. 35b that GHG emissions of the electricity are mainly territorially-based: imported emissions only play a secondary role without being fully negligible in the total carbon footprint. The maximum carbon footprint of electricity is only 11 to 14 % higher when considering imported emissions. It is worth noting that the excluded *climate change* impacts of non-territorial emissions (associated with, e.g., manufacturing of wind turbines components, photovoltaics, MHP outside Europe) does not necessarily favour electricity generation because the benefice for electricity is partially, if not totally, offset by the fact that no account is taken of the transport and extraction of the gas itself. In other words, by evaluating the two generation technologies using the same methodology, the benefits of electrification are broadly similar to those of gas, with or without taking imported emissions into account. In the following, results are presented only without imported emissions

in order to be in line with the European approach, but it is important to remember that these emissions must also be considered in a comprehensive environmental assessment.

Fig. 35 shows that - depending on the COP - large portions of the blue and red areas stand above the blue and red curves, which means that not all EU countries can meet the Paris Agreement targets, as it will be further detailed. The maximum allowable values of the carbon footprint of electricity depends on the type of working fluid used in MHP and its share on overall GHG impact. R1336mzz(Z) has a lower GWP than R134a (2 kgCO_{2e}q/kg for R1336mzz(Z) compared to 1300 kgCO_{2e}q/kg for R134a); therefore, the contribution compared to the maximal acceptable carbon footprint target for R1336mzz(Z) - which is in the range 0.3 - 0.7 ‰ in 2030 and 1.4 - 5 ‰ in 2050 - is much lower than R134a. Indeed, for R134a, the refrigerant has a share between 17 % and 33 % in 2030 and 48 % and 77 % in 2050. As a result, for R1336mzz(Z), overall emissions are mostly driven by energy which explains the difference of slope with R134a, especially in 2050, when the carbon contain of electricity is supposed to have been significantly reduced.

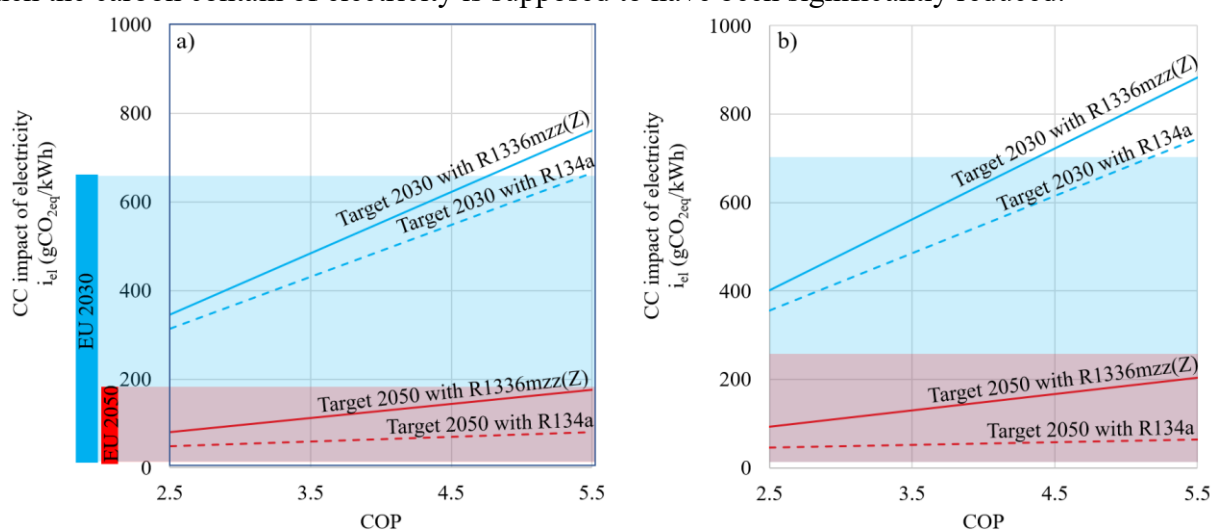


Fig. 35 - Maximum impact of electricity to achieve the GHG reduction targets of 35 % in 2030 and 85 % in 2050, a) without imported emissions b) with imported emissions.

Based on the carbon footprint thresholds (blue and red curves in Fig. 35), a classification can be done for the different European countries, depending on the carbon footprint of their electricity grid mix in 2030 and 2050 (Table 26):

- Those with a low electricity carbon intensity are compliant with the European targets for any of the process with a COP greater than 2.5 (blue-marked cells in Table 26). This, for example corresponds to 22 EU countries in 2030 and 16 EU in 2050 in the configuration with a low GWP refrigerant (e.g., R1336mzz(Z)).
- Those with a medium electricity carbon intensity allowing the solution to be compliant with the European targets for some of the process studied, with a limit COP varying between 2.5 and 5.5 depending on the country (yellow-marked cells in Table 26); This corresponds to 2 countries in 2030 and 7 in 2050 in the configuration with a low GWP refrigerant (e.g. R1336mzz(Z)).
- Those with a carbon intensity of electricity too high for any process with a COP below 5.5 to be compliant with the European targets (orange-marked cells in Table 26). No country is in this case in 2030 and only Belgium in 2050, when using a low GWP refrigerant (e.g., R1336mzz(Z)).

Table 26 - Impact intensity of electricity and analyses of the environmental requirements for EU countries without imported emissions in 2030 and 2050 for R134a and R1336mzz(Z)

	2030 icc,el (gCO _{2eq} /kWh)	2050 icc,el (gCO _{2eq} /kWh)	2030 R134a	2030 R1336mzz(Z)	2050 R134a	2050 R1336mzz(Z)
Austria	103	57				
Belgium	228	191				
Bulgaria	298	57				
Croatia	67	41				
Denmark	103	57				
Estonia	437	46				
Finland	99	68				
France	33	28				
Germany	283	80				
Greece	105	70				
Hungary	87	86				
Ireland	106	84				
Italy	197	96				
Latvia	144	39				
Lithuania	59	27				
Luxembourg	21	17				
Netherlands	173	106				
Poland	663	155				
Portugal	29	7				
Romania	166	64				
Slovakia	83	44				
Slovenia	209	150				
Spain	42	24				
Sweden	31	22				

III.1.1.3 Analysis of results for a few industrial applications

Another way of presenting these results is to determine the minimum COP value for the process to be compatible with the GHG reduction targets and to compare this value to the COP required by different industrial processes with the current MHP technologies. As explained in chapter I, available data on temperature requirements in industrial processes are scarce. For the present work, values given by Cudok et al. [151] are considered (Table 27). The COP are calculated following the methodology developed in section II.2.2.1 and presented in Table 27 in relation to the temperature level of the process.

Table 27 - Process temperature levels used in this study based on [151]

	Food industry	Alcohol production	Polycrystalline silicon	Poly film manufacturing	Ammonia production	Chemical industry
T _{up} [°C]	144.5	158	144	157	125	125
ΔT [°C]	48.4	38	39	49	28	44
COP	3.6	4.6	4.4	3.7	5.7	3.8

Fig. 36 presents the minimum COP to reach the environmental target for both refrigerants and each European country in 2030 and 2050. The orange shaded area is for the range of COP presented previously in Table 27. For most countries, all processes are compatible with the

reduction targets in 2030 regardless of the COP or the nature of the refrigerant (Fig. 36a). Poland energy mix, with a projected electricity carbon intensity above 400 gCO₂/kWh, is only compatible for COP above 5.5 for R134a and 4.8 for R1336mzz(Z). The influence of the refrigerant is low in 2030, as it is shown in the figure with a limited difference between the two configurations, because the carbon content of electricity is the main contributor. Therefore, it is possible to meet the targets even with high GWP refrigerants. Fourteen countries are still compatible even with a COP of 1, which means than any process using electricity can meet the target (including electricity boilers). In contrast, in 2050, a larger influence is observed. Fig. 36b shows that 7 of the 24 studied countries cannot meet GHG reduction target with a fluid like R134a regardless of the COP that can be achieved, and 3 more can achieved the target only for a few processes. With low GWP refrigerants, all EU countries, except Belgium, can consider the integration of MHP to achieve the EU targets. For Belgium, the impact of electricity is too high to reach the target even with a low GWP refrigerant. Among the other countries, 2 of them (Poland and Slovenia) do not achieve the targets for all processes with the integration of MHP, so case-by-case studies need to be carried out to assess their suitability. As a conclusion, the MHPs need to continue its transformation toward a low-GWP working fluid to be relevant in the future. Switching from a refrigerant with a GWP over 1000 kgCO₂eq/kg to a refrigerant with a low GWP, around 2 kgCO₂eq/kg in this example, significantly increases the number of processes that can comply with the decarbonisation pathway.

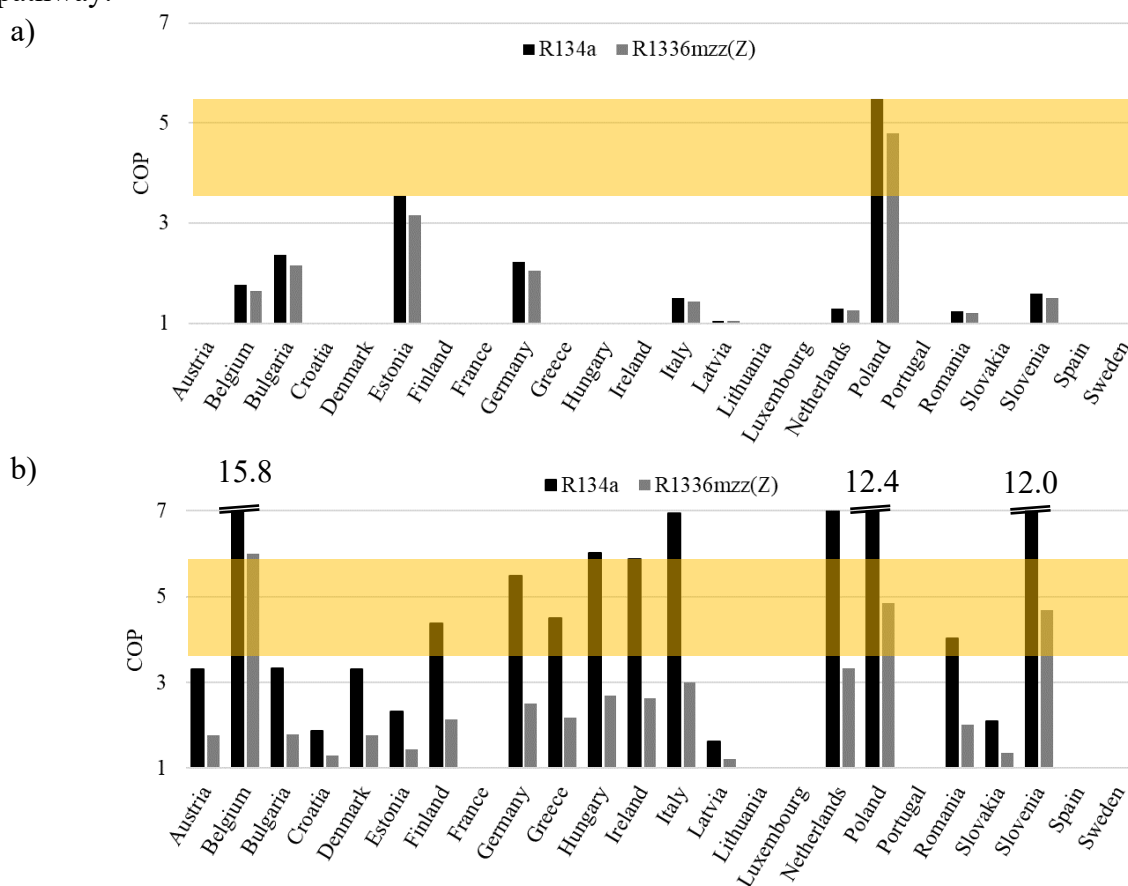


Fig. 36 – Minimum COP in a) 2030 and b) 2050 to comply with the 2-degree target of the Paris Agreement for each EU members (without imported GHG emissions) based on reduction objective for each country. Projected electricity grid mix compositions stem from ref. [35]. COP display is limited to values between 1 and 7. The COP range considered for the 6 case studies are presented in the orange-shaded area.

III.1.2 Economic assessment of MHP-based solutions

III.1.2.1 Minimum gas cost to make MHP competitive

Decarbonisation is a major challenge for the transformation of the industrial energy system, but change remains limited by the economic efficiency requirements of industries and, in particular, by the low payback time, as indicated in section II.5. For the economy, an approach somewhat similar to that of the environmental model is adopted. We investigate what must be the minimum cost of gas for a solution based on MHP waste heat recovery to be economically viable.

The economic criteria used for this study is the payback period (PBP) described in equation III-7. The flexibility requirements of industrial production sites make investments over long periods more complex. The choice to focus on the payback time rather than the total cost of heat production is intended to address the potential lack of long-term visibility for the industries, with an objective of PBP below 5 years as described in section II-5.

$$\text{PBP} = \frac{\text{CAPEX}}{\text{savings}} \quad \text{III-7}$$

where the savings are the difference between the reference cost (natural gas in this example), with the cost of electricity and OPEX of the new installed configuration (MHP) as presented in equation III-8.

$$\text{PBP} = \frac{\text{CAPEX}}{E_{\text{in}} \cdot c_{\text{ng}} - \frac{E_{\text{in}}}{\text{COP}} \cdot c_{\text{el}} - \text{OPEX}} \quad \text{III-8}$$

By reformulating equation III-8 it is possible to find the minimum price of the natural gas $c_{\text{ng,min}}$ per unit of energy required for MHP to have a PBP below a given value as a function of electricity price (equation III-9). The price of energy for all the countries are taken from Eurostat data for costs with non-recoverable taxes for the second half of 2020 [152], [153]. The other data used are presented in Table 28.

$$c_{\text{ng,min}} = \frac{c_{\text{el}}}{\text{COP}} + \frac{\frac{\text{CAPEX}_{\text{MHP}}}{\text{PBP}} + \text{OPEX}_{\text{MHP}}}{E_{\text{in}}} \quad \text{III-9}$$

Table 28 - Economic parameters for MHP

Parameters		Ref.
CAPEX by power unit	0.7 M€/MWth	[154]
Annual fix OPEX by power unit	3 k€/MWth	[155]
Annual variable OPEX by energy unit	1.8 €/MWth	[155]
Return time	5 years	[130] [131]

III.1.2.2 Economic viability with current energy prices

The minimum gas prices required for MHP to be competitive with gas boiler are plotted in Fig. 37 versus electricity price and as a function of COP. Furthermore, the energy prices in 2019 of

different EU-countries [152], [153] are reported as well to identify for which of them competitiveness is already achieved (i.e. country mark above the considered curve) .

The results highlight the low economic competitiveness of MHP compared to heat produced with a gas boiler in most of the European countries, with the current prices of gas and electricity. Even with a COP as high as 5.5, only Denmark, Finland, France, Serbia and Sweden have an energy price that could make the MHP solution competitive with gas.

Ratios of gas over electricity prices, which should not be exceeded to maintain competitiveness, are not linear. As the initial investment is not linked to the performance of the system, the share of electricity in the MHP economic balance decreases from a range of 85 - 95 % for a COP of 2.5 to a range of 67 - 86 % for a COP of 5.5, depending on electricity price (from 60 to 180 €/MWh). This implies that the lower the temperature between the process requirement and the waste heat temperature, the more important are the investment costs in the economic balance. In addition, the investment share of MHP becomes less important as energy prices are higher. Hence, heat pumps are more easily competitive with a high energy price. For example, with a gas to electricity price ratio of 0.36 and an electricity price of 70 €/MWh (represented by a black square in Fig. 37) the integration of MHP is not compatible with the economic objectives even for a COP of 5.5. However, for the same ratio of 0.36 with an electricity price of 140 €/MWh (represented by a black circle in Fig. 37), the integration of MHP becomes economically compatible for a COP higher than 4. This can be explained by the high CAPEX of a typical MHP solution, which represents a smaller share of the total cost when energy price is high. These trends suggest that a wide deployment of MHP technologies at EU scale is not attractive under current conditions.

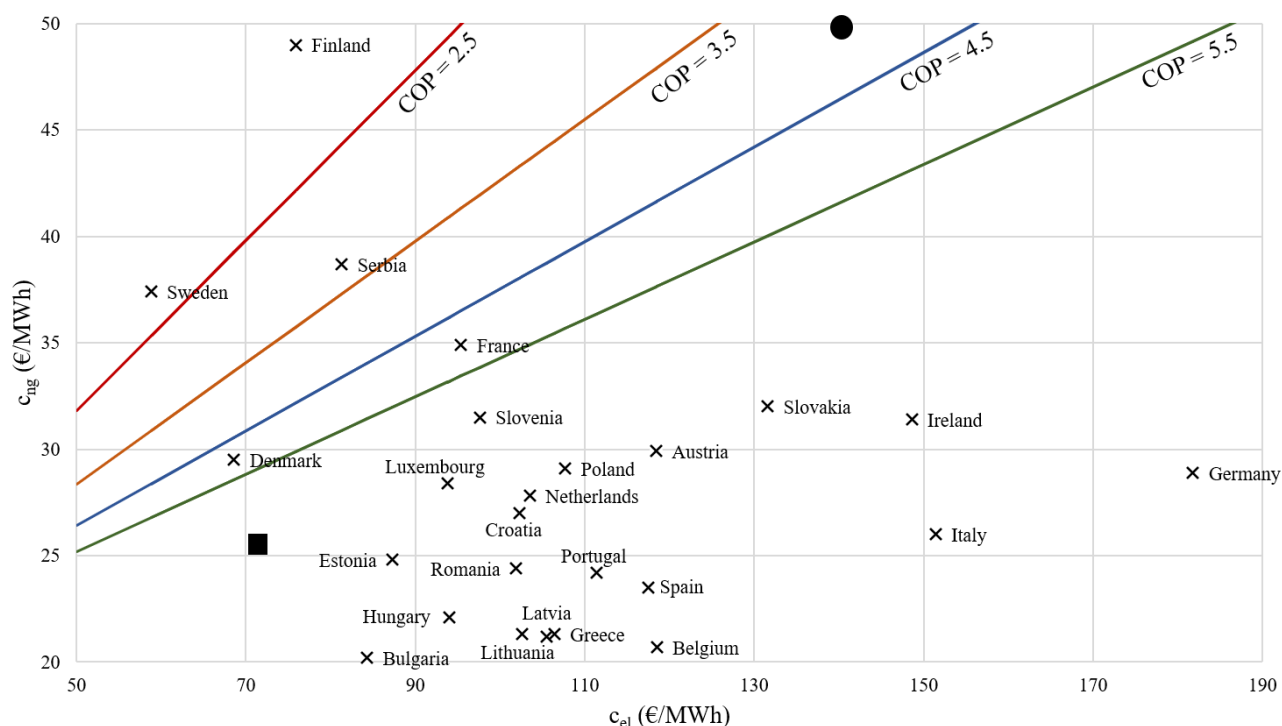


Fig. 37 - Positioning of European countries according to the gas price limits ($c_{ng,min}$) allowing the economic profitability for current COP range of MHPs. Coloured lines indicate the minimum gas cost ($c_{ng,min}$) that makes MHP cost-effective for a given COP. Cyprus, Malta, Czech Republic missing on the graph due to lack of economic data.

III.1.2.3 Influence of carbon tax and grid mix composition

To simulate a change in electricity and gas prices in the future, the impact of the evolution of the carbon tax and that of the electricity grid mix carbon footprint have been quantified, taking representative countries with contrasting characteristics. Four EU members are thus considered, namely Belgium (low gas price and average electricity price), Denmark (low electricity price and average gas price), France (high gas price and average electricity price), and Germany (high electricity price and average gas price). The evolution of the carbon footprint of electricity was taken from the European commission scenario [35]. Two cases were considered for the evolution of the carbon tax with a first scenario, termed “reference scenario”, based on the EU Reference Scenario 2016 (i.e. tax of 25 €/tCO_{2eq} in 2030, 50 €/tCO_{2eq} in 2040 and 85 €/tCO_{2eq} in 2050; see Fig. 38a) and a more constraining scenario, termed “constrained scenario” with a tax of 50 €/tCO_{2eq} in 2030, 100 €/tCO_{2eq} in 2040 and 200 €/tCO_{2eq} in 2050 (Fig. 38b) [150].

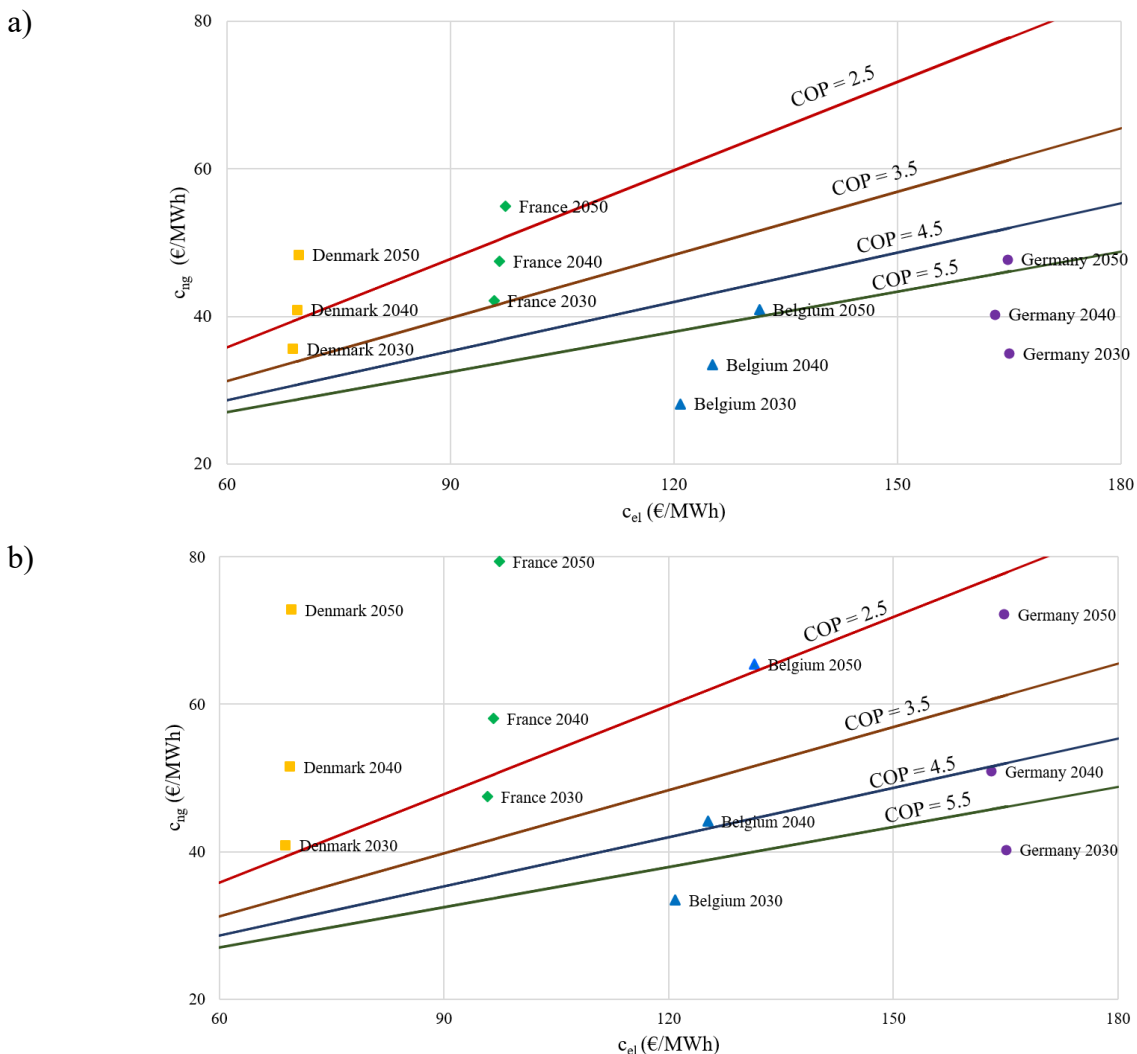


Fig. 38 - Projection of the evolution of energy cost and compatibility with natural gas price limit ($c_{ng,min}$) for current COP range of MHP a) Reference scenario b) Optimistic scenario

Results presented in Fig. 38a show that for the reference scenario, France and Denmark can achieve profitability between 2030 and 2040 for most MHP industrial integration (where COP are typically all above 2.5). Germany and Belgium, in contrast, are not found to meet the same cost efficiency, even by 2050. For the second scenario presented in Fig. 38b, France and Denmark can

expect profitability before 2030 for most processes, Belgium between 2040 and 2050 and Germany after 2050. Because the competitiveness of MHP solutions depends on the gas to electricity price ratio, the carbon tax can play a major role to MHP development by making them more cost-effective than gas solutions. This tax results in a change in the ratio gas to electricity price from 0.44 to 0.52, 0.59 and 0.69 in Denmark, from 0.39 to 0.44, 0.49 and 0.56 in France, from 0.20 to 0.23, 0.27 and 0.31 in Belgium, from 0.19 to 0.21, 0.25 and 0.29 in Germany for years 2030, 2040 and 2050 respectively compared to the 2019 price ratio. This financial mechanism is less effective in countries with a high carbon footprint of electricity, while the ratio is increased by 56 % by 2050 for Denmark, it is increased by only 23 % for Germany. This could stimulate spontaneous uptake of the technology within industries, which could then anticipate GHG reduction regulatory requirements to enter into force by 2050.

III.1.3 Bridging the energy, environmental and economic constraints

Table 29 and Table 30 show - for the 6 industrial processes studied, presented previously in Table 27: food industry, alcohol production, polycrystalline silicon, poly film manufacturing, ammonia production, chemical industry - in which countries MHP-based technologies enable to reach the climate change and economic objectives in 2030 and 2050. The environmental performance is the main limiting factor for 3 countries namely Belgium, Poland, and Slovenia (brown-marked cells in the tables). However, for most countries, unmet conditions are mainly economic, suggesting that economic constraints tend to be a major barrier for the deployment of the MHP technologies in 2030 and that all the studied countries except Poland are able to meet the targets for climate change impact. In contrast, in 2050, the profitability of MHP is no longer an obstacle except for Germany and Italy (only for a COP of 3.6) despite the carbon tax on CO₂. These results show that the development of MHP in the short term can be accelerated by the development of stronger policies on the carbon tax.

There is a great disparity between the considered EU countries. Only 13 out of 24 countries comply with both 2030 and 2050 targets for most industrial processes, i.e. temperature lift resulting on a COP greater than 2.5. Belgium, Poland, and Slovenia are the only country studied for which MHP solution will become cost-effective while the GHG reduction target is not met. For these three countries, although economically viable, the MHP solution will not meet the long-term objectives and is likely to require a change in technology with very low electricity consumption (e.g. absorption heat transformer, more information on heat transformer can be found in [46]) in order to address new regulation with a high carbon footprint intensity of electricity. In this case, MHP can then be used as a temporary solution to reach the 2030 targets before a more efficient technology is available. For all others studied country, MHP are interesting to implement as soon as they become economically viable because they can already meet the GHG reduction targets.

Table 29 - Environmental and economic compliance of different processes for European countries in 2030. The study is carried out with the refrigerant R1336mzz(Z), with a carbon tax following the EU Reference Scenario 2016.

■ Conditions met for MHP development ■ Conditions not met for MHP development												
2030 projection	Food industry		Alcohol production		Polycrystalline silicon furnaise		Poly film manufacturing		Ammonia production		Chemical industry	
COP	3.6		4.6		4.4		3.7		5.7		3.8	
	Envi. compl.	Eco. compl.	Envi. compl.	Eco. compl.	Envi. compl.	Eco. compl.	Envi. compl.	Eco. compl.	Envi. compl.	Eco. compl.	Envi. compl.	Eco. compl.
Austria												
Belgium												
Bulgaria												
Croatia												
Denmark												
Estonia												
Finland												
France												
Germany												
Greece												
Hungary												
Ireland												
Italy												
Latvia												
Lithuania												
Luxembourg												
Netherlands												
Poland												
Portugal												
Romania												
Slovakia												
Slovenia												
Spain												
Sweden												

As far as the studied processes are concerned, there are also large differences across industries in 2030. The most favourable industrial processes for MHP integration based on Table 29 and Table 30 - i.e. for which the MHP can achieved a high COP due to the low temperature lift such as Ammonia production - have great potential in all countries. These industries are more favourable from both an economic and environmental perspectives. In contrast, for less favourable processes such as food industry or poly film manufacturing, both economic and GHG constraints are more demanding. It is therefore likely that MHP will not be installed spontaneously by these industries in the short term. Despite these economic constraints, the MHP solution is very promising from a carbon footprint point of view to decarbonise the industrial energy sector for low temperatures processes. This technology will be further assessed to evaluate the impact on others impact categories in chapter V.

Table 30 - Environmental and economic compliance of different processes for European countries in 2050. The study is carried out with the refrigerant R1336mzz(Z).

■ Conditions met for MHP development ■ Conditions not met for MHP development												
2050 projection	Food industry		Alcohol production		Polycrystalline silicon furnaise		Poly film manufacturing		Ammonia production		Chemical industry	
COP	3.6		4.6		4.4		3.7		5.7		3.8	
	Envi. compl.	Eco. compl.	Envi. compl.	Eco. compl.	Envi. compl.	Eco. compl.	Envi. compl.	Eco. compl.	Envi. compl.	Eco. compl.	Envi. compl.	Eco. compl.
Austria												
Belgium												
Bulgaria												
Croatia												
Denmark												
Estonia												
Finland												
France												
Germany												
Greece												
Hungary												
Ireland												
Italy												
Latvia												
Lithuania												
Luxembourg												
Netherlands												
Poland												
Portugal												
Romania												
Slovakia												
Slovenia												
Spain												
Sweden												

III.2 Environmental assessment of electrification of food industry

The analysis of section III.1 shows that meeting GHG emission reduction targets is possible in most European countries with electrification of the heat production using a MHP. However, as it was mentioned in chapter I, climate change is not the only boundary limit faced by planet earth due to human activities and it is therefore necessary to assess the full environmental impact of electrification.

III.2.1 Presentation of electrification scenarios for Denmark and France

In this section, we propose to carry out this complete environmental analysis to the electrification of the agri-food sector in France and Denmark. This study compares the impact of 3 development scenarios:

- Buisness as usual (BAU), which represents the current state of industrial heat production.
- Low development of electrification (Lo), which represents electrification for all compatible processes.
- High development of electrification (Hi), which represents electrification for all compatible processes with the strong assumption that MHP will be developed to reach temperatures of 300 °C.

The Lo and Hi scenarios represent configurations of complete electrification of the sector to assess their maximum potential for decarbonising the industry. These scenarios are based on energy consumption per energy source, temperature level and type of process of the Danish food industry. The data of industrial heat demand (E_{out}) are from the Danish Energy Agency (Energistyrelsen) [156]; more information about temperature level can be found in Appendix 2. To assess the environmental impacts, this demand needs to be converted in final energy consumption (E_{in}) using the efficiency ratio presented in equation II-1 in part II.2.2. The energy distribution of the Danish food industry is presented in Fig. 39. The main final energy consumption of the current food industry is gas followed by oil and coal. In the future, electricity can cover all the demand except for slaughterhouses and the share of MHP depends on the electrification scenario, for which electrification would only be possible with the development of MHP capable of targeting very high temperatures. The category "other food industry" includes all industries not covered by the other four categories and is the focus of this study because it is composed of a number of different processes to be representative of the average performance.

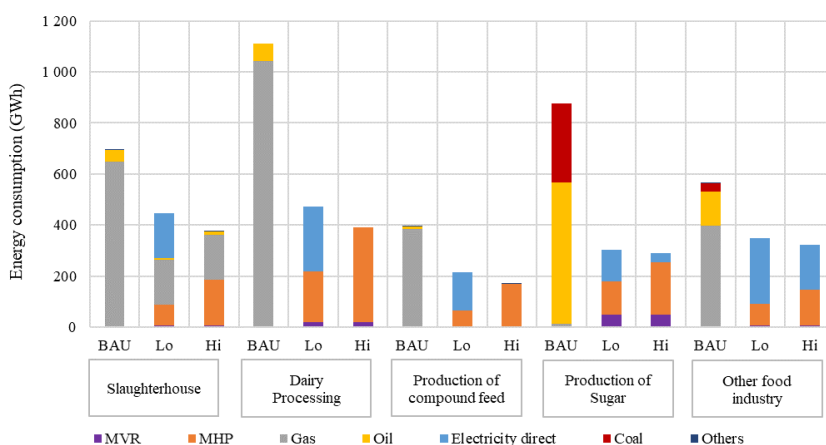


Fig. 39 - Danish processing food industry energy consumption by energy in 2019

The details of final energy demand by energy source of the French food industry, presented in Fig. 40, are taken from the French statistical office (INSEE) [157]. Due to lack of detailed data of the distribution between the different processes and their temperature within a sector for French industry, it is assumed to be the same as for the Danish industry. However, the type and quantities of energy are country specific.

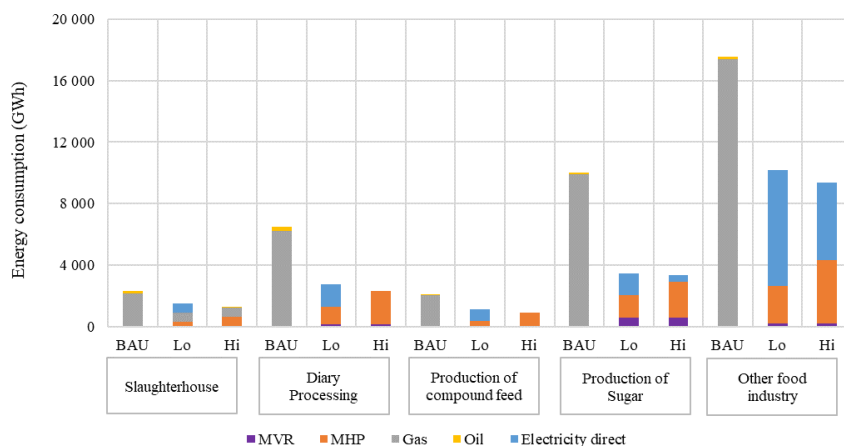


Fig. 40 - French processing food industry energy consumption by energy in 2019

The marginal electricity mix by 2050 for Denmark comes from Ecoinvent 3.7.1 database [88] as presented in Fig. 41. For the marginal electricity mix for France, we have chosen to consider the scenario N1 from the French Transmission System Operator (RTE) for which the allocation is presented in Fig. 41 [109], [158].

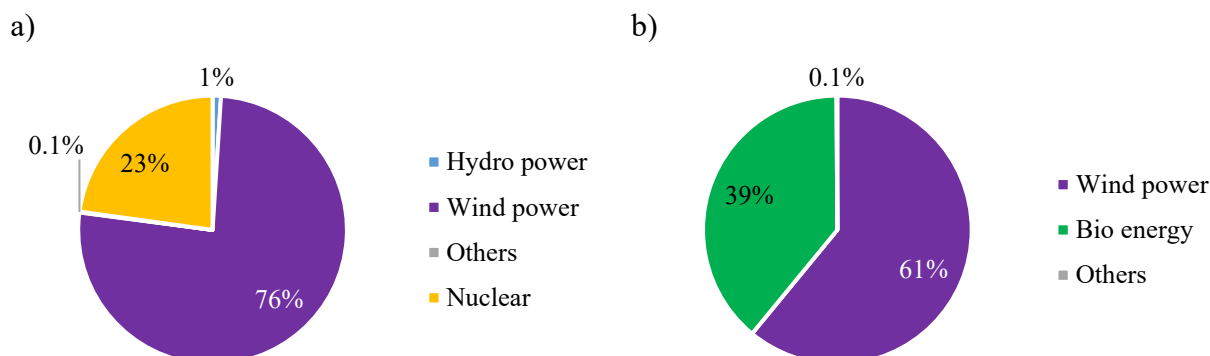


Fig. 41 - New electricity installed capacity by 2050, repartition for a) France based on scenario N1 from French TSO and b) Denmark based on data from Ecoinvent database

Note that in the proceedings of the ECOS 2022 congress [159], from which the results in this section are taken, we applied the reduction factors considering the current environmental impacts of the sector (i.e. $I_{BAU,y}$ in this example) to calculate the sustainable limit (SI). This type of method is often used in GHG reduction programs in industry. This method is slightly different from the one used in the rest of this thesis, where the reduction factor is applied to a sector according to its share in global economy rather than its current impact. We have chosen to keep the reference used in the proceedings of the ECOS 2022 congress in this section to show the consequences of this choice on the results, which are discussed in section III.2.3. Both methods are described in section II.6.3.2.

III.2.2 Detailed environmental assessment of Lo and Hi electrification scenarios

Fig. 42 shows the contribution of the chosen studied sector in relation to the impacts of all human activities for BAU, Lo and Hi scenarios. For example, for the *climate change* indicator, the current contribution of this sector for France is of the order of 0.02 % of global GHG emissions (Fig. 42a). On the same figure, the share of the process's added value in relation to global added value as presented in Chapter II (part II.6.3.2) is shown in blue and the sustainable limit in green.

As presented in logarithmic scale in Fig. 42a for France and Fig. 42b for Denmark, the two electrification scenarios can be compared to the sustainable level, and it can be observed that the *climate change* indicator is within the sustainable threshold for both countries, contrary to the BAU scenario. However, the reduction of the *climate change* indicator through electrification leads to the unsustainability of some other categories concerning human health, such as *human toxicity*, *non-cancer* or resource use such as *resource use*, *minerals and metals*. The assessment of these indicators shows that electrification reduces the impact of 7 indicators for France and 8 for Denmark, going beyond the sustainable threshold for the indicators *climate change* and *resource use*, *fossils* for Denmark. On the other hand, 9 impact categories show higher impacts for France and 8 for Denmark. Of these, two impact categories pertaining to chemicals toxicity impacting human health and ecosystems become unsustainable as well as the *water use* indicator for Denmark.

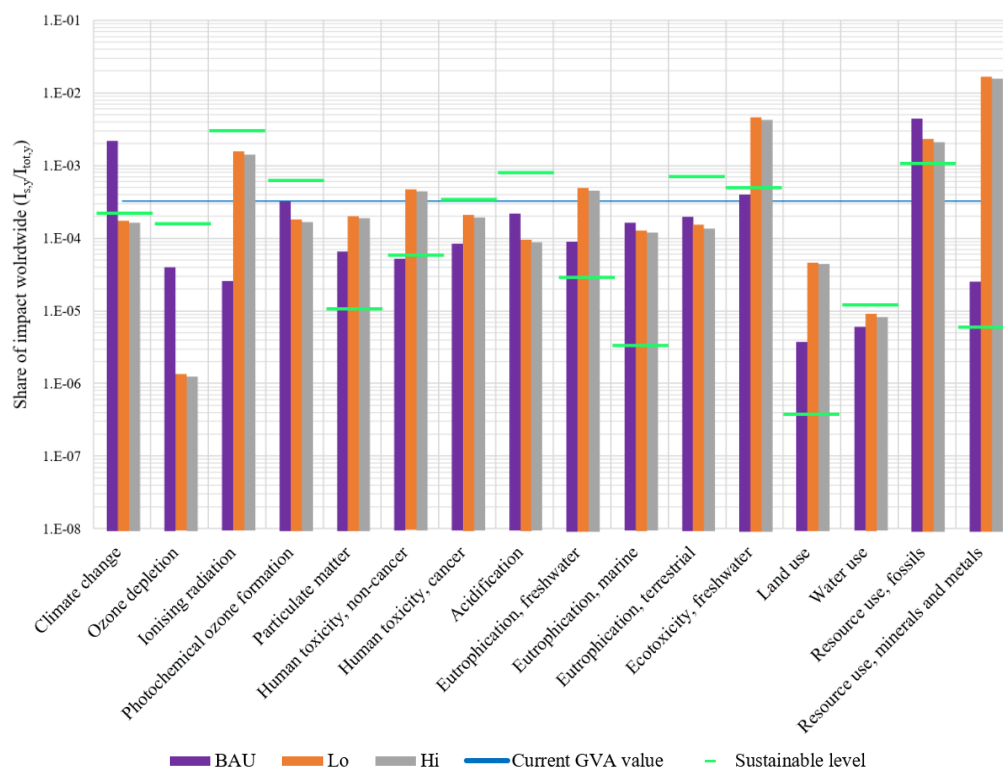


Fig. 42a - Results of the different impact categories for the other food industry scenarios for France using logarithmic scale. The level defined as sustainable is represented with a green line for each impact category; the current share of GVA of industrial sector ($\frac{EVA_{indu}}{EVA_{tot}}$) value is represented with the blue line.

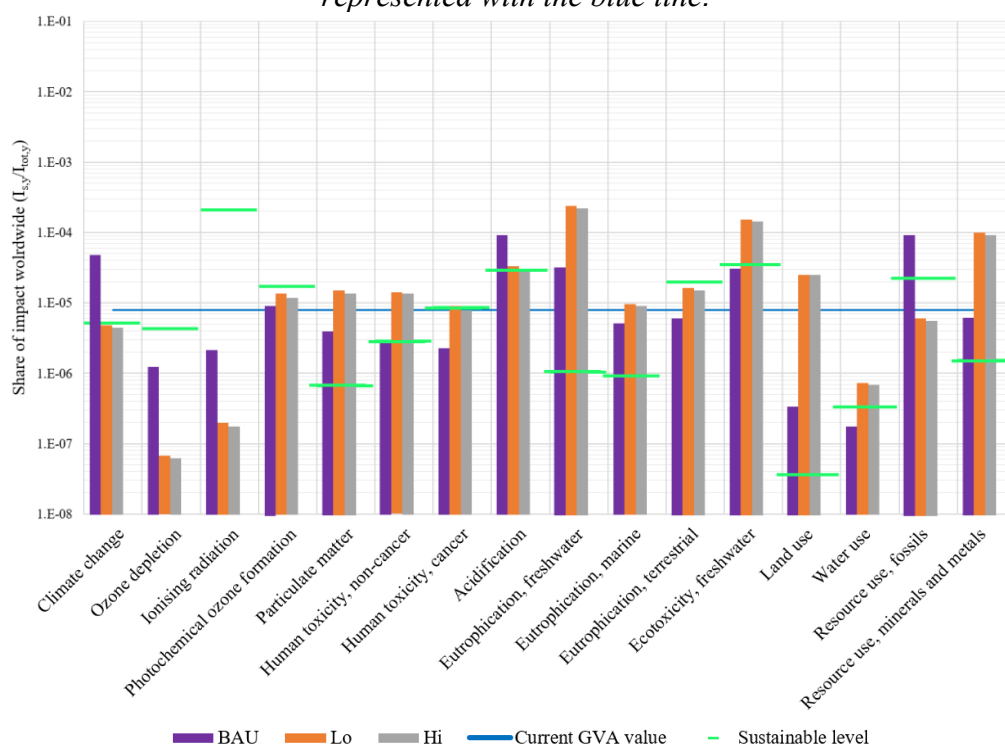


Fig. 42b - Results of the different impact categories for the other food industry scenarios for Denmark using logarithmic scale. The level defined as sustainable is represented with a green line for each impact category; the current share of GVA of industrial sector ($\frac{EVA_{indu}}{EVA_{tot}}$) value is represented with the blue line.

These main differences between France and Denmark stem from the electricity mix, due to the presence of nuclear power in France and biomass in Denmark. This leads to an unsustainable contribution of the *ionising radiation* impact, which is almost zero in Denmark, and of the *resource use, fossils* impact in France, while the Danish electricity mix achieves the targets. At the same time unsustainable contributions are more critical for Denmark than for France for the impact categories *land use* and *particulate matter*, which are characteristics of the use of biomass.

Fig. 43 presents the sustainable ratio (Sr) versus the contribution level (Cl), as defined in section II.6.3, for each environmental impact indicator, considering two electrification configurations, namely BAU and Lo in both France and Denmark. It can be noted that the differences between Lo and Hi scenarios are low for this industrial sector.

Four trends emerge from Fig. 43:

- (i) The low-left zone where the impacts are at (or have reached) a sustainable level and are associated with an impact share below the GVA share of the sector, e.g. *ozone depletion*. The impact categories in this zone are sustainable and the considered sector is not a major contributor for these impact categories in the global economy; it is therefore of lesser importance. Even if this sector grows in the global economy, it is not expected to have a major significance on this impact category.
- (ii) The bottom-right zone where the impacts are at (or have reached) a sustainable level and are associated with an impact share greater than the GVA share of the sector. Even if these categories are sustainable, their relative importance in the global economy suggests considering them. While no impact category is present in this zone for France, some can be found for Denmark because food sector represents a larger share of GVA.
- (iii) The upper left-hand area is for impacts that are unsustainable, but where the impact share is lower than the economic share of the sector. While this impact must be considered, any change (growth or decline) in this economic sector is not expected to lead to a major change in the compliance with global sustainability thresholds for this environmental impact. Water use for both country and land use for France are in this configuration.
- (iv) The impact categories on the top-right have an unsustainable level and a share of impact higher than the economic share of the sector. Categories such as *resource use, minerals and metals* are the most critical as they are not sustainable, while the sector in question is proportionally very impactful. For Denmark, *land use* is also in this case due to the high share of biomass in the electricity mix.

Based on these four trends, it is possible to identify the impact categories for which the process will have the greatest influence, i.e., the categories that need to be improved as a priority in order to reduce environmental impact. In this respect, cases (ii) and (iii) have a level of priority that we consider to be similar. This similarity is considered in the classification methods developed in chapter V to identify the criticality of a process for each impact category and therefore to weight the different impact categories in order to assess the ability of a solution to reach sustainable limits.

Fig. 44 highlights - for the case of Denmark - the evolution of the environmental indicators when switching from the BAU configuration to the Lo scenario. Electrification does not lead to a general improvement in environmental impact categories, but to a shift in impacts from one category to another: some impact indicators decrease (Fig. 44a) while others increase (Fig. 44b). One of the main conclusions reached here is that electrification helps to meet the objective of reducing GHG emissions, but there is very little margin after electrification for the indicator *climate change*,

despite decarbonised electricity mix (Fig. 41). This is due to the fact that it is not possible to use a heat pump for all processes, which are then electrified using an electric boiler. However, as we saw in part III.1, a minimum COP is necessary to meet decarbonisation objectives. There are 3 other impact categories that are improved by electrification, i.e. *resource use, fossils, ozone depletion* and *ionising radiation*. In parallel, all 12 other impact categories are increasing, some very significantly, e.g. *land use, resources, minerals and metals*. The electrification of the processing food industry will therefore result in a large number of environmental trade-offs if the threshold for the *climate change* indicator is to be met. The conclusions are similar for the French case, with important variations for *ionising radiation* or *resource use, minerals and metals*.

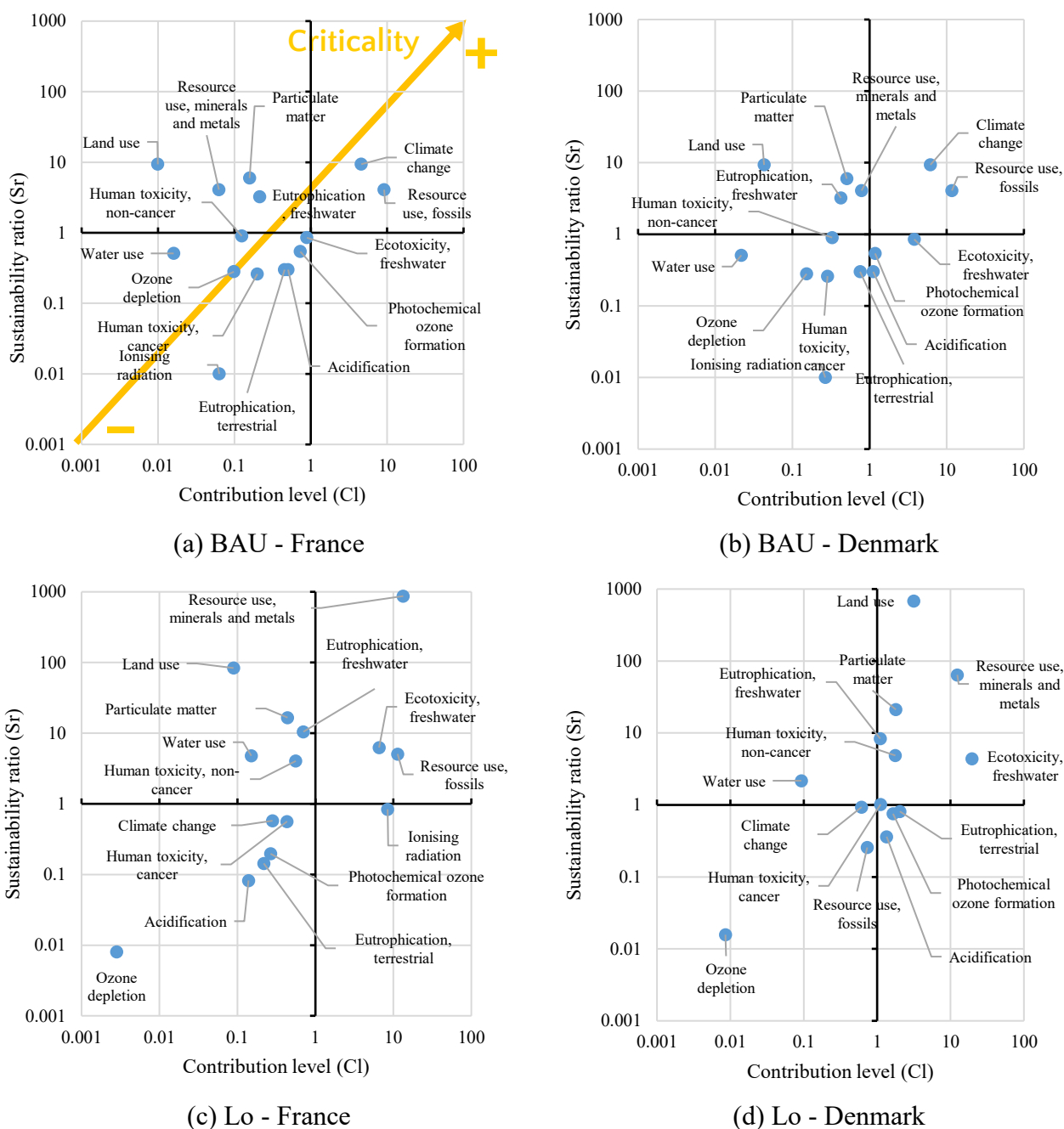


Fig. 43 - Sustainable ratio versus contribution level for each impact category for the sector other food industry and scenarios (a) BAU–France, (b) BAU–Denmark, (c) Lo–France, (d) Lo–Denmark

When comparing the electricity mix of both countries, the French electricity mix is better than the Danish one for some indicators such as *land use* with a factor 8 or *photochemical ozone formation* with a factor 4. On the other hand, Danish electricity mix is better than French one for *ionising radiation* with a factor 1500, *resource use, fossils* with a factor 19 or *resource use, minerals and metals* with a factor 13. We can see two trends emerging here, depending on how the electricity is produced. Biomass enables to limit the consumption of fossil and mineral resources, but this leads to an increase in the consumption of space and particle emissions.

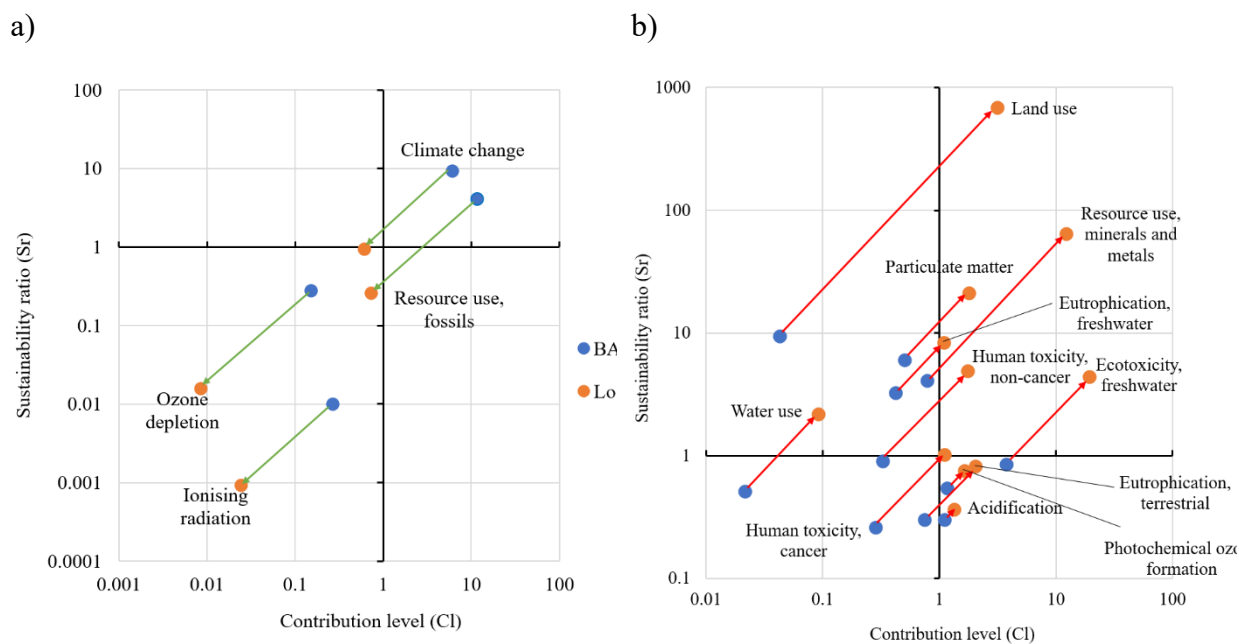


Fig. 44 - Impact categories evolution after electrification between BAU (blue dot) and Lo (orange dot) for Denmark. a) improving impact categories and b) deteriorating impact categories

This full environmental approach confirms and goes beyond the results of part III.1. Electrification of the food processing industry can help meet GHG emission reduction targets, by using MHP only when the process conditions enable it. However, electrification implies a massive increase in certain impact categories depending on the type of electricity used. It is worth mentioning that the results obtained here are due to the fact that the electrification scenarios are compared with a current solution that uses gas as the main energy source. However, gas is the best performing energy source on many indicators, e.g., *land use*, *particulate matter* or *resource use, minerals and metals*, and it is therefore not possible to find alternative solutions competitive with gas on these indicators.

III.2.3 Choosing the reference for defining sustainable levels

In the example presented in section III.2, the sustainable level is calculated by applying the same reduction factor to each human activity considering current level of emissions. This reference penalises the most virtuous sectors and consequently favours the least virtuous ones, since it requires each sector to make the same relative reduction effort for each environmental impact. To avoid this pitfall, we prefer instead to define a sustainability threshold based on the importance of the human activity under consideration in relation to all human activities. As explained in section II.6.3.2, the definition of the importance of a human activity itself is open to question as it may be

based on economic considerations, prioritising basic human needs, etc. In this thesis, we have chosen a simple approach, based on the economic importance of the human activity considered in relation to all human activities.

To assess the impact of this choice on the definition of the sustainable level, we present in Fig. 45 the sustainable thresholds identified for the two methods for the French case. The figure shows that the sustainable levels are different positively or negatively between all the impact categories. The threshold increases for most indicators except for *climate change* and *resource use, fossils*, which shows that the sector is currently heavily dependent on fossil fuels.

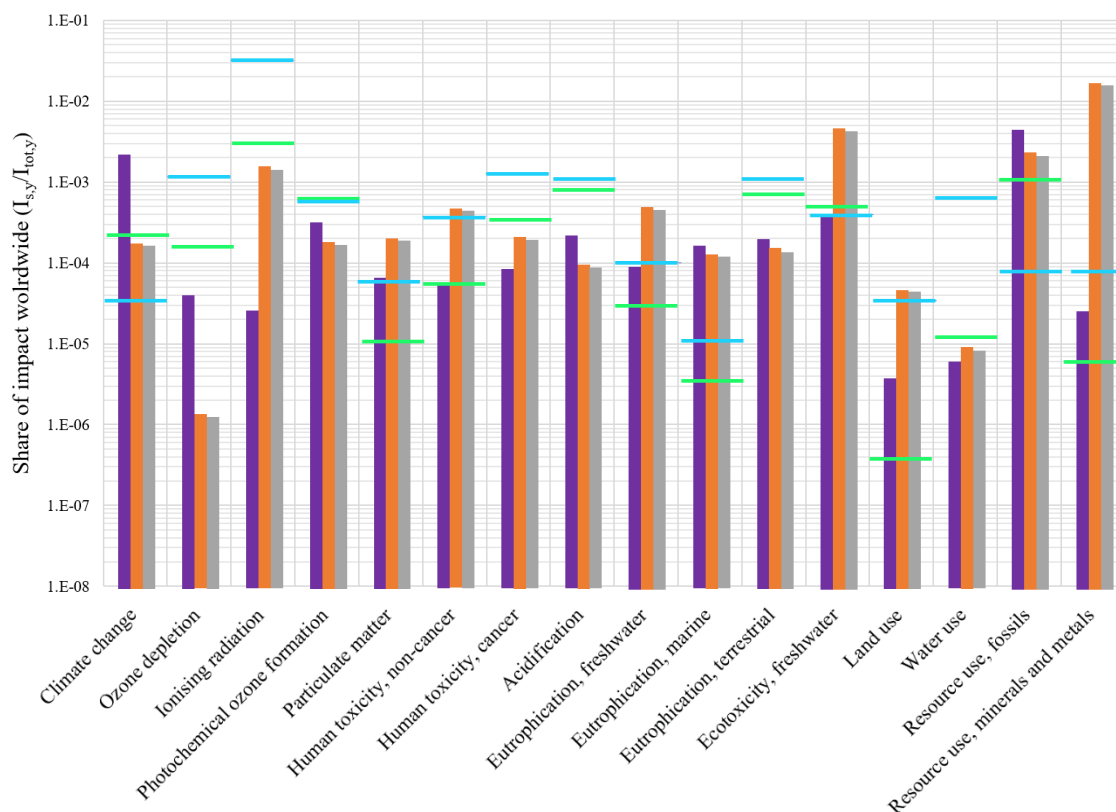


Fig. 45 - Results of the different impact categories for the other food industry scenarios for France using logarithmic scale. The process-based sustainable level is represented with a green line for each impact category when the global approach sustainable level is represented in light blue lines.

In terms of analysis, the conclusions remain similar for the two electrification scenarios, except for the *climate change* indicator, for which the sustainable level defined using the global method can no longer be respected for both electrification scenarios. This change is due to the share of impact of the process compared to the contribution worldwide which is 4.5 times greater than the share of process GVA compared to the GVA worldwide.

The choice of the share of environmental impact authorised for the considered sector may therefore have an impact on the interpretation of the results. For the rest of the study, the approach based on the economic importance of each sector is retained to spread the "right to impact" across all human activities, without penalising the sectors which are currently the most virtuous. However, as mentioned previously, further reflection on these choices could provide an interesting and fundamental perspective to this work.

III.3 Conclusions

This study shows that electrification can be an answer to meet sustainable limit to GHG, but with some economic and technological constraints. To achieve the decarbonisation objectives, it has been shown that there is a minimum COP below which electrification is not sufficient; this limit depends on the electricity mix and the type of process. Using this threshold, it is possible to ensure that the new heat production process enables sufficient decarbonisation in both the short and long terms, as the energy context is set to change rapidly over the next few decades, in parallel with increasing constraints on the reduction of GHG emissions.

This chapter also highlights the environmental trade-offs, which are the result of electrification strategies. Therefore, it is necessary to go beyond a simple carbon footprint analysis to consider all the environmental counterparts of a decarbonisation pathway. The proposed approach provides a framework for integrating sustainable environmental thresholds into the assessment of the transformation of an energy system such as 4E studies.

It has also been shown that it is preferable to start from global emissions and use a downscaling factor to assess the sustainable level. The rest of this work will be based on the principle of economic downscaling, which has the advantage of defining the "right to impact" of each process. This method obviously has its limitations, as it assesses the value of processes rather than their usefulness. But as the notion of utility is very complex to define, it is decided to retain a simpler and more consensual approach.

Defining this sustainable level provides a framework for analysis that is independent of the type of energy selected. Any configuration can therefore be studied, and an optimisation method based on the same criteria can be implemented. As a result, it is possible to assess which production technologies would be most effective to limit overshoot of sustainable thresholds, including all environmental impacts and not only climate change. Chapter IV presents the optimisation method used to generate different solutions that meet industrial demand and offer the best performance in terms of environmental, energy and economic criteria.

Chapitre IV

IV. Optimisation model

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IV.1 Multi-objective optimisation model

IV.1.1 Optimisation framework

This section presents the multi-objective optimisation model developed to determine the best technological choices to produce industrial heat over one year, considering energy, economic and environmental objectives. Four heat production technologies are considered (MHP and, electric, gas and biomass boilers) as well as the possibility of storing heat.

The model aims at minimising the fitness function (equation II-17) developed in part II.6.2. The framework we have developed is iterative, based on an operation similar to that of genetics, i.e. the selection of genes according to their ability to survive natural selection (Fig. 46).

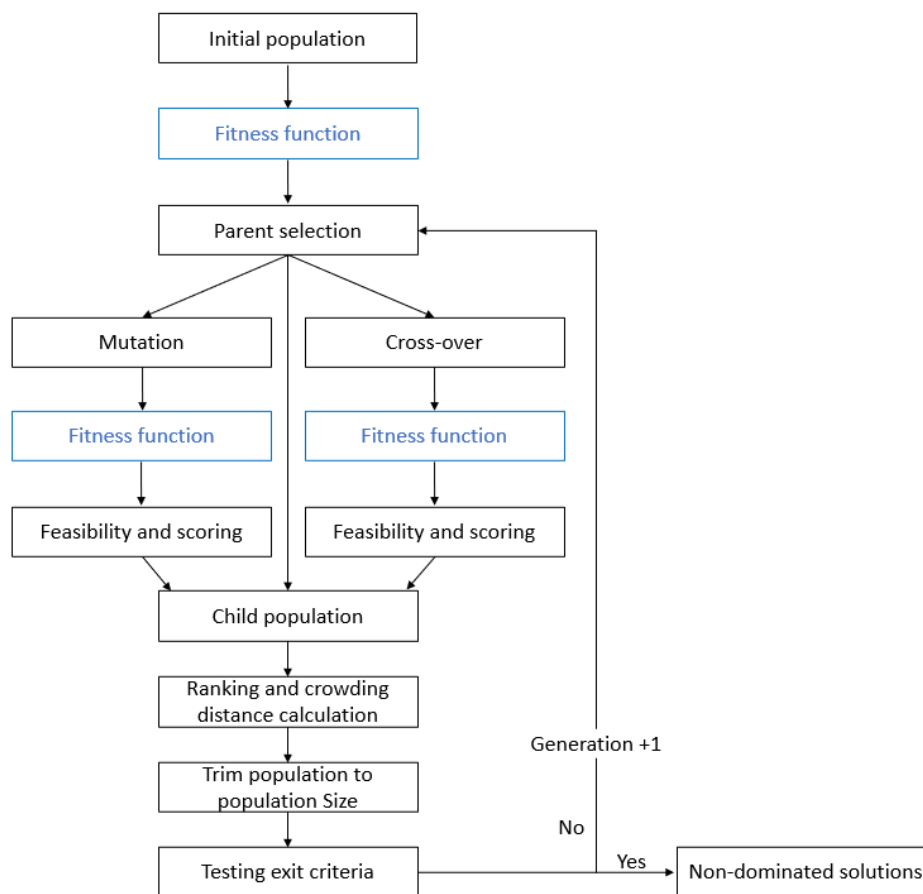


Fig. 46 - Optimisation method framework

The genetic algorithm is built from a population, which represents a set of different configurations - made up of a share of each of the heat production and storage modes considered - capable of meeting industrial heat demand over time. The size of this population is fixed to 100 different configurations in this work. This size is a parameter of the genetic algorithm, whose influence on the final results is studied in section IV.1.6.

Starting from an initial population - which must be wisely constructed so that the method converges rapidly to the final solution - a generation of parents gives birth to a new generation called children. This new generation is the result of a wise combination of the parents, enabling

to converge to the final solution, i.e. a group of heat production methods, varying hourly during one year and having impact outcomes that are non-dominated. The number of generations - which is also the total number of iterations - is another parameter of the model, whose influence on the final results is also studied in section IV.1.6. This section highlights the different elements of the iterative process.

IV.1.2 Resolution matrix definition

The fitness function is calculated from the resolution matrix, which is specific to each population. The principle of this matrix is presented in Fig. 47. It is broken down into a number of columns equal to the number of technologies studied, i.e. 5 columns: 4 for the production technologies ($\alpha_{x,j}$) and one for storage ($\gamma_{5,j}$) where x is the technology and j the considered time-step. In the first row, in blue in the figure, a binary variable 1 or 0, indicates the presence or absence of a technology over all time-steps. Each subsequent row, shown in green in the figure, corresponds to a time-step; for example, the value $\alpha_{1,1}$ of the matrix represents the first time-step for the first technology, i.e. electric boiler. The values for the first 4 columns are the average heat production power in MW over the time-step Δt , which is set at one hour in this work. The last column is the heat available in the storage tank in MWh at the end of the time-step, i.e. after contributing to the energy balance of the time-step. The share of each production technologies must of course comply with the industrial demand and storage at each time step.

This matrix enables to generate $E_{in}(t)$ values for each energy source in order to calculate the fitness function of the configuration as presented in Chapter II. The objective of the optimisation algorithm is to evolve this matrix for each new generation in order to minimise the fitness function $F(X)$.

Technology availability	Electric boiler	Gas boiler	Biomass boiler	MHP	Storage
$\alpha_{1,0}$	$\alpha_{2,0}$	$\alpha_{3,0}$	$\alpha_{4,0}$	$\gamma_{5,0}$	
$t_1 \rightarrow$	$\alpha_{1,1}$	$\alpha_{2,1}$	$\alpha_{3,1}$	$\alpha_{4,1}$	$\gamma_{5,1}$
$t_2 \rightarrow$	$\alpha_{1,2}$	$\alpha_{2,2}$	$\alpha_{3,2}$	$\alpha_{4,2}$	$\gamma_{5,2}$
$t_3 \rightarrow$	$\alpha_{1,3}$	$\alpha_{2,3}$	$\alpha_{3,3}$	$\alpha_{4,3}$	$\gamma_{5,3}$
\vdots	\vdots	\vdots	\vdots	\vdots	\vdots
$t_n \rightarrow$	$\alpha_{1,n}$	$\alpha_{2,n}$	$\alpha_{3,n}$	$\alpha_{4,n}$	$\gamma_{5,n}$

Fig. 47 - Description of the resolution matrix

IV.1.3 Definition of initial configurations

The choice of the initial conditions for the 100 configurations of the population is important: it aims at proposing solutions respecting the initial constraints and as diversified as possible in order to accelerate the resolution process. Initial conditions are chosen to cover the possible space in a homogeneous way; they are divided into 6 groups, five of which being presented in Table 31. The last group is an adaptation of group 1 for energy production sources that do not comply with constraints, e.g., when there is not enough waste heat for the MHP to operate, or when the demand variation is too high for the biomass boiler.

Table 31 - Summary of the properties of the initial solutions

Group	1	2	3			4	5	
Generation sources	1 source	2 sources		3 sources			1 source	1 source
Production distribution (d)	100 %	10 %	90 %	60 %	20 %	20 %	200 % or 0 %	200 % or 0 %
		50 %	50 %	20 %	60 %	20 %		
		90 %	10 %	20 %	20 %	60 %		
Condition for storage	None	None		None			$t < \frac{t_{tot}}{2}$	$S(t) < D_{max}$ $S(t) < 2 \cdot D_{max}$ $S(t) < D(t)$
Combinations of s technologies among k	$\frac{k!}{s! \cdot (k-s)!}$						k	3·k
Configurations for 4 heat production technologies with storage	4	6		4			4	12

1. Solutions with a single production source

In this group, the heat production is fulfilled over the year with a single technology. Therefore, this configuration generates 4 initial configurations for each of the 4 energy technologies. In all these configurations, the production is set to meet the process demand.

2. Solutions with a combination of two production sources

In this group, three possibilities of energy share between the two production sources are considered to fulfil the industrial demand (10 % - 90 %), (50 % - 50 %) and (90 % - 10 %). There are 6 possible combinations for the 4 technologies considered, combined with 3 different distributions, generating therefore 18 initial conditions.

3. Solutions with a combination of three production sources

In this group, three heat production technologies are associated to fulfil the industrial demand. The industrial demand is also distributed in three different ways (60 % - 20 % - 20 %), (20 % - 60 % - 20 %) and (20 % - 20 % - 60 %) generating 4 possible energy combinations with 3 heat production technologies, i.e. 12 possible initial conditions.

4. Solutions with continuous storage

This group models a single energy production source with long term storage. The storage is forced during the first half of the simulated time period and the energy stored is equivalent to the industrial demand at each time-step. The addition of storage allows the model to propose periods during which no production mode is operating and time-steps where production is increased. The advantage of this type of initial condition is that one can test the effectiveness of storage only with crossover, i.e. by combining a parent with storage and a parent without storage. The result is a faster progress than working solely on mutation by testing all-or-nothing solutions.

5. Solutions with intermittent storage

In this group, 3 additional initial conditions with storage are considered to test storage over all time-steps. As for the group 4, the technologies also produce twice as much as the demand and the surplus is stored until the storage reaches a threshold defined either by (i) the value of the maximum hourly demand over the year, (ii) twice the maximum hourly demand over the year and (iii) the demand for the next time-step. Once the threshold is reached, the storage is completely emptied and then the cycle starts again, storage occurring until the same threshold value is reached

again. We therefore create different storage and retrieval times with these three conditions. These conditions are applied to all the technologies in order to produce a maximum of genetic diversity, i.e. a complement of 12 initial conditions.

6. Solutions adapted to fit constraints

A last type of initial configuration is also generated for MHP and biomass boiler to avoid discarding them from all the initial solutions presented in the previous groups 1 to 4 because they may not respect the physical constraints presented in part II.3.1 (such as waste heat availability or ramp-up). If these technologies are not present in the initial configurations, their presence in the optimisation iteration is strongly penalised and there is a strong probability that they will not be present at the end of the optimisation. To avoid the complete absence of these 2 technologies, one specific initial configuration is created for each of them:

- For the MHP, the condition presented in group 1 (i.e. for MHP operation only) is used and, at each time-step, if the power demand is higher than the power that the MHP can produce with the available waste heat, it is supplemented with (i) gas boiler or (ii) electric boiler to create two new conditions.
- For the biomass boiler, the same type of adjustment is made; when the power ramp-up needed by the industry is too fast for the technology - which is limited by a maximum ramp-up - the complement is made with gas for an additional initial condition and with the electric boiler for another initial solution.

This generates 4 additional initial solutions.

In total, 53 initial conditions are imposed to start the optimisation model. These values are supplemented by a random generation of initial conditions by the algorithm itself to reach the desired number of 100 elements in our optimisation. These additional elements are based on the upper and lower limits and are not at all efficient, with total heat productions between 3 and 12 times greater than under the initial conditions presented in Table 31. These solutions disappear after only a few generations and do not influence the final result.

IV.1.4 Genetic algorithm

The genetic algorithm is used to solve the multi-objective optimisation and determine the set of non-dominated solutions: a Pareto front. Fig. 48 shows an example of non-dominated solutions on a black line obtained for a two-dimensional optimisation.

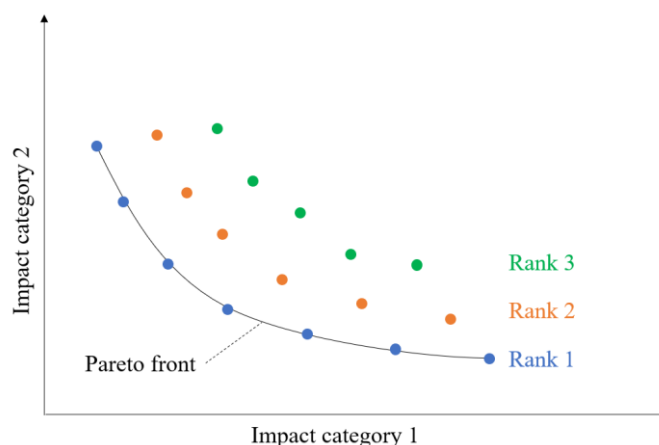


Fig. 48 - Solution rank and Pareto front for a two-dimension optimisation

The Pareto front is represented by blue circles, which are called rank 1 solutions. The rank 2 solutions are dominated by rank 1 solutions, i.e. for each rank 2 element, there is at least one rank 1 element that is better on all evaluation criteria. The same reasoning applies to elements on rank k which are dominated by elements of rank k-1 and lower.

IV.1.4.1 Parent selection

The algorithm generates pairs of parents who will pass on their genes to a child. The aim of the parent selection is to select elements that are both efficient - i.e. having a low rank - and at the same time have a genetic diversity to avoid the model converging towards a single genotype. To ensure that the best-performing elements are retained from a generation to the next one, priority is given to the lowest ranked solution, but higher-ranked elements have also a low probability to be selected as illustrated in Fig. 49 with the probability from each element to be selected. The minimum share of rank 1 elements that are retained in the next generation is a model parameter called the Pareto fraction, which influence on the final results is studied in section IV.1.6. To ensure the diversity of the solutions retained from each rank, the model checks the distance between each solution; this distance is called the crowding distance. The crowding distance is a metric that quantifies the proximity of an individual to its nearest neighbours among individuals of the same rank. The further away an element is from other elements of the same rank, the more likely it is to be selected.

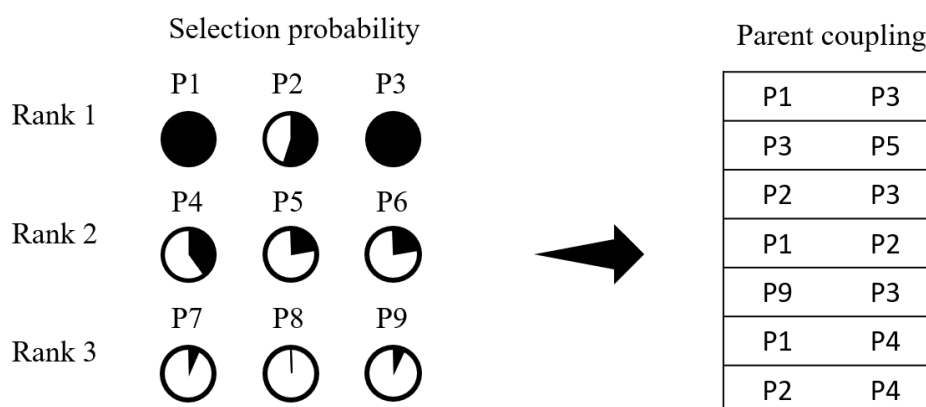


Fig. 49 - Principle of parent coupling according to the rank of the population

The model selects a number of parent pairs equal to the population size. This means that some parents will pass on their genes to several children and others will not be selected if they do not participate in diversity or if they do not perform well enough. The distribution presented in Fig. 50 gives an example for the first generation and a population of 100 elements. The parent pair who is most present in the reproduction appears 8 times and can therefore transmit its genes to up to 8 children. This parent pair has a higher probability of contributing to the genetic diversity of the population, as its genes are being selected more frequently for the creation of new solutions. On the contrary, 24 parents are never selected, either because they do not respect the constraints or because their fitness values are too high and diversity too low. These genes tend to disappear.

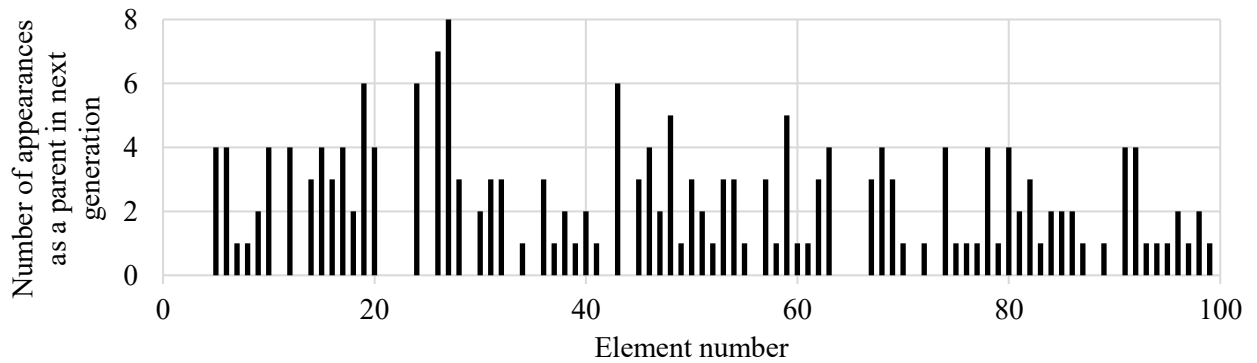


Fig. 50 - Distribution of the number of appearances of each parent for the next generation. The distribution is specific to each generation; the example is made for the first generation and a population size of 100 elements.

IV.1.4.2 Generational evolution

The evolution from generation n to generation $n+1$ is performed following two possible types of evolution on the parent matrices: mutations and crossovers. The share of each of these two possible evolutions, the mutation rate or the crossover rate (mutation rate = $1 - \text{crossover rate}$) is a parameter of the method, which influence on the final results is studied in section IV.1.6. The mutation rate allows to explore areas of the domain not covered by the parent genes, but the higher the mutation rate, the more random the optimisation process becomes. Once the generation $n+1$ is created, it is combined with generation n population: the algorithm selects non-dominated and dominated elements from the new set combining n and $n+1$ sets in order to keep a sufficient diversity to continue exploring the space.

IV.1.4.2.1 Mutation

The mutation process operates differently depending on whether there is only one heat production source or a combination of various solutions, as shown in Fig. 51. Both options involve three steps:

1. In the first step, two genes (represented by blue and red blocks in the figure) are randomly selected. This selection can only be made on heat production technologies and not on storage. It is chosen to modify a single time-step rather than several, because it is more efficient to reach the Pareto front. Indeed, because of compensation effects, an improvement at one time-step may be offset by a deterioration at another. Although this results in a slower evolution of the matrix, it avoids non profitable iterations.
2. In the second step, one of the genes undergoes random evolution with a factor ranging from 0.8 to 1.2. The other gene is adjusted to maintain the same overall final energy production, thus avoiding the constraints from rejecting the solution.
3. The last step modifies the storage level to ensure that it respects the energy balance described in equation II-11. The lack of mutation in the storage genes may appear to be a limitation in exploring the space, but it is a direct consequence of the changes made to the other parameters and thus does not constrain the exploration.

Option 1 : 1 heat production technology

(1) Select 2 hours randomly, a variable value (in blue) and a balancing value (in red)

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 1 \\ 5 & 0 & 0 & 0 & 1 \\ 3 & 0 & 0 & 0 & 2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 2 & 0 & 0 & 0 & 0 \end{bmatrix}$$

(2) Randomly change the variable value by a factor between 0.8 and 1.2 and adjust the balancing value with the difference

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 1 \\ 4 & 0 & 0 & 0 & 1 \\ 3 & 0 & 0 & 0 & 2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 2 & 0 & 0 & 0 & 0 \end{bmatrix}$$

(3) Correct the storage in a way that complies with the constraints if possible (in orange)

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 1 \\ 4 & 0 & 0 & 0 & 0 \\ 3 & 0 & 0 & 0 & 1 \\ 7 & 0 & 0 & 0 & 2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 2 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Option 2 : 2 or more heat production technologies

(1) Select a time step randomly (in orange) and 2 technologies: a variable value (in blue) and a balancing value (in red) for this time step

$$\begin{bmatrix} 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 2 & 0 & 1 \\ 5 & 1 & 1 & 0 & 2 \\ 6 & 1 & 2 & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 2 & 1 & 0 & 0 & 0 \end{bmatrix}$$

(2) Randomly change the variable value for the hours by a factor between 0.8 and 1.2 and adjust the balancing value with the difference

$$\begin{bmatrix} 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 2 & 0 & 1 \\ 5 & 1 & 1 & 0 & 2 \\ 7 & 1 & 1 & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 2 & 1 & 0 & 0 & 0 \end{bmatrix}$$

(3) Correct the storage in a way that complies with the constraints if possible (in orange)

$$\begin{bmatrix} 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 2 & 0 & 1 \\ 5 & 1 & 1 & 0 & 2 \\ 7 & 1 & 1 & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 2 & 1 & 0 & 0 & 0 \end{bmatrix}$$

Fig. 51 - Mutation principle applied to the heat production matrix

IV.1.4.2.2 Crossover

The objective of the crossover process is to blend the genetic material of two parent matrices to produce a child matrix. This procedure is outlined in Fig. 52 and comprises three steps:

1. Initially, a combination of the two parents is performed using a modified version of the "scattered crossover" method, which randomly selects either parent 1 or parent 2 for each time-step and gathers all the energy production systems for that time-step. For instance, in the example depicted in Fig. 52, parent 2 is selected for the first two time-steps (shown in orange), while parent 1 is selected for the third and final time-steps.
2. In the second step, the genes of each selected parent (in orange) are combined to create the child matrix.
3. The last step is to adjust the storage to ensure that the energy balance respects the constraints. This modification is necessary when parents 1 and 2 have different storage usage since it depends on the preceding time-steps. Hence, the storage state must be redefined in accordance with the chosen parents.

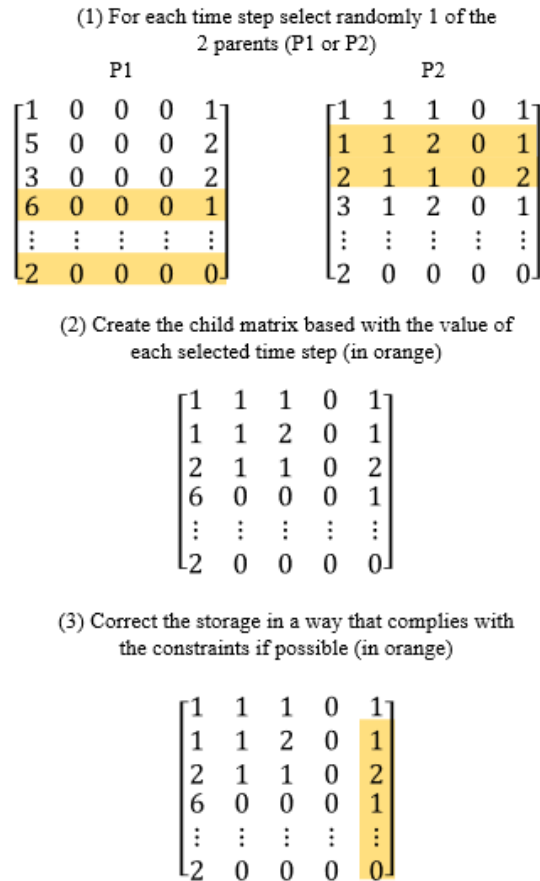


Fig. 52 - Crossover principle applied to the heat production matrix

In the event that the crossover or mutation generates a child that does not respect the constraints of the model, a weighted average of the parents is carried out: this transformation is called "crossover intermediate". The "crossover intermediate" transformation is a technique that helps reducing the rejection rate of the new generation in genetic algorithms. The use of crossover intermediate helps increasing the diversity of the solutions in the population and can improve the chances of finding better solutions in the search space.

IV.1.4.3 Validation and population generation

Once the child generation is created, this new population is combined with the parent generation to create an extended population. This extended population has twice more elements than the population size. A population reduction is realised to get back to the correct number of elements as explained for the parent selection in part IV.1.4.1. Among this new population, elements of both the parent and child generations may be present and the proportion of each depends on whether gains have been made through mutations and crossover.

IV.1.4.4 Exit criteria

The stopping conditions are divided into a criterion on the number of generations and a criterion for stopping the evolution of the front of non-dominated solutions, also called spread. The spread Δ_{Pareto} is calculated using Matlab optimisation toolbox [133], defined in equation IV-1.

$$\Delta_{\text{Pareto}} = \frac{\mu + \sigma}{\mu + \rho \cdot d} \quad \text{IV-1}$$

where σ is the standard deviation of the crowding distance of points that are on the Pareto front with finite distance, ρ is the number of these points, d is the average distance among these points, μ is the sum of the norms for the k-dimension of the objective function between the current minimum-value Pareto point and its previous iteration minimum for all indices. The spread is small when the extreme values of the objective function do not change much between iterations (i.e. μ is small) and when the points on the Pareto front are evenly distributed (i.e. σ is small). Matlab provides default values for these parameters, which have not been modified in this work.

As some parameters change randomly, such as during the mutation or crossover processes, the final solution to the optimisation problem may differ between two simulations. To overcome this drawback of the genetic method and avoid local minima, 10 simulations are carried out for each study with the same initial data set. The best-performing solution is retained. The influence of the number of simulations on the final result is presented in section IV.1.6.

IV.1.5 Model testing under harsh conditions

To evaluate the capability of the Genetic Algorithm Optimisation Solutions (GAOS), three simple cases are created for which it is possible to directly identify a User-Based Optimal Solution (UBOS). Each of these solutions test very extreme situations to evaluate the ability of the algorithm to respond to rapid variations. Three cases are created to test a particular behaviour of the model:

1. The first case aims at testing the model's ability to follow variations in the carbon content of electricity, by modelling a variation from a production based 100 % on wind to a production based 100 % on gas fired power plant. Model's ability to perform crossovers is then evaluated, as variations by mutations would be too slow to reach a solution in a reasonable time.
2. The second case is created to test the ability of the model to follow huge variations in demand over each time-step e.g. between 1 and 3 MW. This case allows the testing of mutations, as rapid variations restrict the use of MHPs and therefore force the algorithm to find a complementary energy source.
3. The last case is a combination of the first two, with a variation in the carbon content of the electricity and in the demand. This case adds complexity because storage will be constrained by the available waste heat, so it is necessary to combine crossover and mutation to achieve the result.

The impacts of the energy considered in these tests are presented in Table 32. For ease of reading, the results are presented only for the climate change indicator. The case studies are based on 10-hour periods with some additional assumptions:

- 80 % of the wasted energy is recoverable
- COP design fixed at 3.43 ($T_{\text{process}} = 130 \text{ }^{\circ}\text{C}$; $T_{\text{recovered}} = 80 \text{ }^{\circ}\text{C}$)
- 500 generations
- Technologies are not constrained by a minimum value

Table 32 - Impact of energy sources used in the 3 tested cases on climate change indicator

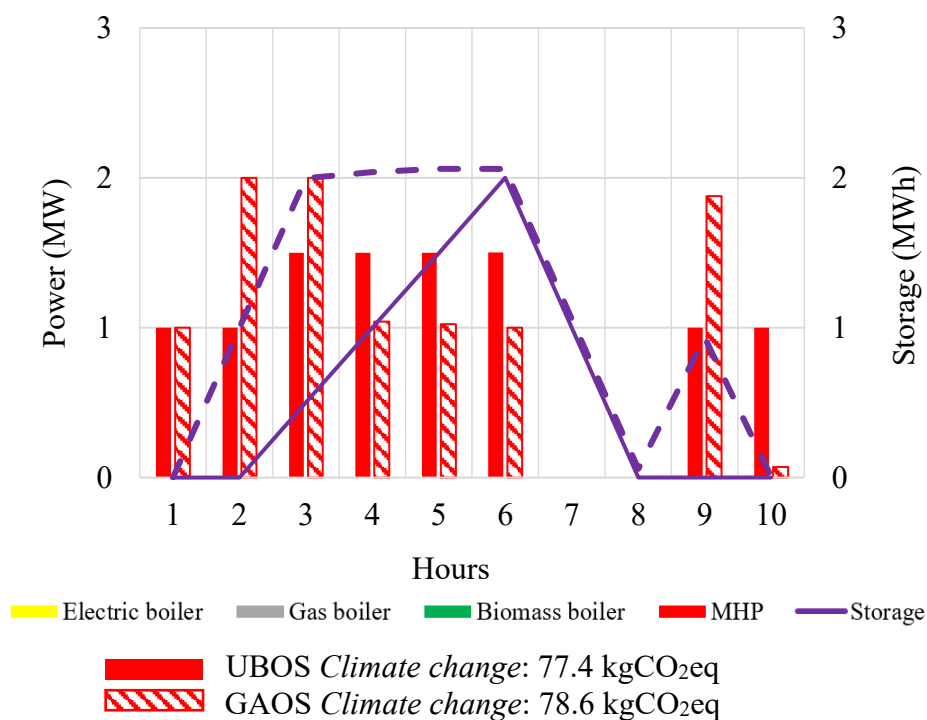
Energy source	Climate change impact (kgCO ₂ eq/MWh)
Electricity from wind production	20
Electricity from gas (100 % natural gas combined cycle 50 % efficiency)	367
Heat production with biomass boiler	37
Heat production with gas boiler	237

Case 1: Constant demand and variable electricity impact

The aim of this first case is to test the ability of the algorithm to detect hours during which it is unfavourable to produce and therefore to test its aptitude to anticipate excessively penalising hours with an appropriate storage strategy. To do this, at hours 7 and 8, the carbon content of the electricity is greatly increased so that the use of storage becomes interesting as presented in Table 33. The UBOS, presented in Table 33 with solid bar, is a case designed to minimise losses by realising a compromise between (i) on one side the storage, which requires to store energy for the shortest period possible and (ii) on the other side MHP partial load efficiency which requires to produce close to the base-load. GAOS found with the optimisation model is also presented in Fig. 53, represented with hatched bar.

Table 33 - Electricity mix and industrial demand over the 10 time-steps of case 1

Time-step		1	2	3	4	5	6	7	8	9	10
Electricity mix	Wind onshore (%)	100 %	100 %	100 %	100 %	100 %	100 %	0 %	0 %	100 %	100 %
	Gas combined (%)	0 %	0 %	0 %	0 %	0 %	0 %	100 %	100 %	0 %	0 %
Industrial demand (MW)		1	1	1	1	1	1	1	1	1	1
Available waste heat (MW) ¹		0	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8



¹ Cf. chapter II.3.2

Fig. 53 - Heat production profile for case 1 for UBOS, represented by the solid bar, and GAOS, represented by the hatched bar, to minimise climate change impact

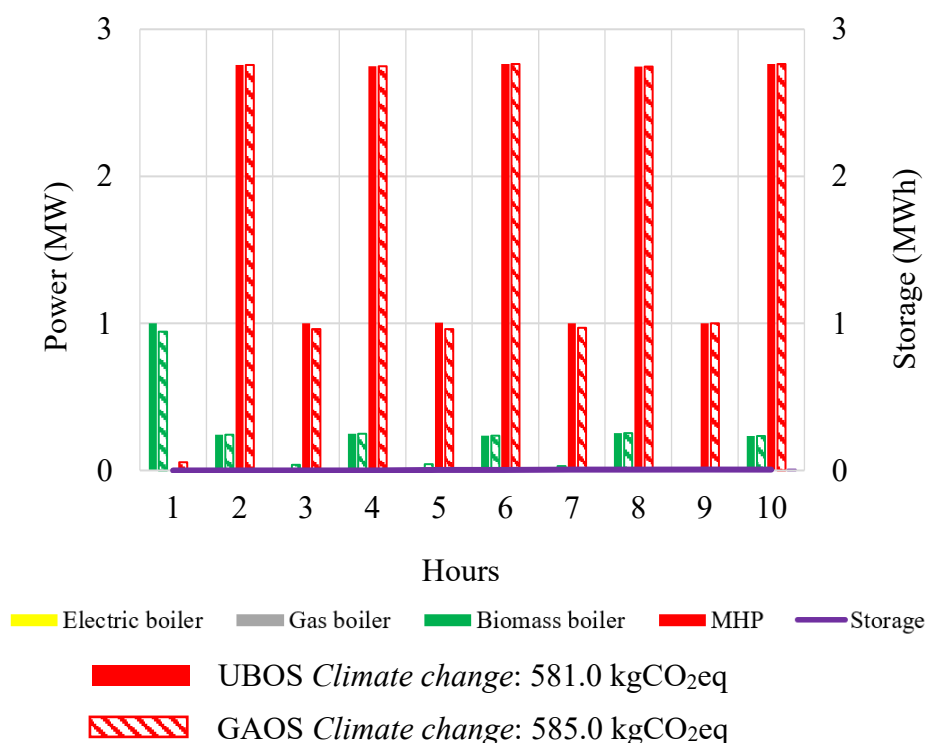
The deviation from the UBOS is 1.6 % for *climate change* indicator and is explained by a higher use of storage and a higher power design of the MHPs, which result in efficiency losses due to partial load operation. The algorithm is able to find a solution without production during the 7th and 8th hour as desired and selects only MHP for the heat production as expected. On the other hand, the algorithm does not converge to a more optimal solution for 2 reasons: (i) the difference between the two solutions is low, therefore the probability to be retained as parent is low, which makes the convergence slower and (ii) the number of generations tested is limited (here 500 generations) to keep a limited computation time. The impact of the number of generations is presented in part IV.1.6.

Case 2: Variable demand and constant electricity impact

The objective of this second case is to evaluate the ability of the algorithm to respond to a large variation in demand (Table 34). This variation in demand restricts the use of MHP because the amount of waste heat is not sufficient to meet the demand. The UBOS is presented in Table 34 with solid bar, consisting of maximising the MHP use as possible and supplementing it with biomass.

Table 34 - Electricity mix and industrial demand over the 10 time-steps of case 2

Time-step		1	2	3	4	5	6	7	8	9	10
Electricity mix	Wind onshore (%)	80 %	80 %	80 %	80 %	80 %	80 %	80 %	80 %	80 %	80 %
	Gas combined (%)	20 %	20 %	20 %	20 %	20 %	20 %	20 %	20 %	20 %	20 %
Industrial demand (MW)		1	3	1	3	1	3	1	3	1	3
Available waste heat (MW) ¹		0	0.8	2.4	0.8	2.4	0.8	2.4	0.8	2.4	0.8



¹ Cf. chapter II.3.2

Fig. 54 - Heat production profile for case 2 for UBOS, represented by the solid bar, and GAOS, represented by the hatched bar, to minimise climate change impact

There is no waste heat available for the first timestep which explains the presence of biomass. The GAOS result is very close to the UBOS as presented in Table 34. The difference found between the UBOS and GAOS is below 1 % for the *climate change* indicator and comes mainly from the presence of a MHP residual power in the first timestep. As in case 1, the result is explained here by a lack of iteration to allow the error to tend towards 0.

Case 3: Variable demand and variable electricity impact

The last case is a mix of the two previous cases with the conditions presented in Table 35. It allows to test both the ability of the algorithm to mutate and to perform crossovers. The problem here comes from the variation in demand, which forces the model to store heat when the demand is low, even though these are also the time-steps when the wasted heat is available. Therefore, the model must dissociate demand and production.

Table 35 - Electricity mix and industrial demand over the 10 time-steps of case 3

Time-step		1	2	3	4	5	6	7	8	9	10
Electricity mix	Wind onshore (%)	100 %	100 %	100 %	100 %	100 %	100 %	0 %	0 %	100 %	100 %
	Gas combined (%)	0 %	0 %	0 %	0 %	0 %	0 %	100 %	100 %	0 %	0 %
Industrial demand (MW)		1	3	1	3	1	3	1	3	1	3
Available waste heat (MW) ¹		0	0.8	2.4	0.8	2.4	0.8	2.4	0.8	2.4	0.8

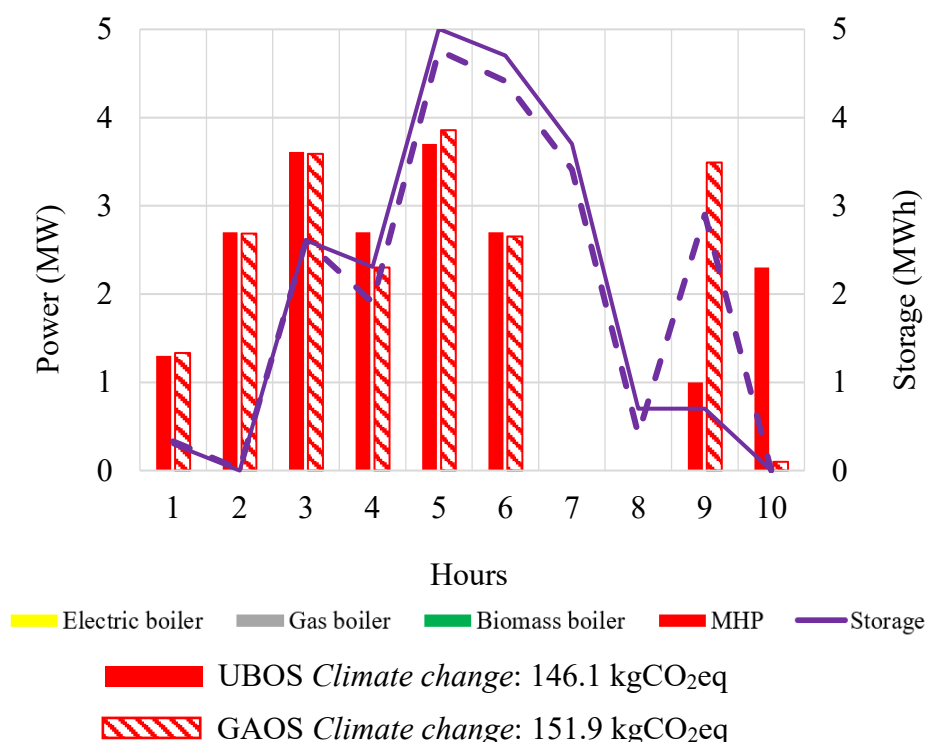


Fig. 55 - Heat production profile for case 3 for UBOS, represented by the solid bar, and GAOS, represented by the hatched bar, to minimise climate change impact

As the initial conditions are all demand based, i.e., that production at each time step does not exceed demand, the model has to use mutations to move towards the optimal solution shown in

¹ Cf. chapter II.3.2

Table 35. GAOS solution has a 3.95 % higher value for the *climate change* indicator than the UBOS. The profile presented in Table 35 has a deviation at time-steps 9 and 10 as well as an increase in storage losses and partial load losses. Another contribution is the slight increase of 3 % on the first timestep where the absence of heat does not allow to valorise the presence of MHP.

This study shows that the GAOS results presented are close to the UBOS, even if some deviations are present. These extreme cases with instantaneous variations are the most difficult configurations for a genetic optimisation model, which has difficulty in evolving rapidly on a specific gene. Despite this, the results presented provide a realistic approximation of the use of each technology. For case 3, the deviation comes from a non-optimal storage management due to thermal losses and not an over-production with an excess production of MHP below 0.02 %. With a more conventional case with fewer discontinuities on average, lower deviations are expected.

IV.1.6 Influence of numerical parameters on convergence

To evaluate the influence of the optimisation parameters, i.e. the population size, the number of generations, the pareto fraction and the crossover fraction (or the mutation fraction), a parametric study of these variables is performed taking case 3 (Table 35) as an example. The nominal conditions are a population of 100 configurations, 500 generations, a pareto fraction of 0.3 and a crossover fraction of 0.8. The choice of initial solutions presented in section IV.1.3 leads to an initial climate change indicator about 20 % higher than the UBOS; the algorithm converges to a solution that has an impact lower than this initial value, regardless of the chosen parameters.

Due to the randomness of the genetic algorithm, the results are not fully reproducible; as explained earlier, 10 simulations are realised for each study to cope with this drawback of the method. In this section, we also evaluate the influence of this parameter on the results (Fig. 56). The optimisation algorithm is repeated 100 times for 100, 200, 500, 1000, and 2000 generations and the deviations between the results of the optimisation and the optimal solution for the climate change indicator are plotted. The figure shows a distribution close to a normal distribution, with some residual values between 8 % and 16 % above the target value, which shows that it is wise to repeat the algorithm several times in order to avoid a local minimum.

The mean value of the standard deviation for the 100 tests decreases with the number of generation and reaches a plateau for 500 generations, which shows that a number of 500 generations is a good compromise between the calculation time and the precision. However, to avoid errors associated with random generation, each optimisation presented below is repeated 10 times to maximise the chances of obtaining a value close to the optimum. All solutions with a value greater than the mean plus the standard deviation of the simulated values for at least one impact category are removed. If several solutions are retained, the one with lowest Euclidean distance with the mean of impact categories is selected. If no solution meets these conditions, the number of repetitions is doubled to avoid retaining a value that has not yet converged. Note that in real cases, the variations between the different time-steps are lower and more gradual, so the deviation between the different iterations is much smaller than in the extreme cases presented here.

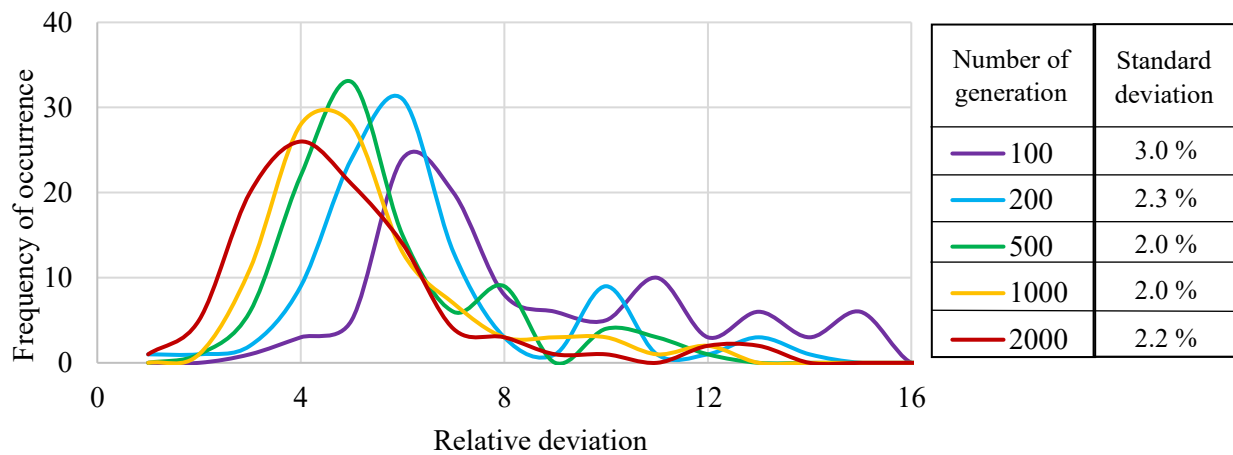


Fig. 56 - Frequency of occurrence of the relative difference in climate change impact between the best solution of the optimisation model and the optimal configuration for different numbers of generations after 100 repetitions of the optimisation

Fig. 57 presents the influence of the population size, the number of generations, the pareto fraction and the crossover fraction on the results. On these graphs, the left-hand ordinate axis shows the calculation time, while the right-hand axis shows the relative deviation from the UBOS for the climate change indicator. The average value of the 10 tests carried out is shown with the range of these values between the minimum and the maximum.

Fig. 57a shows a significant increase of the calculation time according to the size of the studied population, whereas the relative deviation from the optimal solution is not necessarily lower. This is due to the greater presence of solutions with few genetic interests, i.e. that increase the risk of selecting a second parent less performant. Increasing the size of the population can bring greater precision but it must be coupled with an increase in the number of generations and therefore at the expense of the speed of calculation. In our configuration where the number of technology combinations is relatively limited (with 4 production sources), it is not necessary to increase the population to get closer to the optimal. Therefore, a value of 100 configurations is selected for this study.

Fig. 57b shows the influence of the number of generations for a population of 100 elements and confirms the results presented in Fig. 56 with a plateau reached for a number of generation equal to 500, which is retained for the rest of the study.

Fig. 57c shows that the Pareto fraction - i.e. the minimum share of rank 1 elements that are retained in the next generation - has a limited impact on the result. The average value is better for low Pareto fraction values (between 6.4 % error for 0.1 and 7.6 % for 0.9) but there are better solutions for Pareto fractions of 0.3 and 0.5. The default value of 30 % seems to provide sufficient genetic diversity by retaining sufficient dominant elements without slowing down reproduction with several elements that do not provide genetic interest. This value of 30 % is retained for the rest of study.

Finally, Fig. 57d also shows that the crossover rate has a limited impact on both the calculation time and the results. The result is better for this configuration, for which the optimal value is based on a high level of storage demand and therefore periods of overproduction that can only be obtained by mutation. In real configurations with less extreme variations, the impact of mutations will be less impactful, while the calculation time will increase significantly. For this reason, it is preferable to keep a crossover rate close to 80 % in order to maintain efficient space exploration.

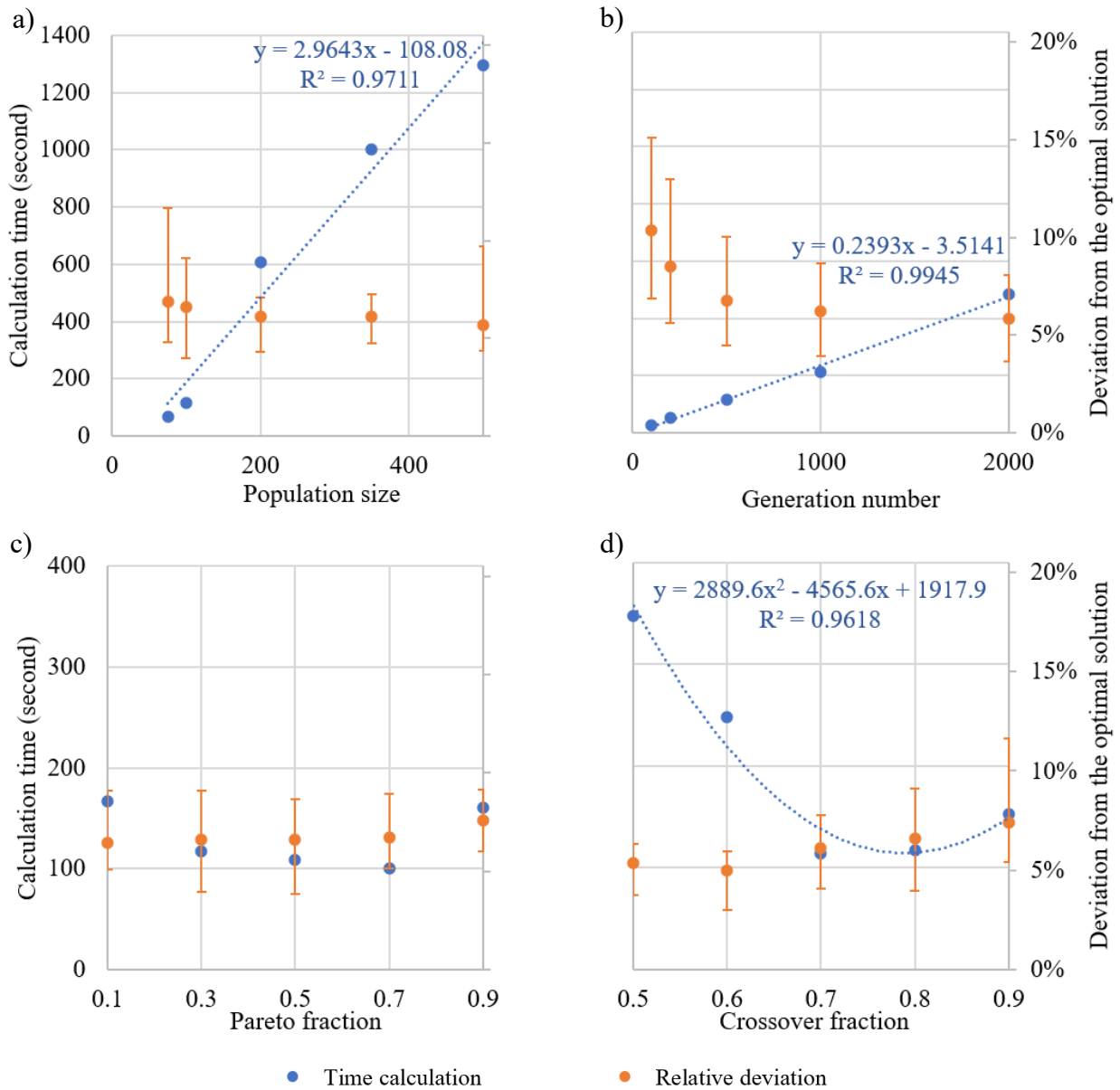


Fig. 57 - Range of relative deviation from climate change impact optimal solution calculated 10 times and average time calculation for a) a population size between 50 and 500 elements, b) a number between 100 and 2000 generations, c) a Pareto fraction between 0.1 and 0.9, d) a crossover fraction between 0.5 and 0.9

IV.2 Model input reduction

The model uses hourly values that vary greatly throughout the year, such as capacity factor or electricity cost. It is therefore necessary to carry out a calculation over the whole year to integrate all these specificities. One of the limitations for a yearly calculation is the computation time. It is not possible to simulate a full year in one optimisation due to the matrices size, so the year has to be split into three 4-month periods of industrial demand. With a conventional desktop computer, the calculation time to simulate each 4 months period is approximately 12 hours, which is too much to perform an exhaustive parameter analysis such as the one presented in chapter V. To limit the consumption of computational resources, we have chosen to carry out a clustering and group together all the time-steps having the same characteristics so that the algorithm only has to optimise them once. This choice enables to carry out the optimisation without using the resources of a computing centre. This type of reduction method is widely used in genetic algorithms problem as described by Zeebaree et al. [160]

The aim of the cluster is to group together all the time-steps with similar characteristics, in order to reduce the number of calculated time-steps, i.e. the number of rows in the matrix. The principles of the clustering are similar to those used in part II.2.3.1 to reduce the number of electricity mix at the European scale. For example, if a cluster is representative for 10 different hours over the year, the calculation is performed once and the impact over the whole year is assumed to be 10 times the value obtained. The representative hour for this cluster of ten elements is the average of the 10 elements in the cluster. The goal of the clustering is to select the smallest number of clusters to represent with the greatest possible fidelity, the 4 parameters that vary hourly over the one-year period:

- (i) The share of each energy source in the mix, which affects the calculation of the price and the environmental impact of the electricity
- (ii) the total demand of the country, which influences the calculation of the price of the electricity
- (iii) the hourly industrial demand
- (iv) industrial demand variation between time-step t and time-step $t-1$ to integrate the constraints on production variations in particular for biomass

In order to obtain a sufficient level of detail for these 4 parameters, it is recommended to increase the number of clusters to reduce the RRMSE, previously defined in equation II-8. Using the C2 electricity mix (defined in part II.2.3.1) as an illustration, with a weekly process demand and 2015-2040 as the period of reference, we present in Table 36, the RRMSE for the industrial demand and the industrial demand variation for 20, 50 and 100 clusters. For this study, a number of 100 clusters has been selected to ensure the relevance of the values obtained, but above all to ensure that the profile recreated can accurately integrate the variations in demand. When the number of cluster increases, the computation time also increases (threefold increase in calculation time between 20 and 100 clusters), but with 100 clusters, the calculation time is equal to about 5 minutes, which remains reasonable for our study.

Table 36 - RRMSE of industrial demand and industrial demand variation obtained by comparing real data cluster C2 for the weekly process demand with the output of the clustering for 20 to 100 clusters

Number of clusters	20	50	100
RRMSE industrial demand (%)	5.5	3.4	2.6
RRMSE industrial demand variation (%)	5.9	4.2	3.5

Weekly demand profile is more critical to cluster than continuous and batch processes (Table 37). Indeed, the continuous and batch profiles show better RRMSE results because:

1. The continuous profile has very small demand variations, which reduces the number of parameters that vary with time to those depending on the production of electricity by the country. The overall error is therefore smaller for both the demand approximation and the demand variation approximation.
2. For the batch profile, the demand varying only between values of 1 and 0, the clustering is decomposed in two sub-clusters, the first for the hours with production and the second for the hours without production. As for the continuous profile, only the parameters depending on the production of electricity by the country vary with time. Clustering is therefore done with fewer constraints and gives better results.

Table 37 - RRMSE of industrial demand and industrial demand variation obtained by comparing real data cluster C2 for the weekly, continuous and batch processes with 100 clusters

Profil	Weekly	Continuous	Batch
RRMSE industrial demand (%)	2.6	1.6	0
RRMSE industrial demand variation (%)	3.5	1.9	0

Fig. 58 presents the results of the clustering for 20, 50 and 100 clusters, taking the 77th week of the year for the French configuration (electricity cluster C2) and a weekly process as an example.

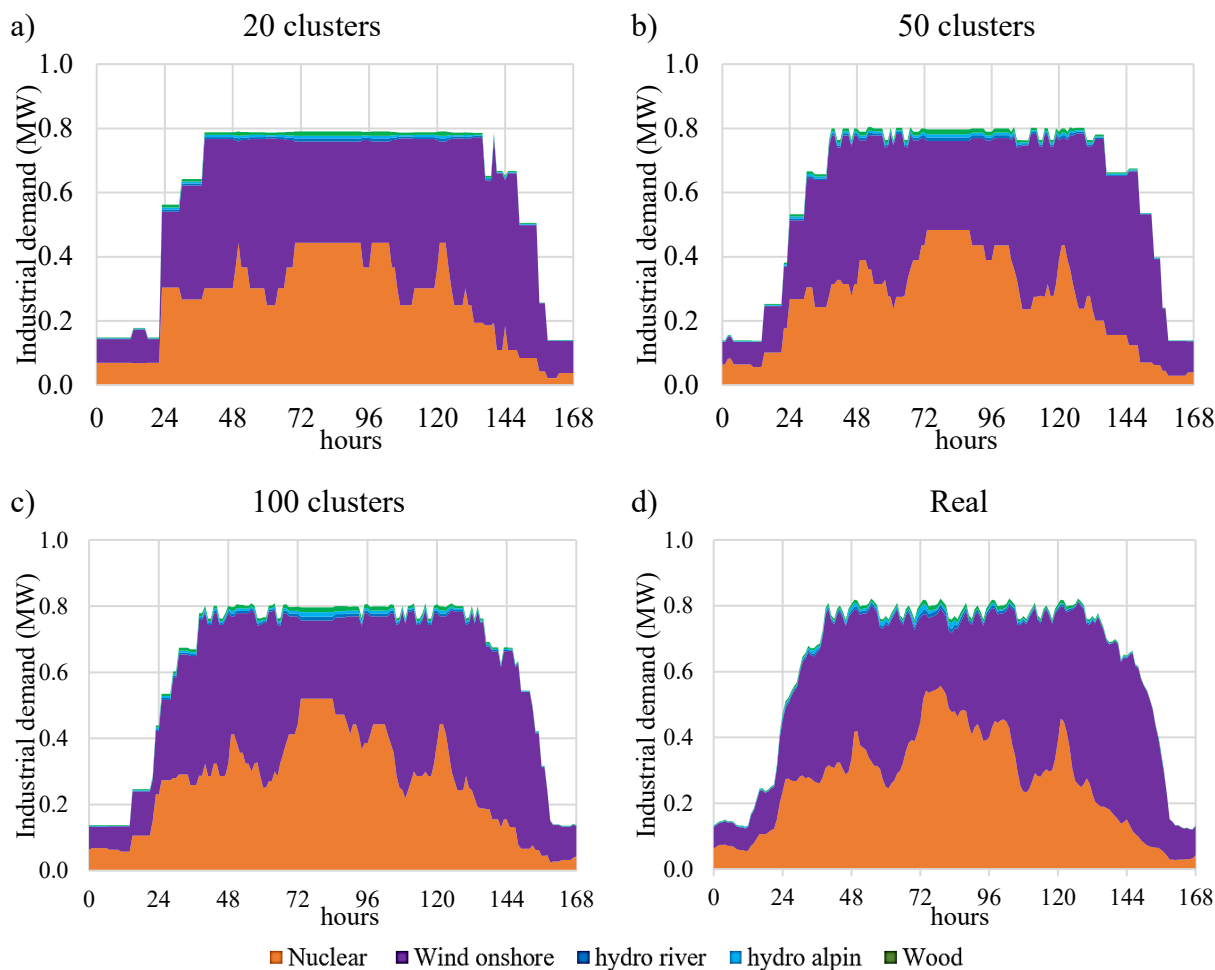


Fig. 58 - Profile of the industrial need for the weekly demand profile for France (representing the C2 electricity mix cluster Cf. II.2.3.1) and share of energies present in the electricity mix. Profiles resulting from a) 20 clusters b) 50 clusters, c) 100 clusters and d) real data set. The industrial demand is represented by the total area and is decomposed by the rate of each energy present in the electricity mix over this time-step.

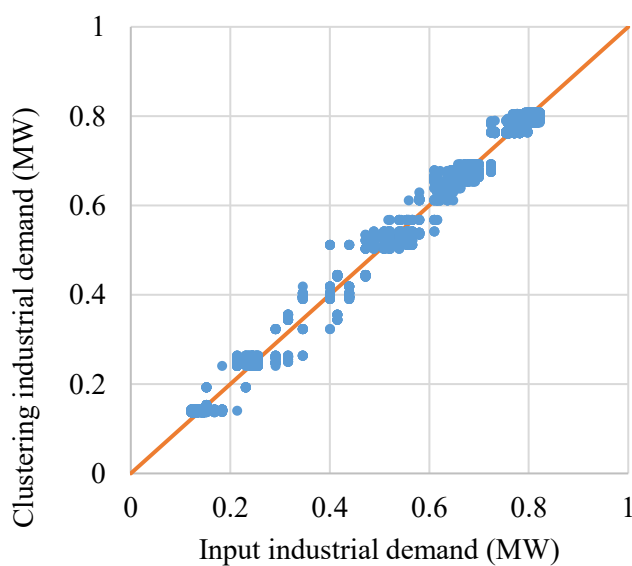
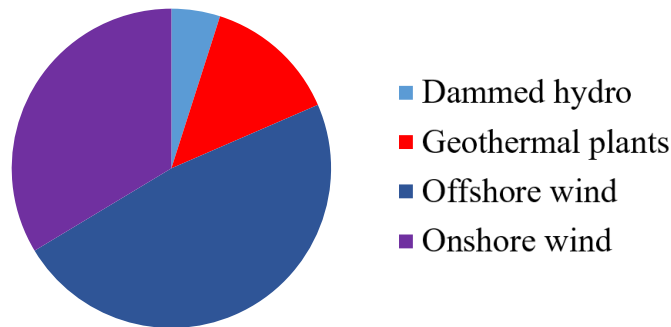


Fig. 59 - Dispersion between original and clustered values, for weekly process and mix C2

IV.3 Example of results from the optimisation algorithm

In this section, a detailed example is presented to show the outputs of the optimisation model and the Pareto front of the optimal solutions. The case of the weekly process defined in section II.2.4 is recalled in Fig. 60b, for the period 2015-2040 with the C1 renewable based electricity cluster presented in section II.2.3.1. The electricity mix is based on a majority of renewable energy and - for the particular case of the high-tension network used in industry - mostly onshore and offshore wind as shown in Fig. 60. All the detailed results can be found in Appendix 8.

a)



b)

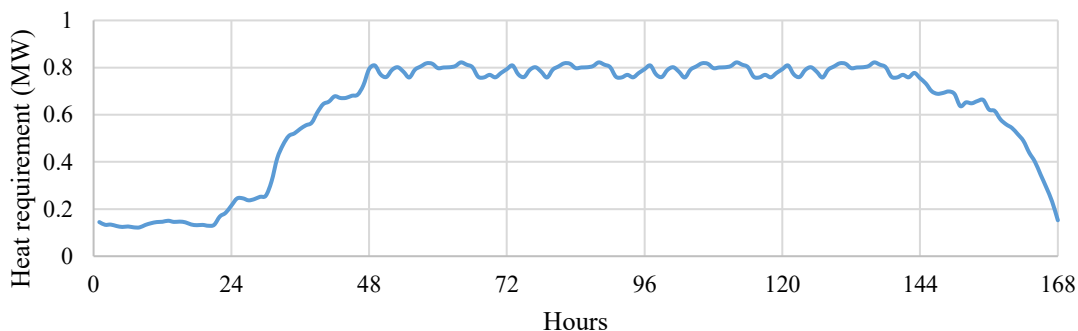


Fig. 60 - Electricity share for a) new installed electricity production technology used in industry (high tension) and b) weekly profile demand from the industrial process

The optimisation model generates iteratively a large number of elements equal to 35912 in this case. With 500 generations and a population of 100, a maximum of 50 000 elements could be generated. However, some elements are of rank 1 during the iteration process and do not change during one or more iterations, which reduces the number of new elements generated. At the end of the iterative process, the Matlab algorithm retains 35 non-dominated solutions, which are located on the Pareto front. The non-dominated solution set is directly related to the size of the population and would double if the population size was 200. The value of 35 solutions retained ensures that there is sufficient diversity in the solutions obtained, i.e. that there are approximately 2 times as many solutions retained as there are impact categories, and guaranties that:

1. At least all the best performing solutions for each impact category are present on the Pareto front.

- Solutions with medium impacts on all categories, neither very low nor too impactful, i.e. a solution on the Pareto front that is never the best in one impact category but that never exceeds too much the other impact categories.

All the other solutions are the dominated solutions. The final 35 solutions on the Pareto front are presented in Table 38, for the 19 objectives used in the optimisation.

Table 38 - Results of Pareto front's solutions, for the 19 parameters used in the optimisation process. Values above the sustainable threshold are presented in orange.

	Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (€/MWh)
Sustainable ratio (Sr)																			
1	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.0	0.0	0.8	0.0	0.0	0.2	9.3	68%	94%	16
2	2.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.9	0.1	29%	84%	21
3	1.6	0.0	0.0	0.1	4.6	0.4	0.0	0.0	0.3	0.3	0.1	1.3	1.6	0.0	4.3	0.3	24%	73%	20
4	0.5	0.0	0.0	0.3	16.5	1.2	0.1	0.1	0.7	0.7	0.1	4.2	5.8	0.0	0.5	0.7	16%	51%	14
5	0.5	0.0	0.0	0.3	16.5	1.2	0.1	0.1	0.7	0.7	0.1	4.2	5.8	0.0	0.5	0.7	16%	51%	14
6	1.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.3	0.0	0.0	4.7	2.6	31%	85%	59
7	1.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.0	0.0	3.4	4.3	38%	87%	25
8	0.5	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.4	0.1	0.0	0.9	0.0	0.0	1.3	8.9	49%	85%	49
9	1.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.2	1.5	30%	84%	29
10	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.0	0.0	0.8	0.0	0.0	0.2	9.5	64%	93%	27
11	1.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.0	0.0	2.8	5.2	41%	88%	25
12	0.9	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.0	0.0	2.3	6.0	43%	90%	30
13	2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.8	0.4	29%	83%	30
14	0.5	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.4	0.1	0.0	0.8	0.0	0.0	1.3	8.4	49%	88%	55
15	0.6	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.0	0.0	1.6	7.8	46%	86%	34
16	1.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.0	0.0	3.0	4.9	40%	87%	24
17	0.5	0.0	0.0	0.3	16.5	1.2	0.1	0.1	0.7	0.7	0.1	4.2	5.8	0.0	0.5	0.7	16%	51%	14
18	1.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.0	0.0	3.8	4.0	35%	85%	36
19	2.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.5	0.8	29%	84%	29
20	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.0	0.0	0.8	0.0	0.0	0.2	9.5	64%	93%	23
21	0.8	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.0	0.0	2.2	6.6	44%	89%	37
22	1.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.0	0.0	3.6	4.0	36%	87%	33
23	1.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	4.8	2.1	32%	84%	28
24	1.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.0	0.0	4.3	3.5	33%	84%	41
25	0.7	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.0	0.0	1.8	7.1	46%	90%	49
26	1.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	4.5	2.9	32%	83%	34
27	1.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.0	0.0	3.3	4.7	37%	87%	45
28	0.9	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.0	0.0	2.3	6.5	43%	86%	40
29	1.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.5	0.0	0.0	3.2	4.7	38%	87%	41
30	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.4	0.1	0.0	0.8	0.0	0.0	0.7	9.0	56%	91%	46
31	0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.8	0.0	0.0	0.9	9.0	52%	87%	29
32	0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.4	0.1	0.0	0.8	0.0	0.0	1.0	8.6	54%	90%	50
33	0.5	0.0	0.0	0.3	16.5	1.2	0.1	0.1	0.7	0.7	0.1	4.2	5.8	0.0	0.5	0.7	16%	51%	14
34	2.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.9	0.1	29%	84%	21
35	1.6	0.0	0.0	0.1	4.6	0.4	0.0	0.0	0.3	0.3	0.1	1.3	1.6	0.0	4.3	0.3	24%	73%	20

Each line of the table, numbered from 1 to 35, corresponds to a heat production mode, combining one or more energy sources, the share of each energy source being presented in Fig. 61. For each solution, the table presents:

1. the sustainable ratio S_r of the 16 environmental indicators, defined in part II.6.3,
2. the energy efficiency, defined as the ratio between E_{out} and cumulative energy demand,
3. the exergy efficiency, defined as the ratio between the exergy corresponding to E_{out} at temperature T_{up} (set at 130 °C in the configuration studied) and the cumulative exergy demand,
4. the total cost over one year per unit of energy, defined in section II.5.

All values greater than 1 are considered unsustainable from an environmental point of view and are identified in orange in Table 38. For example, the factor 9.3 in the first line for *resource use, minerals and metals*, indicates a resource consumption 9.3 time greater than the sustainable threshold level for this indicator.

The share of each energy source used in the 35 non-dominated solutions are presented in Fig. 61. Among these 35 configurations, the model covers a large number of configurations, including all configurations with a single energy source, as well as a large number of MHP/Gas boiler combinations with a greater or lesser proportion of storage. Some solutions are extremely close, for example the 4 productions with a biomass boiler close to 100 % have differences of less than 0.1 %, and do not provide any additional information. For this example and for the study as a whole, the 35 non-dominated solutions provide a large diversity to be representative and to ensure that all combinations are considered.

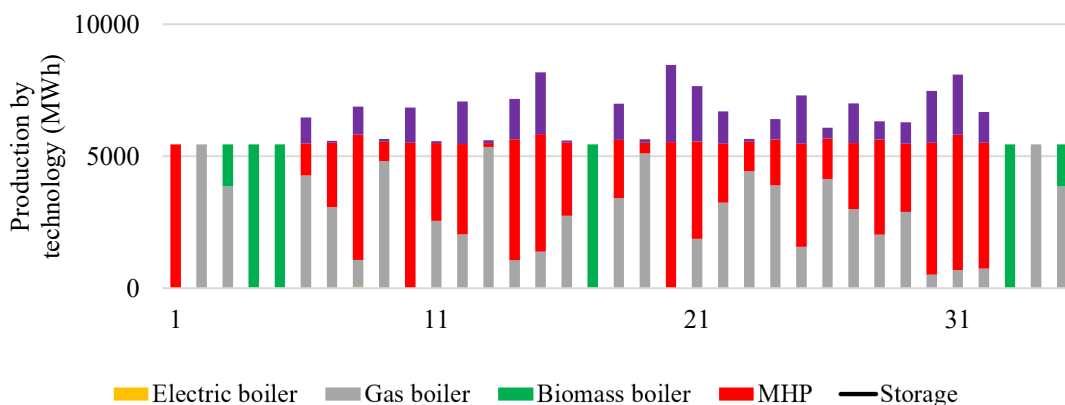


Fig. 61 - Heat production from of each technology for the 35 solutions of the Pareto front

The elements of Table 38 are presented graphically in Fig. 62 for all impact categories, each row of the table being represented by a coloured line ; the value of each impact can be read at the intersection of this line with the horizontal axis of each impact category. The best-performing solutions on the indicator *climate change* are shown in green and the worst-performing solutions in red. The solutions that perform well on *climate change* also perform well on impact categories such as *resource use, fossils*, whereas they are less good on *resource use, minerals and metals*. The behaviour of the biomass solution also stands out, having a much greater impact on certain impact categories such as *land use* and *particulate matters*. It is possible to compare these values with the sustainable threshold, identified by the dotted line. For some impact categories, all the configurations are close to 0, so the solution is well below the sustainable threshold for the impact category in question (e.g. *ozone depletion* or *ionising radiation*). On the other hand, some

solutions exceed the sustainable threshold, in particular solutions based on biomass boilers, where the *particulate matter*, *human toxicity*, *non-cancer*, *ecotoxicity*, *freshwater* and *land use* impacts exceed the sustainable thresholds but are sustainable in terms of both *resource use* indicators. Solutions based on gas, which are identified in red because they have an important impact on the *climate change* indicator, largely exceed the sustainable threshold for *resource use*, *fossils* indicator, while solutions using MHP exceed the sustainable threshold for *resource use*, *minerals and metals*.

The presence of storage varies greatly between the different solutions. Only the solutions with an electrical contribution have storage because of the hourly variations in their impact and cost. Storage is used by the optimisation model as a means of minimising the impact of certain categories to the detriment of others. As an illustration, solutions 10 and 20 of Fig. 61 are compared to solution 1 in Table 39. The three solutions are supplied exclusively by a MHP, but the proportion of storage varies. Configuration 10 performs worse overall than solution 1, but reduces the impact on *ecotoxicity*, *freshwater* and *ionising radiation* indicators, at the expense of all the other indicators. Solution 20, on the other hand, presents interesting results because it reduces the impact of several indicators: *climate change*, *eutrophication*, *freshwater*, *ecotoxicity*, *freshwater*, *water use* and *resource use fossils*. The presence of storage can provide a benefit by allowing production to take place during the hours with the least impact. On the other hand, storage has an environmental impact during installation and will lead to losses during storage, as presented in section II.2.2.4. For each configuration, there is therefore a balance between the benefits of using the storage and these trade-offs.

It can be noted that solution 20 performs better than solution 10 on all the environmental criteria but not on the energy criteria, which explains the presence of solution 10 on the Pareto front.

Table 39 - Relative deviation of configurations 10 and 20 compared to configuration 1

	Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals
Configuration 10 compare to 1	5%	9%	-5%	6%	7%	5%	21%	4%	5%	5%	5%	-1%	7%	2%	5%	3%
Configuration 20 compare to 1	-3%	4%	-19%	2%	3%	3%	10%	0%	-2%	1%	1%	-9%	5%	-5%	-2%	2%

The previous results focus on the 35 non-dominated solutions, but it is also interesting to analyse the 35877 dominated solutions. Table 40 presents the share of occurrence of each technology for the non-dominated and the dominated solutions.

While the electric boiler solution appears in 77 % of cases in the dominated solutions, it is never more than 0.1 % present in the non-dominated solutions. This means that the electric boiler rank is close to the Pareto front (high chance of being selected) but it is always dominated by the MHP solution on each impact category and therefore never present on the Pareto front.

The opposite is true for biomass, which appears in 17 % of the non-dominated solutions, while it is never more than 1 % present in the dominated solutions. The share of biomass in the non-

dominated solutions is due to its benefits in some impact categories like *ozone depletion*, *ionising radiation*, *climate change* or *resource use*, so that solutions with a high biomass share are retained in the Pareto front. However, the high presence of biomass in the non-dominated solutions must be put in perspective as the solutions are very close to each other on the Pareto front; for example, in this case, there are 4 solutions with more than 99 % final energy produced by biomass boiler. However, solutions with gas boilers and MHP have for many indicators lower sustainability ratios than biomass boiler. Therefore, the biomass-based solution has lower chance of being selected as a parent for the next generation.

Table 40 - Share of occurrence of each technology in the dominated and non-dominated solutions

	Dominated solution	Non-dominated solution
Electric boiler	77 %	0 %
Gas boiler	87 %	80 %
Biomass boiler	1 %	17 %
MHP	93 %	74 %

For the dominated configuration, there are on average 2.6 energy sources per solution (excluding storage), while for the non-dominated solutions this number decreases to 1.7. This analysis shows that the Pareto front favours solutions with two means of production or less, while solutions with more means of production tend to be penalised by the weaknesses of each energy source and have a higher rank than the parent solutions of which they are composed.

IV.4 Conclusions

In this chapter we have developed an optimisation framework based on a genetic algorithm. This algorithm is used to iteratively generate different combinations of technologies, favouring the best-performing solutions while ensuring that sufficient diversity is retained to explore the entire space. This optimisation model is coupled with a reduction model to limit the computing resources required to obtain these results. The main conclusions considering the set of non-dominated solutions on the Pareto front are:

1. No solution respects all sustainable levels, which would be the ideal case from an environmental point of view. In consequence, there is different approach that can be imagined, the first one would be to find alternatives or improvements to unsustainable categories, e.g. improve metal recycling. The second option could be to modify the distribution of “rights to impact” and therefore define non-priority sectors that will see their share reduced.
2. No solution is better than all the other non-dominated solutions ones for the impact categories that are non-sustainable. This means defining solutions that will be better than others without meeting sustainability criteria. In other words, the recommended solution is not sufficient as it stands, but it is the least impacting.

Unfortunately, none of the solutions on the Pareto front respect any of these two points. It is therefore necessary to take the analysis a step further and define ranking method(s) to differentiate between these 35 Pareto-front solutions. These methods and their analysis are presented in chapter V.

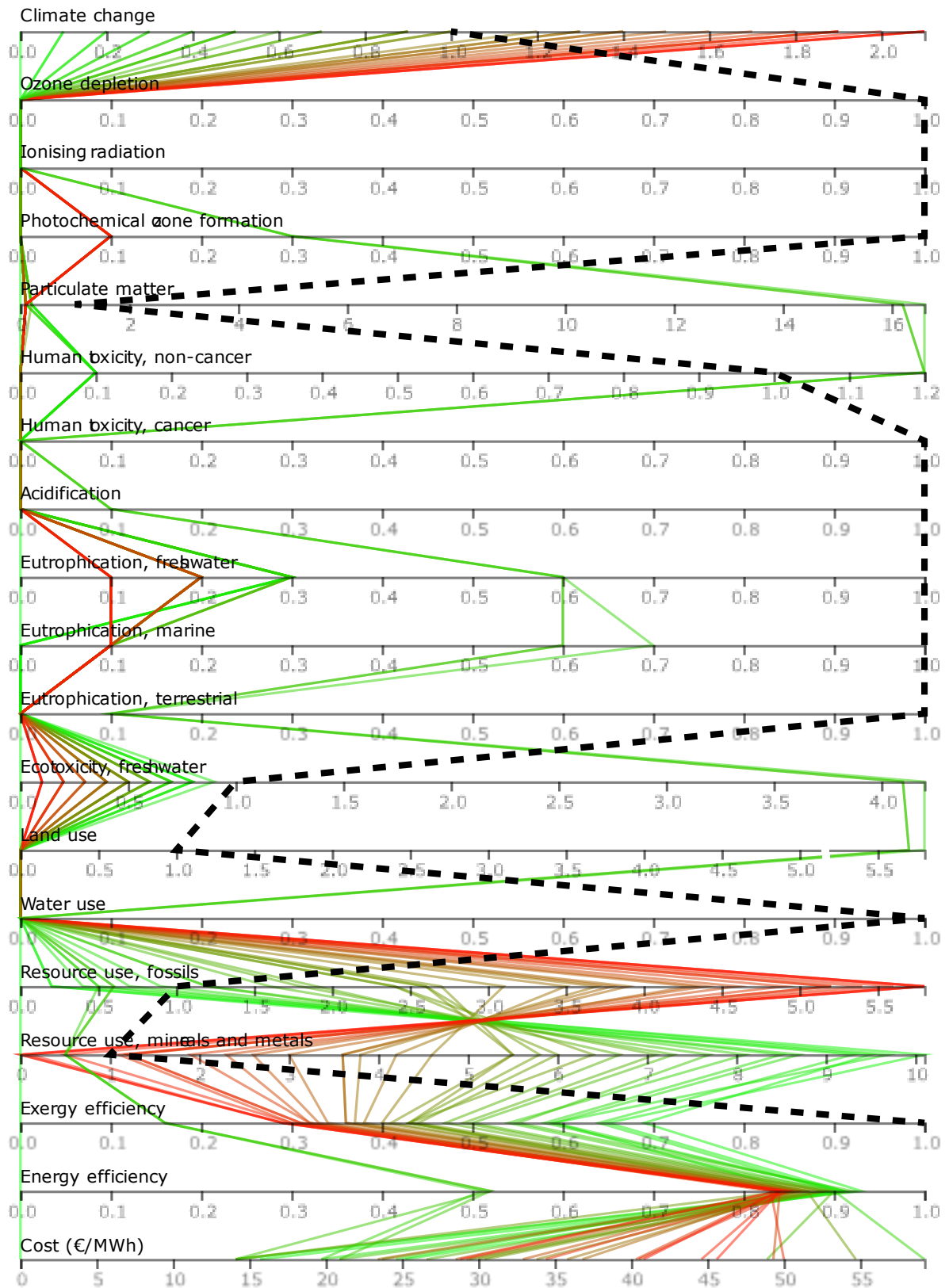


Fig. 62 - Sustainability ratios for each impact category taking C1 as the case study and 35 non-dominated solutions of the Pareto front, represented by a colour code varying from green to red, from the lowest to the highest value of climate change indicators to present the trade-offs

Chapter V

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In this section, the objective is to evaluate and rank the different solutions on the Pareto front in order to identify whether certain technologies are more likely to meet GHG reduction targets than the others without degrading other environmental impact categories.

The methodology is applied to 45 configurations made up of combinations of 3 processes, 5 energy mix linked to 5 trends representative of 2050 electricity mix projections in Europe and for 3 time periods (2015-2040, 2040-2065 and 2065-2090). Each of these configurations is analysed using three ranking methods to incorporate different penalty levels for solutions that exceed the sustainable thresholds.

The study is divided into 3 parts:

- i) starting with analysis of environmental performance to highlight the environmental impacts of the various technologies studied in relation to sustainable limits, and the creation of a ranking of each technology to limit the extent to which it exceeds thresholds.
- ii) This is followed by a study to assess the correlations between energy and exergy efficiencies and environmental scores.
- iii) Finally, a study of the cost over the life cycle of each technology (including CAPEX, OPEX, energy, carbon tax) are put into perspective with environmental scores.

V.1 Ranking methods

As mentioned in chapter IV, analysis criteria are needed to rank the 35 solutions of the Pareto front, since there is no solution that satisfies all sustainability criteria. To the best of our knowledge, the most widely accepted way of classifying solutions is to use weighting scores W_{Sy} derived from the Life Cycle Impact Assessment (LCIA) and presented in Table 41. Even if, as explained in the introduction (part I.3.3), the use of weighting scores introduces additional uncertainties when it comes to translating the midpoint categories into damage, it is a simple way of considering all environmental criteria in a single value.

Table 41 - Weighting scores from EF 3.0

Weighting (W_{Sy})	EF 3.0	Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals
		21 %	6 %	5 %	5 %	9 %	2 %	2 %	6 %	3 %	3 %	4 %	2 %	8 %	9 %	8 %	8 %

However, LCIA weighting scores do not consider sustainable limits, which are the scope of this thesis. Therefore, in addition to the standard weighting approach, which is named R1, we propose two alternative ranking methods - R2 and R3 - combining LCIA weighting scores and new proposed indicators (S_{ry} , C_{ly}) to assess the level of sustainability. For each ranking method, a lower score is better than a higher one.

- (i) **Ranking 1 (R1)** weighs the different impact categories y with the standard EF 3.0 impact weighting scores W_{S_y} presented in Table 41 (equation V-1).

$$R1 = \frac{\sum_y W_{S_y} \cdot S_{r_y}}{\sum_y W_{S_y}} = \sum_y W_{S_y} \cdot S_{r_y} \quad V-1$$

- (ii) **Ranking 2 (R2)** is based on R1 but adjusts the weighting score W_{S_y} using a new factor C_y^* based on both the sustainable ratio S_{r_y} and the contribution level C_{l_y} of the solution; this factor increases the weighting of impact categories that have a significant impact on the environment as presented in equation V-2.

$$R2 = \frac{\sum_y W_{S_y} \cdot |C_y^*| \cdot S_{r_y}}{\sum_y W_{S_y} \cdot |C_y^*|} \quad V-2$$

C_y^* adds to the sustainable level criterion, the importance of the sector to the total impact contribution. Indeed, as it was highlighted in Chapter III (Section III.2.2, case ii and iii), if the sustainability ratio is high, but the contribution level is low, reducing the environmental impact of this sector may not have a significant impact on the global sustainability but remains a needed target. On the contrary, reducing the environmental impact of a sector having a high contribution level can have a significant effect on the impact category even if the impact level of this sector is below the threshold. Therefore, both configurations can be considered as equivalent. This equivalence is reflected by the factor C_y^* , which value corresponds to the coordinates of the orthogonal projection (S_{r_y} , C_{l_y}) of the considered sector on the linear function “sustainability = contribution” as presented in Fig. 63. This figure shows the sustainability ratio versus the contribution level for three different sectors A, B and C. B has a high sustainability ratio (i.e. a poor sustainability) but a small contribution level (i.e. this sector has a limited contribution when considering all the contributions from all sectors for this specific impact), while C behaves in the opposite way. With the proposed method, we obtain $|C_{y,B}^*| = |C_{y,C}^*| = 1.25$ so that the contribution of B and C are equivalent in their ability to achieve or maintain a sustainable level for the considered impact category y . For the sector A, we obtain $|C_{y,A}^*| = 0.6$.

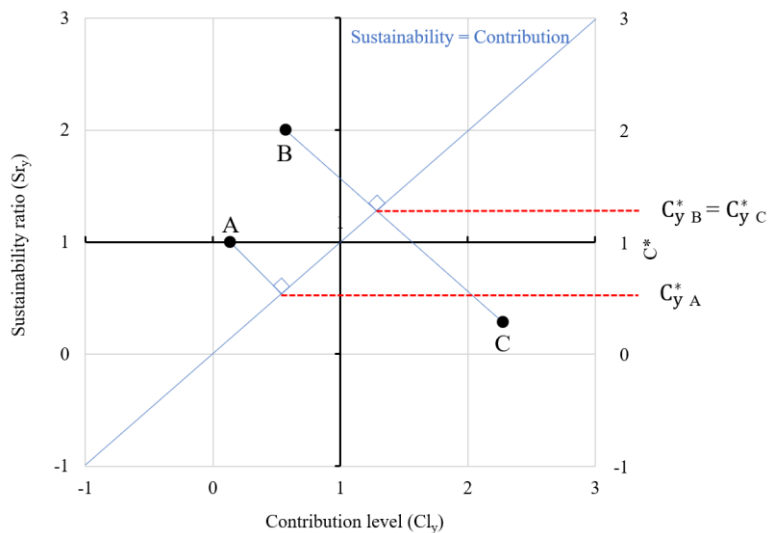


Fig. 63 - Weighting factor C_y^* for different processes

Note that the absolute value of C_y^* factor has to be used in eq. V-2. Indeed, while for most indicators the resulting value is generally positive (i.e. the impact to the environment is negative), this is not the case for biomass associated with CCS, which can have negative values corresponding to the benefice on climate change due to the sequestration and storage of carbon which is removed from the atmosphere.

(iii) **Ranking 3 (R3)** is similar to R2, but adjusts the weighting score W_{S_y} using another factor C'_y which penalises even more the values above the sustainable level than factor C_y^* (equation V-4) and less the values below it (equation V-3).

$$R3 = \frac{\sum_y W_{S_y} \cdot C'_y \cdot S_{r_y}}{\sum_y W_{S_y} \cdot C'_y} \quad V-3$$

$$\begin{cases} C'_y = e^{[C_y^*]^{-1}} & \text{if } C_y^* < 0 \\ C'_y = [C_y^*]^2 & \text{if } C_y^* > 0 \end{cases} \quad V-4$$

Adjustement factors C'_y and C_y^* are plotted versus C_y^* in Fig. 64. The C'_y factor aims to increase the score for any value that significantly exceeds the sustainable limit and/or has an important contribution. For positive C_y^* , the squared value implies that the more a solution exceeds the threshold of 1, the more its weighting increases and thus the overall score of the solution is degraded. For impact categories exceeding the sustainable threshold, a higher weighting is applied with R3 (in blue in Fig. 64) than with R2 (in orange in Fig. 64), whereas the opposite is true for values below 1. Moreover, it ensures that compensation is not possible with negative values, i.e. when biomass is combined with CCS (negative emissions from the growing phase of biomass are stored after combustion and therefore counted negatively in the GHG balance).

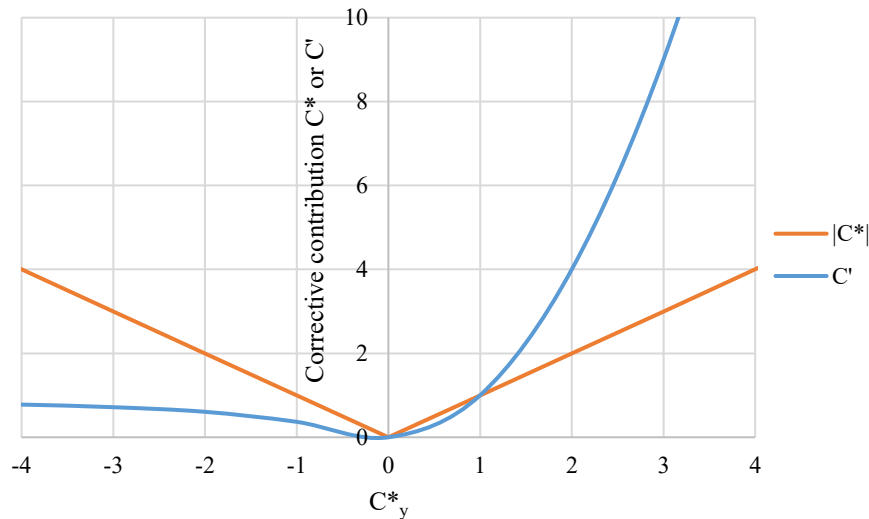


Fig. 64 - Graphical representation of corrective coefficients $|C_y^*|$ and C'_y versus C_y^*

Concerning the negative values of C_y^* , that can appear with biomass and CCS, the value $|C_y^*| \cdot S_{r_y}$ is going to be negative (S_{r_y} is always negative by definition when C_y^* is negative) and therefore can compensate for positive values on other impact. To limit this compensation effect, C' value are always lower than 1, even for solutions with a very strong negative impact. In this way, the

value $C'_y \cdot Sr_y$ is still negative but gives a lower share to the impact categories to limit overcompensation of other indicators exceeding sustainable thresholds.

Of course, these different weighting proposals are not the only ones possible, but they do allow various options for penalising sustainability limits to be tested.

V.2 Reminder of the studied configurations

This study considers different configurations to assess the best technology or combination of technologies to produce industrial heat in the following conditions:

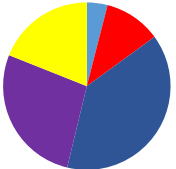
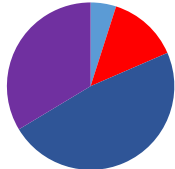
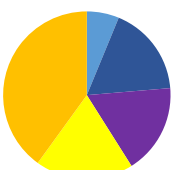
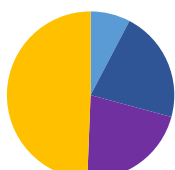
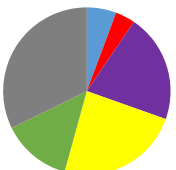
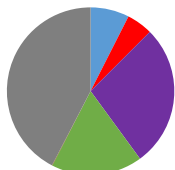
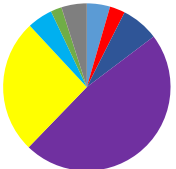
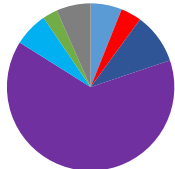
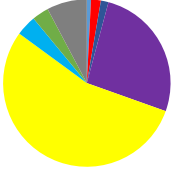
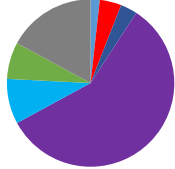
1. Three different industrial demands: Weekly, Continuous and Batch processes presented in part II.2.4.
2. Three different periods of time (2015-2040; 2040-2065; 2065-2090). The difference between these time periods is the development of CCS and a more ambitious target for the *climate change* threshold to follow the GHG reduction scenarios to limit warming to 2 °C compared with the pre-industrial era.
3. Five electricity mix for MHP and electric boilers, which represent the trends for new installations in Europe as presented in part II.2.3.1. The share of each energy source among the new installed sources for electricity production and the high-voltage mix used by industry are presented in Table 42.
4. Three ranking methods presented in part V.1, used to rank the production

For each case studied, there is therefore a type of process, a time period, an electricity mix and a type of ranking, which will be named as follows: *Weekly, C1, 2015-2040, R1* in the rest of the manuscript.

Due to the large number of configurations - 45 configurations plus parametric studies - it is not possible to present all the results in detail. The full set of results is available in Appendix 8. The data sets are classified by mix, then by process type and finally by time period. The formatting of the results data sheets is presented in Fig. 65, and is divided into 3 parts:

1. The section identified in blue shows the rankings and scores for the 3 ranking methods of the 35 non-dominated solutions according to the energy sources used.
2. The section marked in green shows the electricity mix considered for the cluster.
3. The red section presents the detailed results of the Pareto front, with each line corresponding to a solution that meets the industrial need. The rank of each solution is shown for the 3 ranking methods. Boxes in orange correspond to criteria that exceed the sustainability limit.

Table 42 - Electricity share for new installed production technologies for the 5 mix considered

	New installed electricity production technologies	New installed electricity production technologies used in industry (high tension)
C1		
C2		
C3		
C4		
C5		

- Dammed hydro
 - Onshore wind
 - Biomass
 - Gas
- Geothermal plants
 - Photovoltaic
 - Solid
 - Nuclear
- Offshore wind
 - River hydro
 - Petroleum

A4 1 - C1 Germany - 2015-2040 - Continuous process

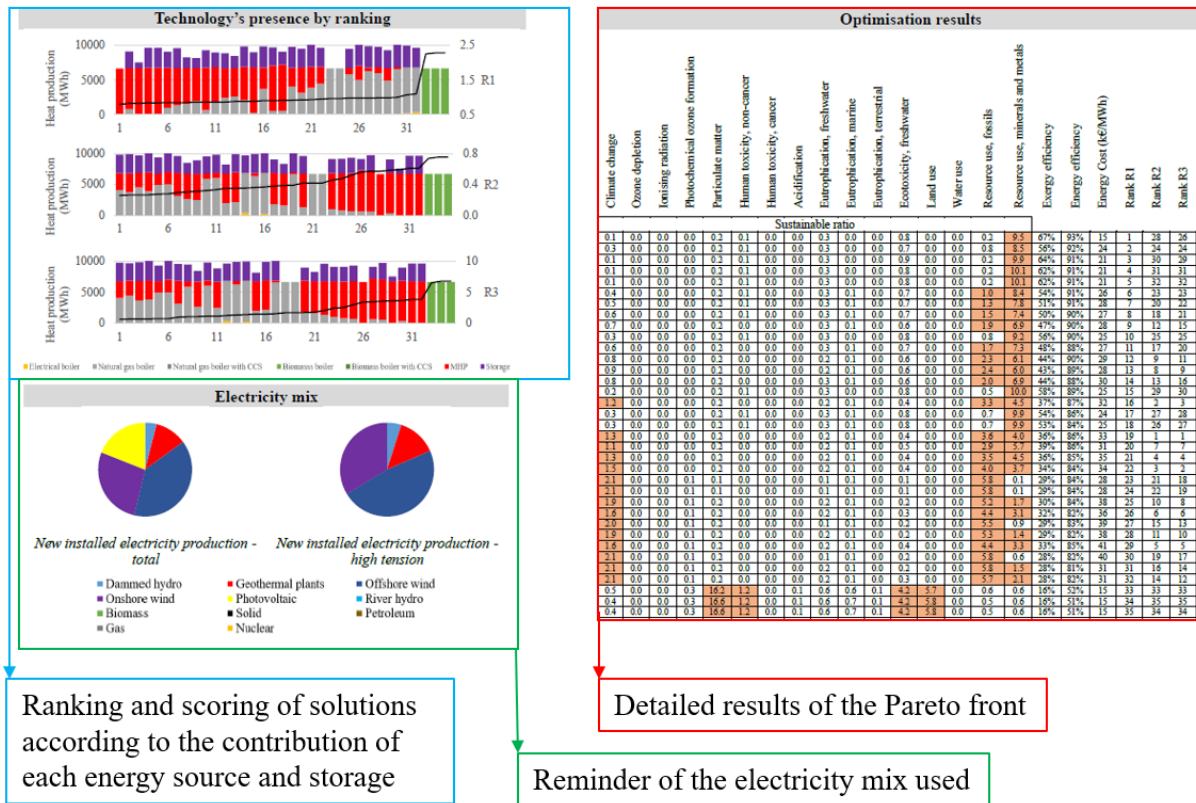


Fig. 65 - Format of the results available in Appendix 8

V.3 Overall trends

In this section, the analysis is performed on the raw results of the optimisation algorithm in order to identify general trends that can be found across all testing configurations without using ranking methods.

V.3.1 Identification of recurring technology patterns

V.3.1.1 Continuous and Weekly processes cases

Some technologies (MHP, biomass and gas boilers) are always present in the 35 non-dominated solutions, while the electric boiler is always dominated by the MHP. For example, the results for configuration C1, weekly, 2065-2090 is presented in Fig. 66. The 35 solutions of the Pareto front are classified depending on their impact on (a) climate change, (b) resource use, fossils, (c) resource use, minerals and metals and (d) energy cost. The share of each energy in the total energy consumption over the one-year period is reported in the y-axis. The biomass boiler performs best on the climate change and energy cost indicators, MHP on the resource use, fossils indicator and the gas boiler on the resource use minerals and metals indicator. The electric boiler is always dominated by the MHP and is therefore never present in the Pareto front, even if it performs better than biomass or gas boilers on some indicators.

This result can be generalised to all cases so that, whatever the choice of electricity mix, there is no technology is worse than the others on all environmental criteria, with the exception of the electric boiler. It is therefore necessary to use ranking methods to assess which solution performs best as carried out in the next section.

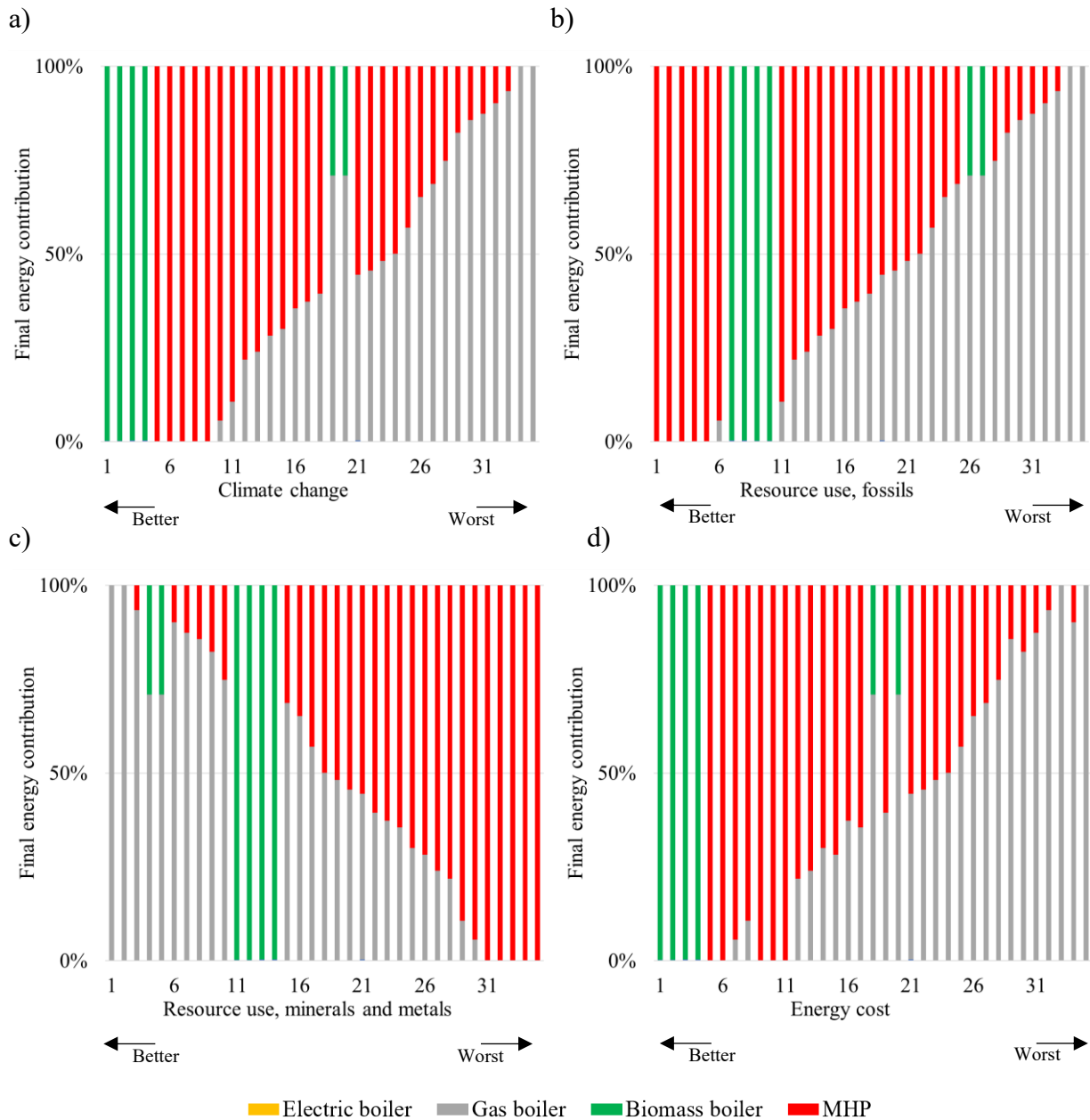


Fig. 66 - Ranking of Pareto front's technologies for configuration C1, Weekly, 2065-2090 based on impact categories a) climate change, b) resource use, fossils, c) resource use, minerals and metals and d) energy cost

V.3.1.2 Batch process case

As it can be seen on Fig. 67 for the 2015-2040 period, the identified configurations differ significantly from those of continuous cases. Indeed, electric boiler is present as the main heat generation source when considering economic criterion (Fig. 67b). The results are different due to the limits on the available amount of waste heat due to intermittency. Hence the heat production from MHP varies and need to be combined with a storage (Fig. 67). Biomass boiler also needs to be coupled with storage in order to comply with its ramp-up limit. For the batch process case, the electric boiler is present in some configurations in 2015- 2040 thanks to its economic competitiveness. Electric boiler solution offers the advantages of flexibility and a lower initial cost, making it more economically competitive compared to MHP combined with storage.

This trend reverses from 2040-2065 period (the trends are the same compared to the one presented for period 2065-2090), as energy price inflation and the development of MHP - which leads to a reduction in investment in this technology - make the electric boiler less competitive, causing it to disappear from the Pareto front. For the batch process, all the technologies have more chance to be in the Pareto front, which increases the possibility of combinations. For this type of process, the results are less straightforward because (i) there is more production technologies and (ii) as production is intermittent, storage plays a key role in limiting impacts and allows the use of biomass and MHP.

As with the continuous and weekly processes, it is not possible to select a technology without using ranking methods, because each technology studied is on the Pareto front and therefore has strengths and weaknesses.

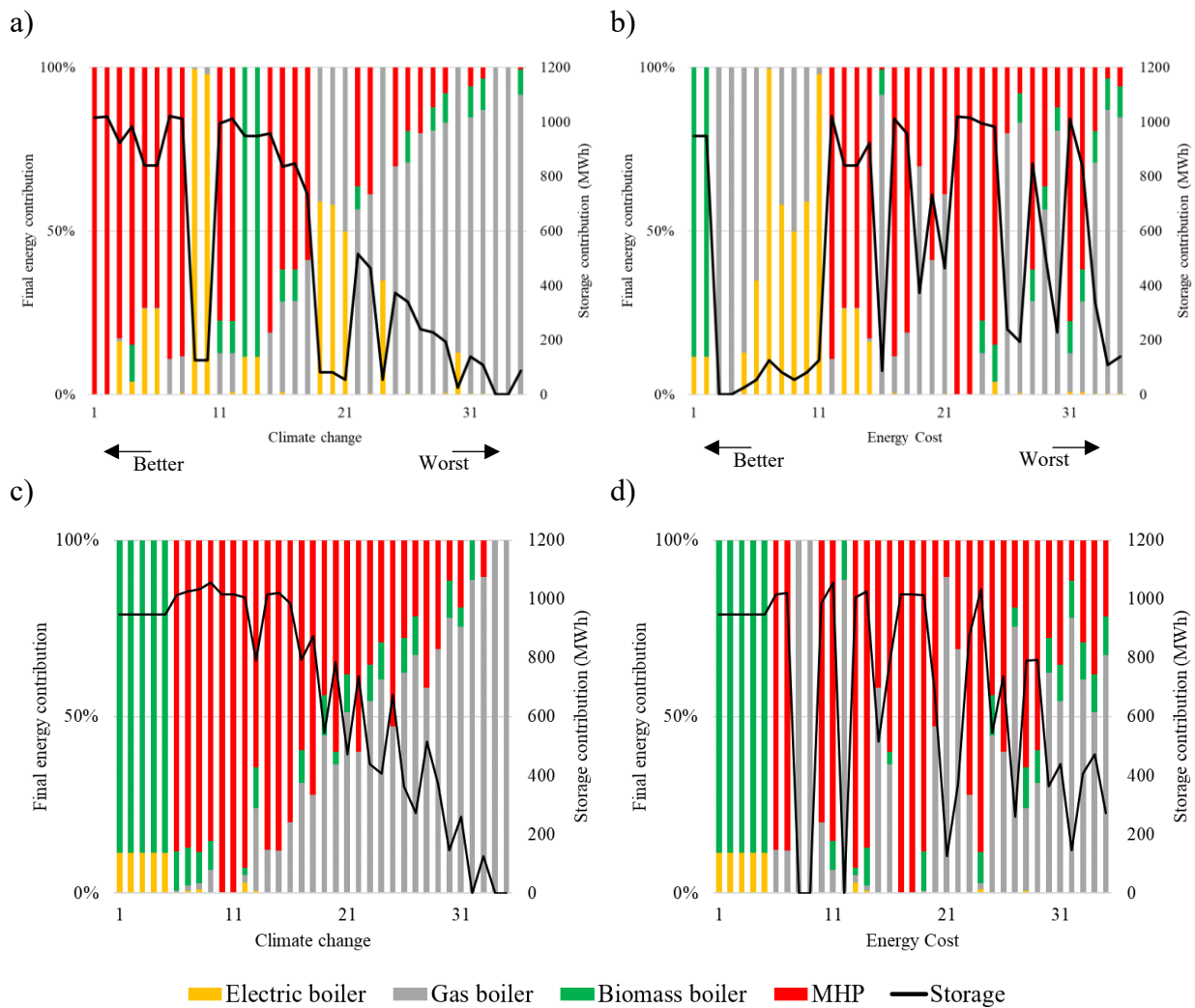


Fig. 67 - Ranking of Pareto front's technologies for configuration C1, Batch, based on impact categories a) climate change for 2015-2040 and b) energy cost for 2015-2040, cc) climate change for 2065-2090 and d) energy cost for 2065-2090.

V.3.2 Performance of non-dominated solutions with respect to sustainable thresholds

The sustainable ratio (Sr) of each technology is presented in Fig. 69 for (a) 2015-2040 and (b) 2040-2065 and c) 2065-2090. The plotted result corresponds to the cases for which the heat demand is covered by one single technology. This enables to assess for which impact category a technology meets the sustainable threshold, defined by a value lower than 1. When considering each technology separately, no solution respects all the sustainable thresholds for all the processes and the electricity mix studied. This can be explained by the presence of drawbacks specific to each technology as synthesised in Table 43.

Table 43 - Unsustainable impact category for the studied technologies

Technology	Impact categories above sustainable level
Electricity-based technologies with an electricity mix based on renewable (C1, C4 and C5)	Resource use, minerals and metals Ecotoxicity, freshwater Climate change
Electricity-based technologies with an electricity mix based on nuclear (C2)	Resource use, fossils Resource use, minerals and metals
Electricity-based technologies with an electricity mix based combustion-based technologies (C3)	Resource use, fossils Climate change Resource use, minerals and metals
Gas boiler	Climate change Resource use, fossils
Biomass boiler	Particulate matter Human toxicity, non-cancer Ecotoxicity, freshwater Land use

Some impact categories such as *ozone depletion*, *ionising radiation*, *human toxicity cancer*, *acidification* and *water use* have a low impact (at least 10 times below the sustainable threshold) whatever the conditions. These impact categories are therefore not considered further because their small contribution does not bring relevant information for classification despite their criticality for other sectors, e.g. water use for agriculture (Fig. 68). In addition, for these impact categories the sector studied does not use all the available safe operating space allocated for the sector when using the method based on GVA.

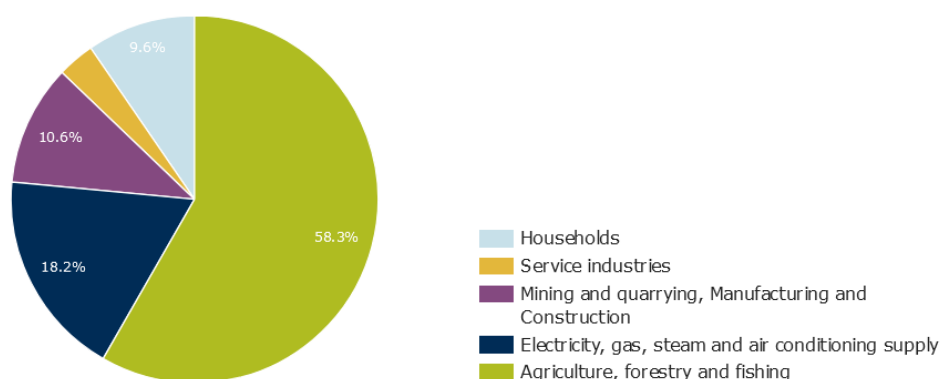


Fig. 68 - Water use in Europe by economic sector in 2017 from [161]

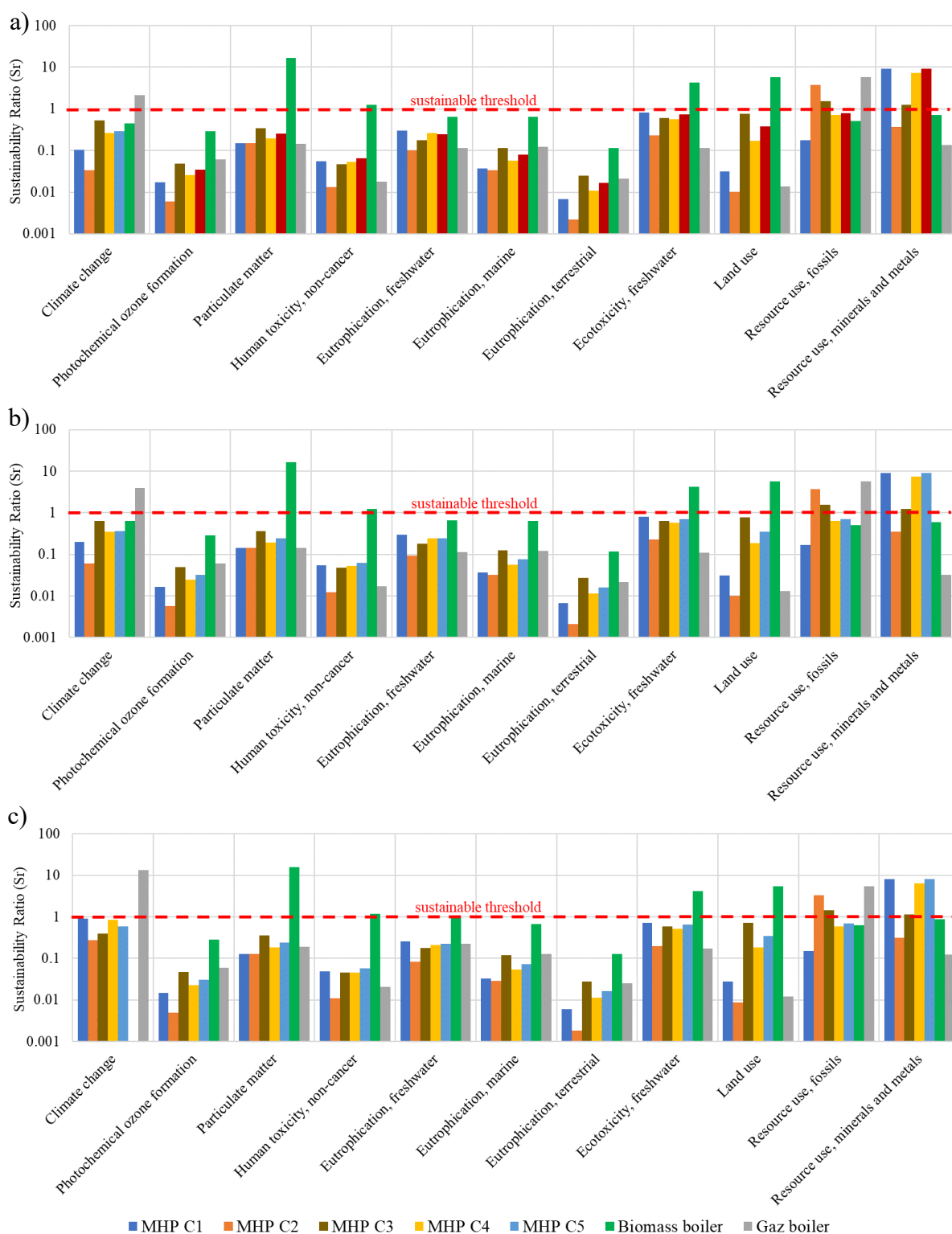


Fig. 69 - Sustainable ratio in logarithm scale for weekly process, during periods a) 2015-2040 b) 2040-2065 and c) 2065-2090. The red dotted line represents the sustainable level. Each technology selected on the Pareto front is used 100 % of the year

V.3.3 Impact of CCS in non-dominated solutions

Carbon Capture and Storage (CCS) is one of the strategies proposed to limit the greenhouse gas emissions of combustion-based technologies as presented in part I.2.6. This technology enables to limit the impact on *climate change*, which is one of the two main weaknesses of gas-based solutions (with the consumption of fossils resources). However, adding CCS to these technologies degrades their other impact categories due to the addition of capture, transport and storage steps and of the energy consumption linked to them. In particular, the impact *resource use, minerals and metals* - which is a characteristic of the solutions based on electricity (Table 44a) – increases significantly.

Table 44 - Ratio of the environmental indicators between a) gas boiler and gas boiler with the average CCS projected in 2065-2090 and b) electric boiler for the average electricity mix C1 with gas boiler with the average CCS projected in 2065-2090. The red colour is used when gas with CCS performs worst and green when it performs better.

	Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals
a)	1.36	0.94	0.94	0.9	0.64	0.71	0.71	0.79	0.42	0.82	0.73	0.54	0.94	0.49	0.94	0.18
b)	0.17	0.05	0.53	0.52	1.66	3.38	3.39	0.5	3.01	0.52	0.4	7.01	4.32	4.04	0.08	13.28

The addition of CCS in case a) leads to a reduction in *climate change* indicator but an increase in all the other indicators. In particular, there will be a significant increase in the *resource use, minerals and metals* or *eutrophication, freshwater* categories, due to capture and storage, but above all due to the transport of CO₂ to the storage site. In comparison in case b), gas with CCS has a more significant impact than an electric boiler on *climate change* (and other impact categories identified in red in Table 44), but simultaneously, a far less impact on *resource use, minerals and metals* category (13 times lower compared to the electric boiler), despite the additional contribution due to CCS implementation. From multi-objective optimisation point of view, gas boiler combined with CCS has therefore an impact closer to electricity-based solutions and therefore a lower distance with them on the Pareto front because it reduces the gap between impact categories with significant distance without CCS (e.g., *climate change*, *Resource use, minerals and metals*). This change in distance therefore frees up an area of the multi-dimensional space and modifies the Pareto front with a lower impact on the *climate change* indicator and an increase on the other impact categories.

It is interesting to highlight that the growth rate of CCS does not allow to decrease GHG emissions enough to follow the reduction of the sustainable level for the climate change indicator. Indeed, between the periods 2015-2040 and 2065-2090 for the CCS development rate presented in part II.2.3.3, the reduction of GHG emissions is on average 26 % for gas boilers with CCS when the sustainable threshold for the climate change indicator is reduced by 89 % (as presented in part II.6.3.1). Even with a higher or total penetration of CCS, the effectiveness of this solution is not sufficient to compensate for the reduction in the sustainable threshold of climate change, with the assumption use in this work a CCS with 100 % penetration can only reduce by 67 % the GHG emission. The solution will therefore increasingly exceed the sustainable threshold over time.

For BioEnergy with Carbon Capture and Storage (BECCS), the *climate change* impact becomes negative, enabling to decrease the quantity of GHG in the atmosphere. Unlike the gas boiler with CCS, the performance of the BECCS solution will become increasingly interesting over time, as it is the only solution that can offset the impact of other technologies on the *climate change* indicator. This may explain why this solution is so often found in the integrated assessment scenarios synthesised in IPCC Group III assessment reports.

V.4 Environmental assessment and ranking

V.4.1 Analysis of reference configurations during period 2015-2040

In this section, the results of the different case studies (electrical mix, type of process) are presented and analysed for the 3 ranking methods R1, R2 and R3 for the period 2015-2040. As presented in the previous section, the impacts of the electricity clustering C1 to C5 can be divided into 3 categories for which the trends are similar:

1. Mix based on renewable energies, including clusters C1, C4 and C5, are represented by C1.
2. Mix based on a significant share of nuclear represented by C2.
3. Mix based on a significant share of thermal powerplant represented by C3.

Similarly, the processes can be divided into 2 categories:

1. Weekly and continuous processes have the same trends, thus only the weekly process is presented.
2. Batch process leads to different results due to waste heat availability.

There are therefore 6 different configurations that are presented in this study. For each configuration presented in Table 45, all the 3 ranking methods are presented, although R2 and R3 rankings give very similar ranking in most cases. When R2 and R3 rankings are similar, only the result of R3 is presented.

Table 45 - List of configurations studied for the reference cases with the link to their corresponding Appendix 8

	Weekly and continuous processes	Batch process
Mix based on renewable	Configuration 1: A4 - 4	Configuration 2: A4 - 7
Mix based on nuclear	Configuration 3: A4 - 13	Configuration 4: A4 - 16
Mix based on thermal powerplant	Configuration 5: A4 - 22	Configuration 6: A4 - 25

V.4.1.1 Detailed analysis for mix based on renewables

Weekly and continuous processes

For configuration 1, solutions with a higher proportion of MHP tend to be better ranked with R1, while solutions predominantly gas or biomass-fired tend to be ranked lower (Fig. 70). R3 (or R2) tends to promote solutions with a mix of gas and MHP rather than solutions relying only on one source like gas or MHP, which rank 20th or higher. It can be noted that for R1, the score is very similar for configurations made up of MHP and gas boiler. There is no real difference between these different configurations, whereas the solutions using the biomass boiler have a much higher score. For R3, on the other hand, the best solutions are those with approximately 1/3 MHP and 2/3 gas boiler. As the proportion of either MHP or gas boiler increases, the R3 score rises. A significant increase in MHP leads to a significant increase in the R3 score, with a score 4 times higher than the optimum for the 100 % MHP-based solution.

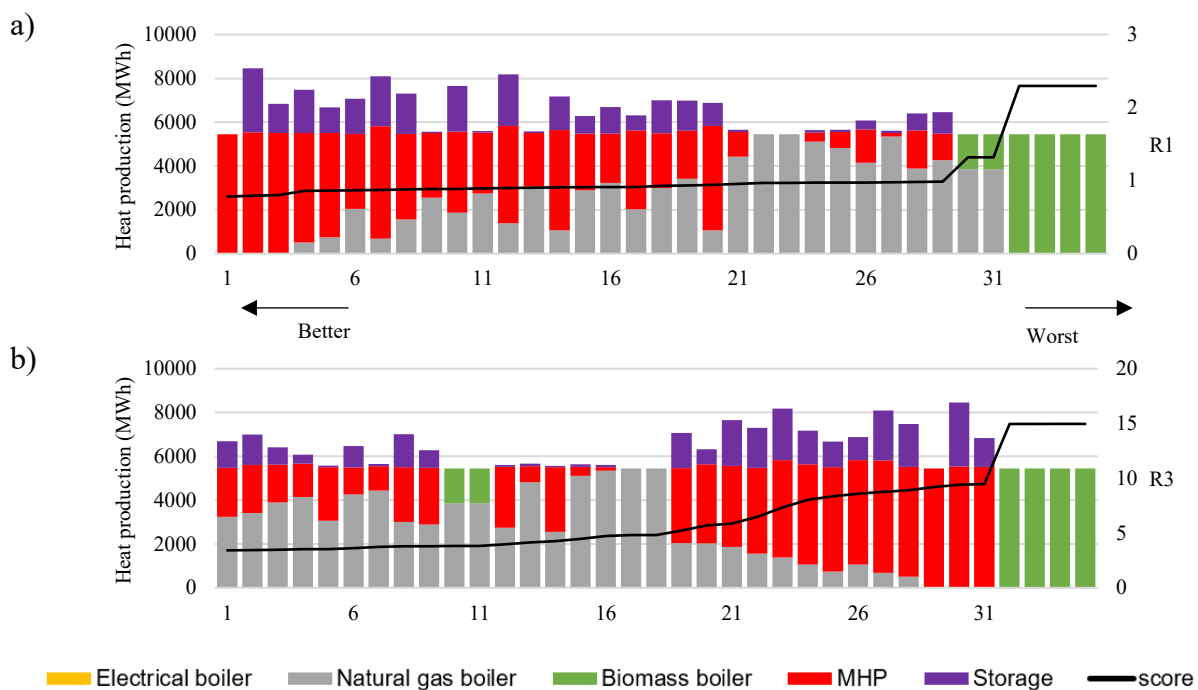


Fig. 70 - Ranking of the Pareto front solutions for C1, Weekly, 2015-2040, and ranking methods a) R1 and b) R3

The best-ranked solution for R1 exceeds the sustainability ratio only for the *resource use, minerals and metals* indicator with a factor of 9.3 (Fig. 71). For the best-ranked solution for R3 (or R2), the sustainable threshold is exceeded for 3 impact categories with a sustainability ratio of 1.5, 4 and 3.2 respectively for *climate change, resource use, fossils* and *resource use minerals and metals* indicators. The uneven distribution of weights in the ranking method R1 tends to favour solutions with low contributions for high weights. Therefore, the solution with a lower contribution on *climate change*, which contributes to 21 % of total weight, is preferred to the solution with a low contribution on *resource use, minerals and metals*, which contributes only to 8 % of the total weight. Because R3 (or R2) penalises more the solutions exceeding the sustainable thresholds, the best-ranked solutions identified with R1 are poorly ranked with R3. For the solutions based only on MHP, the weight of *resource use minerals and metals* indicator rises from 8 % with R1 to 89 % and 99 % for R2 and R3 respectively. As the sustainable threshold for this impact category

is considerably exceeded, its score increases sharply, and its rank rises from 1st place with R1 to 27th place with R3 (Fig. 70).

For gas, the conclusions are similar to MHP but for opposite reasons. The average gas share of the best solutions is 0 % for R1, but 54 % for R2 and R3. Indeed, gas is strongly penalised with R1 due to the important weight of *climate change*. On the other hand, since R2 and R3 penalise more indicators exceeding sustainable limits, the optimum solution is a mixed solution, which spreads out the most significant impacts. Gas exceeds *climate change* and *resource use, fossils* indicators, but is the best solution on the *resource use minerals and metals* indicator, principal drawback of the MHP solution.

For the 3 ranking methods, solutions based solely on biomass are always the lowest-ranked, as the sustainability thresholds for certain impact categories are significantly exceeded, as presented in part V.3.2 in Table 43.

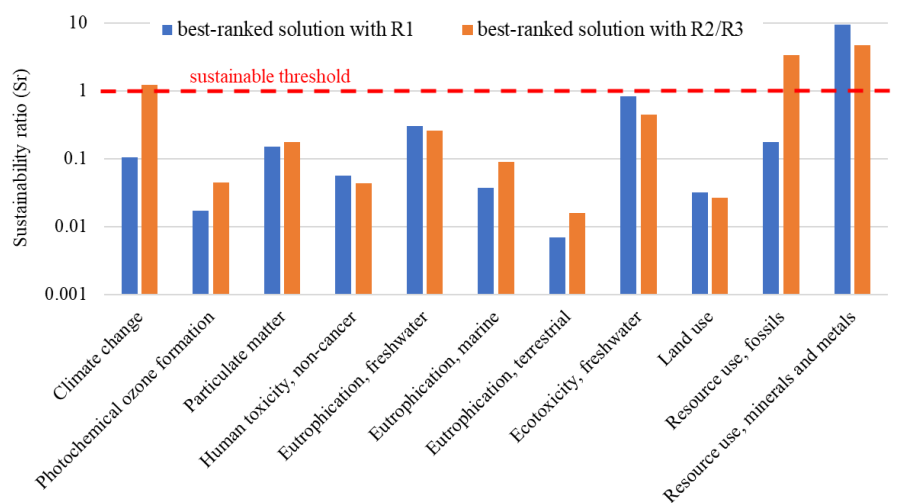


Fig. 71 - Sustainability ratio of the best ranked solutions obtained with R1 and R2/R3 for configuration C1, Weekly, 2015-2040. Note that R2 and R3 have exactly the same value for the best ranked solution.

As explained in chapter I, the different impact categories (midpoint assessment) lead to different damage area (endpoint assessment). Therefore, a distinction can be made between impact categories that contribute either to endpoints *damage to human health* and *natural environment* and those that contribute only to endpoint *resource availability*. With R2 and R3, the renewable energy solutions are strongly penalised for significantly exceeding the resource availability limit, even if they do not exceed the sustainable ratio of the indicators linked to endpoint categories *human health* and *natural environment* (Fig. 71, R1). However, as it is not physically possible to exceed the resource consumption limit, R2 and R3 methods enable to eliminate solutions that are virtuous on many indicators but not physically realistic.

Batch process

The conclusions for configuration 2 (same period, batch process) are generally similar, with solutions relying mainly on MHP and gas boiler better ranked by the 3 ranking methods (Fig. 72). Furthermore, for the three rankings, there is no significant variation in score between solutions based mainly on gas or MHP compared to other solutions on the Pareto front. Despite the high weighting of the *climate change* indicator, gas is well ranked because of the huge impact of the indicator *resource use minerals and metals* for electricity-based solutions in this configuration.

Because of the lack of waste heat in this process configuration compared to weekly and continuous processes, MHP is forced to be coupled with storage, which reduces the global efficiency of the production of heat due to heat losses during the storage hours. Furthermore, with the small operating time of the batch process (operating less than 13 % of the time), the initial impact of the installation of the MHP, its working fluid and the storage system cannot be compensated by a lower impact of energy. As a result, the MHP production are less dominant than in continuous and weekly processes especially for ranking R2 and R3.

Biomass-based and electric boiler solutions are poorly ranked for all rankings. For biomass, this is because it has either very low or very high impacts, which penalises its rankings overall. The 4 best solutions in the R3 scoring have a biomass component (around 5 %), which limits resource consumption without exceeding sustainable thresholds for *particulate matter* and *land use* in particular. The presence of Electric Boiler on the Pareto is due to its economic competitiveness, but all environmental criteria are worse than those of MHP, resulting in higher R1 and R3 scores (Fig. 71).

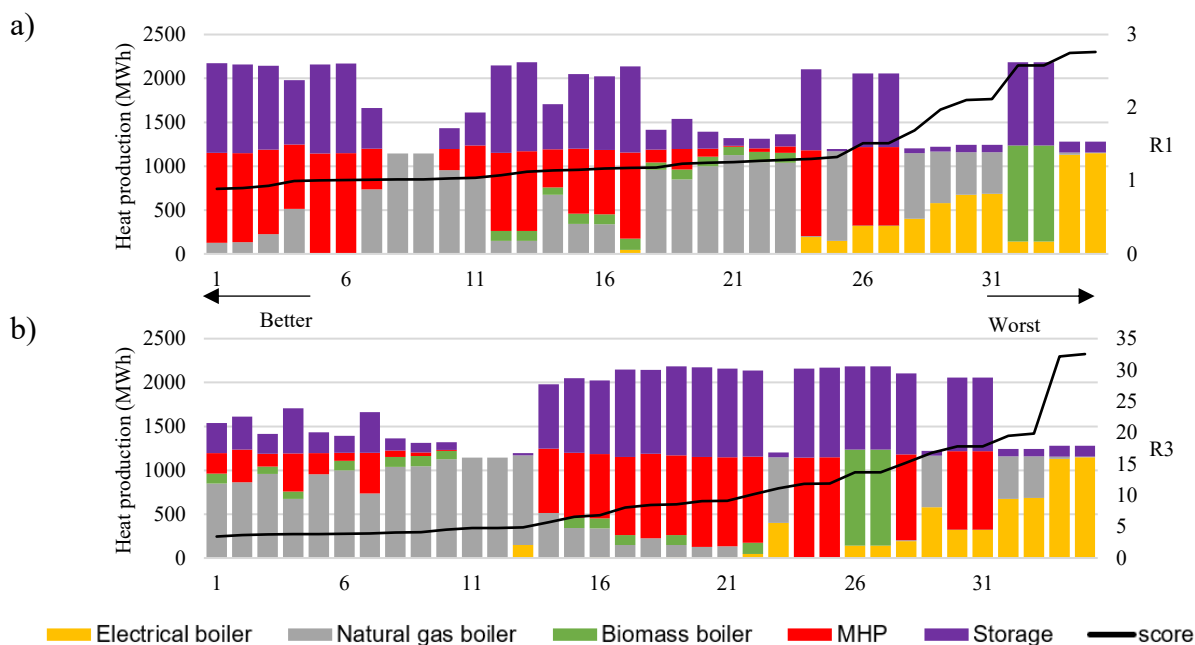


Fig. 72 - Pareto front solution's ranking for configuration C1, batch, 2015-2040 with ranking a) R1 and b) R2/R3. The best solution is the one on the left with the index 1.

V.4.1.2 Detailed analysis for mix with significant nuclear share

Weekly and continuous processes

The nuclear-intensive mix of cluster C2 are represented by a French scenario also named configuration 3. For the periods 2015-2040 and for the 3 ranking methods, the trend is the same with a ranking dominated by MHP based solutions (Fig. 73). As far as the R1 score is concerned, there is a gap between solutions based solely on MHP and other technologies. There is an even higher score for biomass solutions, which reflects the very negative impacts on categories highlighted in section V.3. However, it is worth noting that MHP solutions combined with a share of biomass (about 10 %) or gas (up to 5 %) obtain a better score for ranking R3 than MHP alone. It can be seen in Fig. 74 that the presence of biomass is the best way to reduce the overshoot of *resource use*, *fossils* for MHP due to nuclear combustible consumption in the electricity mix. This

category is the only indicator that exceeds (by a factor 3.8) the sustainable threshold for MHP. On the other hand, the quantity of biomass is limited to avoid exceeding other limits, as the use of biomass boilers can lead to a strong increase in indicators such as *particulate matter* and *land use* (Fig. 74). Solutions with a high share of gas boiler are ranked lower because they cannot compete with the MHP driven by electricity mix C2, which perform better on all impact categories, except those that are already sustainable. However, gas-based solution is worse for unsustainable impacts such as *climate change* with a S_r of 2.10 compared to 0.03¹ for MHP, and *resource use, fossils* with a S_r of 5.8 compared to 3.8 for MHP.

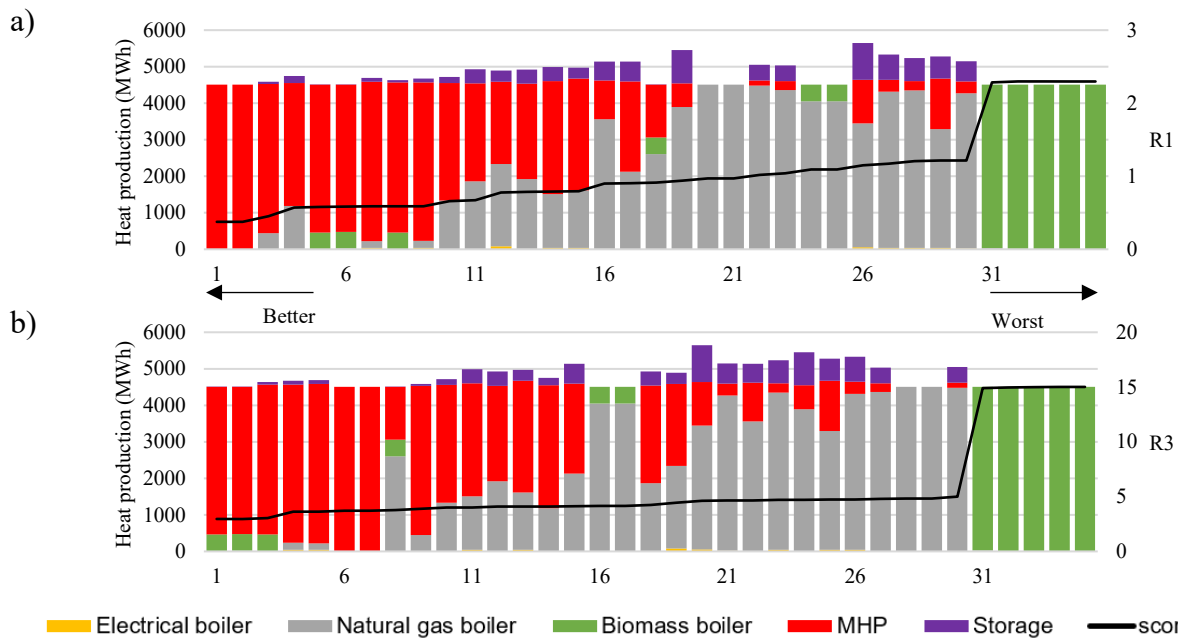


Fig. 73 - Pareto front solution's ranking for configuration C2, weekly, 2015-2040 with ranking a) R1 and b) R3. The best solution is the one on the left with the index 1.

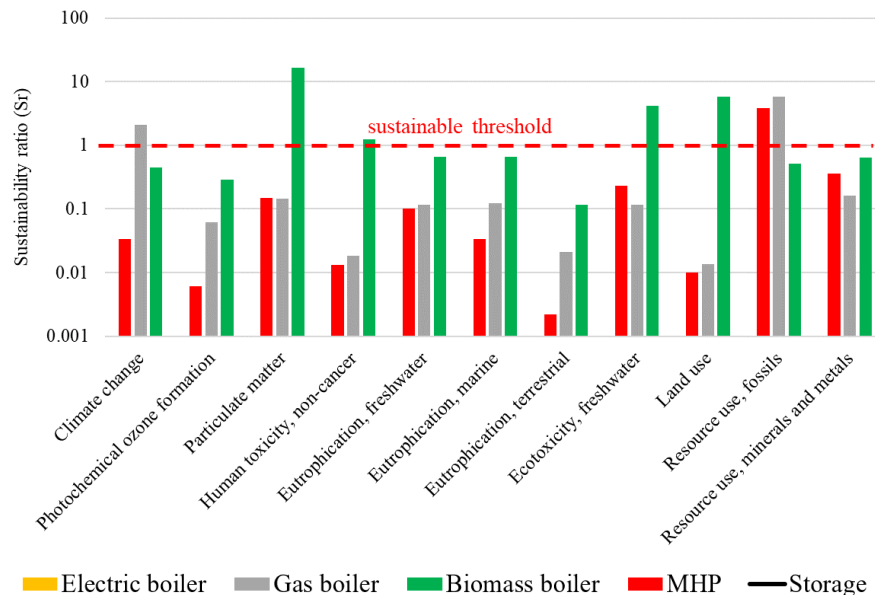


Fig. 74 - Sustainability ratio for MHP, gas boiler and biomass boiler solutions for configuration C2, weekly, 2015-2040

¹ The carbon content of gas boiler is taken at 237 gCO_{2eq}/kWh, the hourly variation of carbon content for electricity is within the range 10 to 20 gCO_{2eq}/kWh (without taking into account MHP COP).

Batch process

For the batch process (configuration 4), the best solutions are dominated by a mix of MHP with a share of biomass boiler (between 5 and 10 %), while the biomass-based and electric boiler solutions remain the worst ranked in all methods similarly to the mix C1. For both rankings presented in Fig. 75, MHP have a score significantly lower than other technologies, while gas and electric boilers have an equivalent score for the R1 ranking and gas boiler obtains a better score for the R3 ranking. Biomass boilers still score well above other technologies for all rankings.

The results for the electric boiler are much better for the C2 mix than for the C1 mix, in particular for R3, with a score of 3 for the C2 mix compared with a score of about 40 for the C1 mix. This means that the C2 mix is closer to sustainable limits, making the electric boiler a viable option for reducing GHG emissions at a lower cost than MHP over the period 2015-2040.

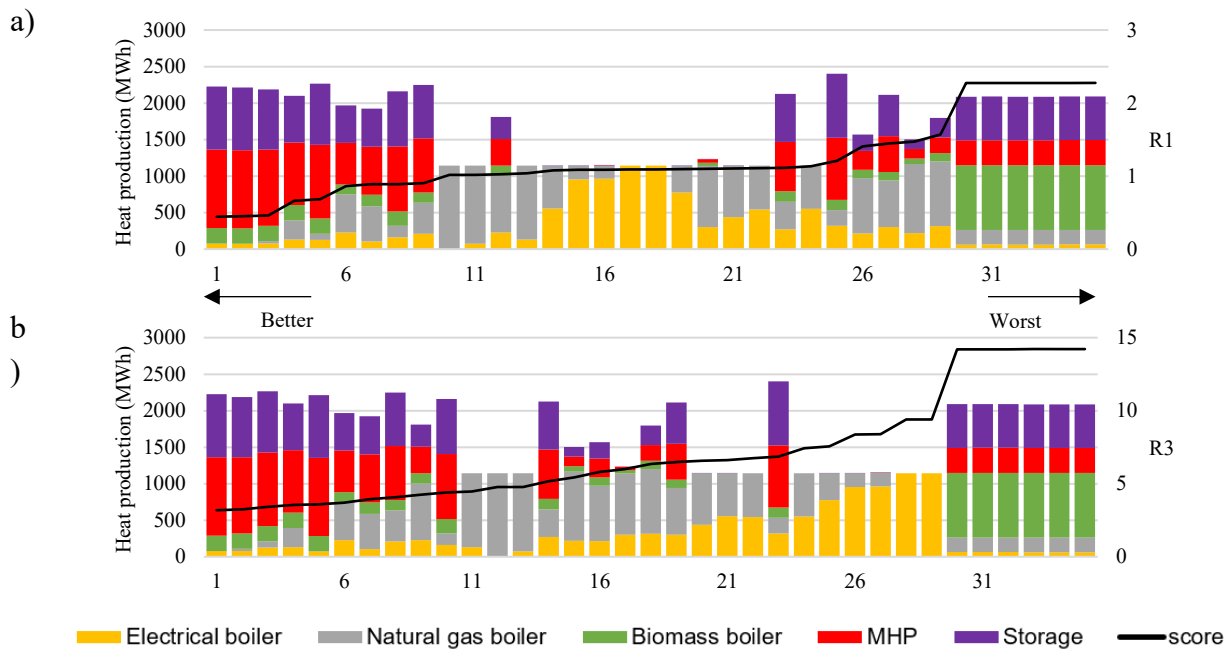


Fig. 75 - Pareto front solution's ranking for configuration C2, batch, 2015-2040 with ranking a) R1 and b) R3. The best solution is the one on the left with the index 1.

V.4.1.3 Detailed analysis for mix with significant thermal share

Weekly and continuous processes

The conclusions for the continuous and weekly processes are similar to those presented for cluster C2. The solutions with a high MHP rate in heat production are found in the best ranked solutions (Fig. 76). There is a direct correlation between the share of MHP and the rank of the solution, even though the score does not increase significantly for solutions based on gas boilers.

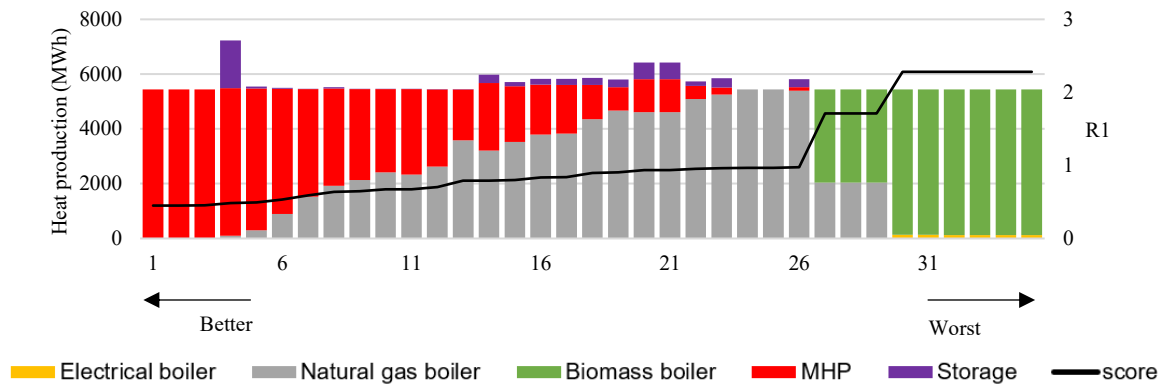


Fig. 76 - Pareto front solution's ranking for configuration C3, weekly, 2015-2040 and ranking method R1 (R2 and R3 give the same ranking for the top 24 solutions). The best solution is the one on the left with the index 1.

The environmental impact of MHP is different than in the previous configurations, with a distribution of sustainable threshold exceedances between *resource use, fossils* by a factor of 1.5 and *resource use, minerals and metals* by a factor of 1.3 for the best ranked configuration of Fig. 77. The conclusions for gas and biomass production remain similar to the other clusters, and these two sources are dominated by MHP for all rankings.

Unlike in case C2 (configuration 3), there is no MHP/biomass combination in the non-dominated solutions, even though biomass is better than MHP in the 2 impact categories exceeding the sustainable threshold (Fig. 77). The absence of this combination can be explained by the fact that the MHP solution exceed the thresholds only slightly for the 2 categories, while on the contrary, the impact of the biomass on the *particulate matter, ecotoxicity freshwater* and *land use* categories, is significantly beyond. Furthermore, these impacts are already close to the sustainable level due to the share of biomass in electricity production. There is also a less extensive contribution from storage, due to the low variation in the impact of electricity over time.

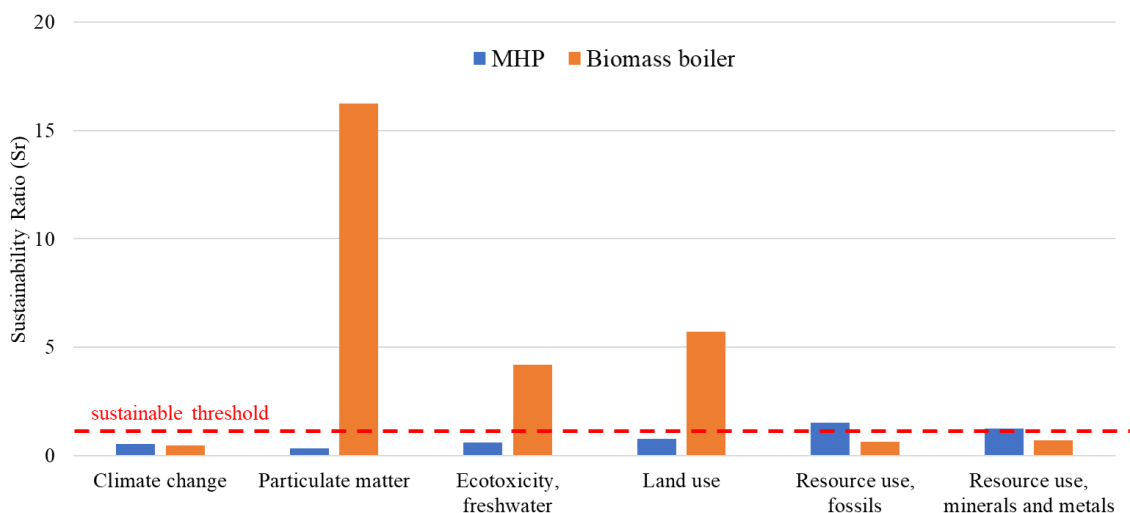


Fig. 77 - Sustainable ratio of MHP and Biomass boiler for configuration C3, weekly, 2015-2040. The results are based on the configuration ranked 1st for the MHP and 35th for the biomass boiler of Fig. 75.

Batch process

For the batch process, the solutions relying mainly on MHP are also the highest-ranked for R1 (Fig. 78), with an overshoot of sustainable limits distributed between *resource use, fossils and resource use, minerals and metals*. Despite having a greater and unsustainable impact on the *climate change* indicator, the gas-based solution has a score that is only slightly higher than that of MHP for all rankings. As for the previous configurations, the solutions with biomass boilers as the main source of production have the lowest ranking.

One of the main differences with the previous configurations is the absence of electric boiler as the main source of heat generation on the Pareto front. Indeed, as the cost of electricity is higher in this case, the share it represents in the overall balance is larger, fostering electricity efficient solution like MHP. Electric boilers are then dominated by MHP both economic and environmental criteria and always dominated by them in consequence.

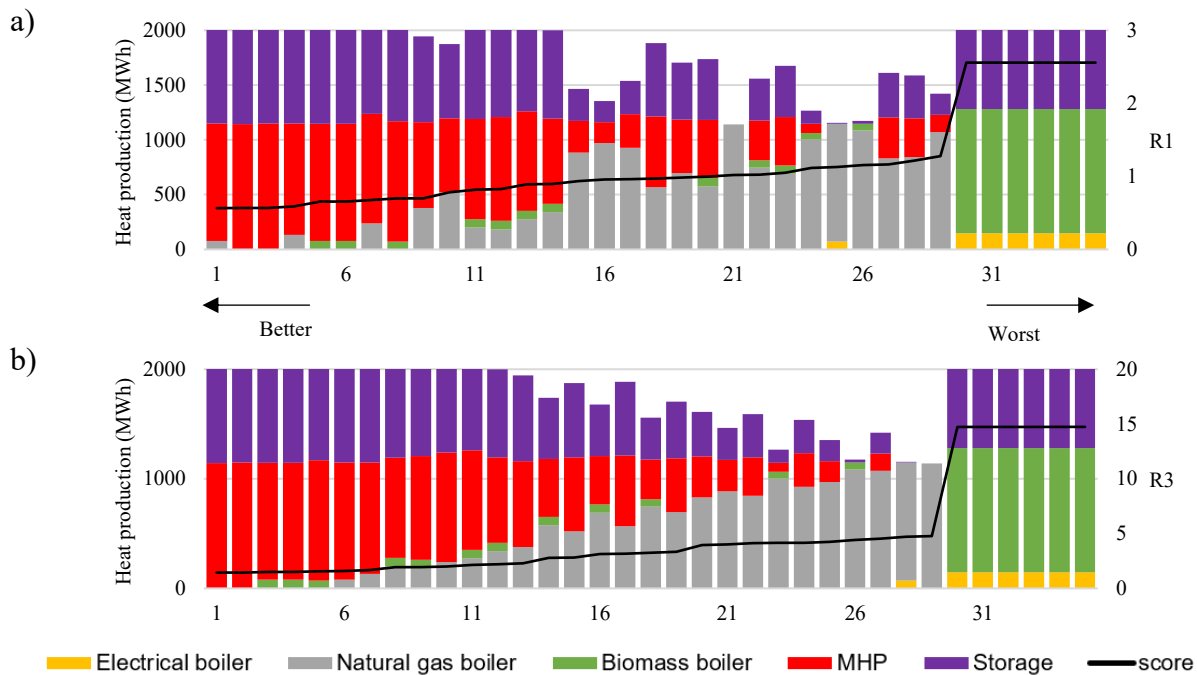


Fig. 78 - Pareto front solution's ranking for configuration C3, batch, 2015-2040 with ranking a) R1 and b) R3. The best solution is the one on the left with the index 1.

V.4.1.4 Global analysis of the impact of the electricity mix

In this section, the performance of the 5 different electricity mix is compared using the global scores. Fig. 79 compares the score of best solution with the average scores of the 5 best solutions, the 10 best solutions and all solutions for a weekly process during period 2015-2040 and for the 3 ranking methods.

A small difference between the best solution and the top 5 and 10 average ranking can be observed, whatever the ranking method, which shows that many solutions have a similar global impact and the ranking between them does not necessarily make sense. On the other hand, there is a significant gap between the average of all solutions and the top 5 or top 10, which shows that many solutions of the pareto front are not competitive and may exceed significantly certain sustainable thresholds.

a) b) c)

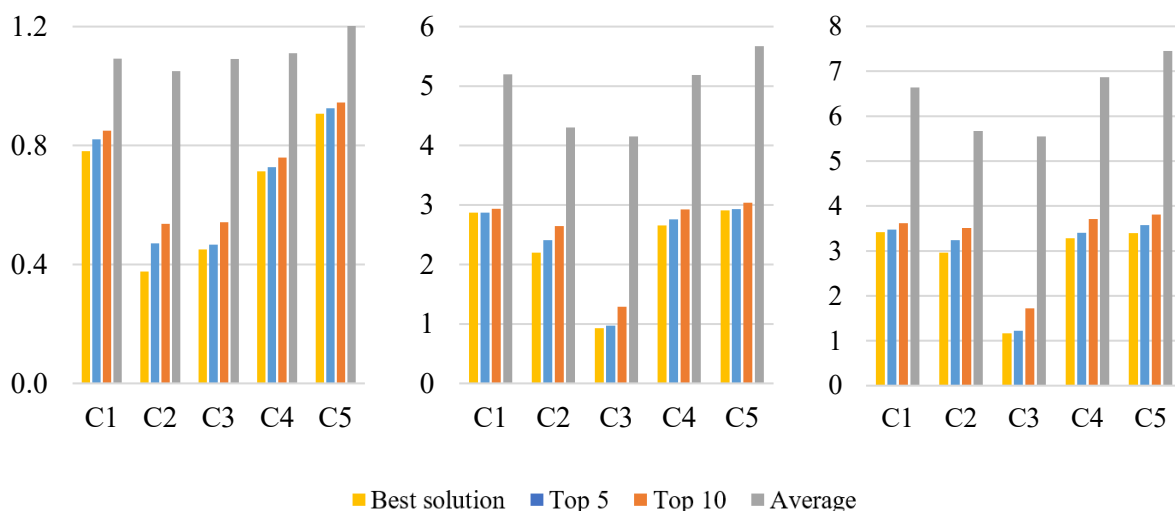


Fig. 79 - Best solution compared to average environmental score of top 5 and 10 and all solutions for configuration weekly, 2015-2040 and ranking a) R1, b) R2 and c) R3

As presented in introduction of section V.4, renewable-based mix give similar results with slight nuances between C1, C4 and C5. The lowest average score of all the solutions for the R1 score is for the C2 mix slightly ahead of the C3 mix. Both mix score about half those of renewable based mix, whose high score is due to exceedance in resource consumption as shown in Fig. 80 for the best ranked solution of ranking R3. This gap is the consequence of the difficulty in sourcing mineral resources, which force the best solution to add gas boiler or even biomass to MHP (see part V.4.1.1).

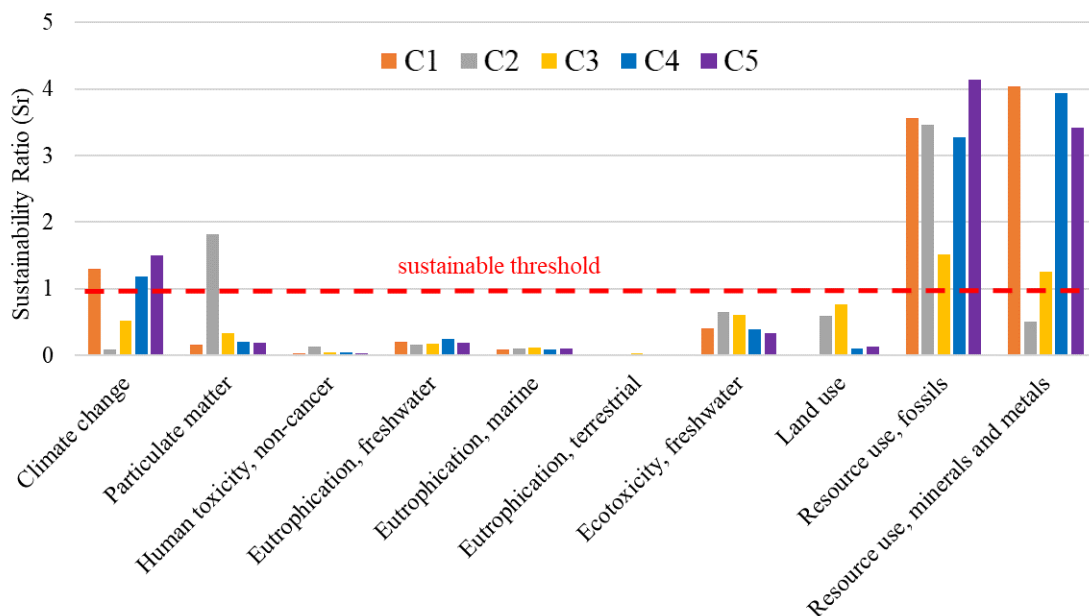


Fig. 80 - Sustainable ratio of environmental impact indicators for the configuration weekly, 2015-2040 and the best ranked solution of ranking R3.

Electricity mix based on nuclear (C2) have a better score than fossil or biomass fired electricity based (C3) for ranking R1 but are behind for R2 et R3. The weighting used for R1 favours C2 because the impact on *climate change* is significantly lower compared to C3 (Fig. 80) which relies on a large share of gas for electricity production. On the contrary, for R2 and R3, the fossil or biomass fired electricity gets a much better ranking because the overshoot of the sustainable limits

is distributed between *resource use, fossils* and *resource use, minerals and metals*. The three mix (C1, C2 and C3) keep most impact categories concerning human or biodiversity health below the sustainable limit (Fig. 80), but mix C3 and to a lesser extent C2 are less resource intensive than C1, C4 and C5.

To manage this issue in supplying raw materials, it is preferable for C2 to integrate a proportion of biomass production, which results in exceedance of *particulate matter* sustainable level by a factor 1.5 and 2 and a reduction in *resource use, minerals and metals* from 3.8 to 3.5. For the renewable-based mix C1, C4 and C5, the strategy is different, with the use of gas, which enables to reduce the consumption of mineral resources more than biomass, but this is done at the expense of the impact on *climate change*, with the sustainable threshold being exceeded by a factor of 2.

V.4.1.5 Global analysis of the impact of the process

The objective of this section is to present the differences between the Continuous and Weekly processes that have limited constraints on the operation of the technologies and the Batch process that has 2 main constraints:

- The rapid increase in demand means that the biomass solution is unable to respond; this solution must be coupled with storage.
- The time delay between 2 demands, which has for consequence that no waste heat is available at the time of production, so MHP must be coupled with storage.

It can be observed that the higher the level of constraint, the greater the impacts, and therefore a higher overall score across all rankings (Fig. 81). Thus, the continuous process consistently has a lower score than the weekly process, which in turn has a lower score than the batch process. This is the case for the C2 and C4 mix, where reducing constraints has a lower impact. In the case of C1, C3 and C5, the solutions have a similar score for continuous and weekly process because the existing constraint does not lead to any change in production technology. This result shows that the increase in constraints may affects the ability of the processes to meet sustainable levels and therefore that some processes are more difficult to make sustainable than others.

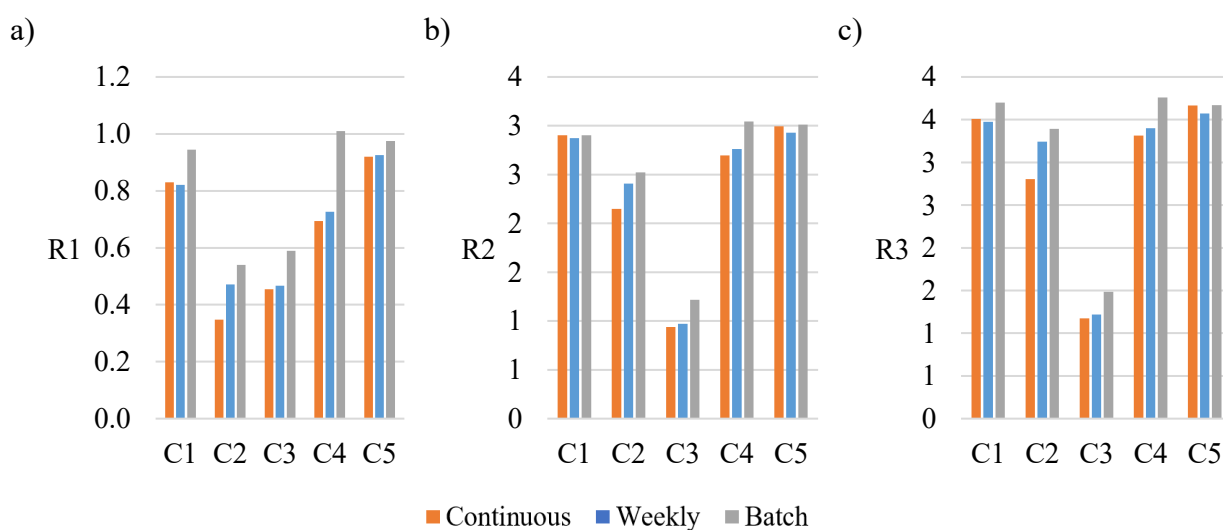


Fig. 81 - Average environmental score of the top 5 solutions for period 2015-2040 according to the type of process for ranking a) R1, b) R2 and c) R3

V.4.2 Analysis of reference configurations for periods 2040-2065 and 2065-2090

Section V.4.1 focused on the period 2015-2040. In this section, the analysis considers a more distant future with the periods 2040-2065 and 2065-2090, when the constraints on greenhouse gas emissions will be more important and a development of CCS is foreseen as a way of reaching negative emissions to cope with climate change.

V.4.2.1 Detailed analysis of the impact of the period for ranking R1 and R2

The evolution of the classified non-dominated solutions for the 3 periods of time are presented for the three different electricity mix C1, C2 and C3 for ranking R1 in Fig. 82, Fig. 83 and Fig. 84 respectively. As the conclusions are similar for R2, the results for this ranking are not presented here but are available in Appendix 8. The first trend that emerges is the absence of variation of the top-ranked solutions for any electricity mix for periods 2015-2040 and 2040-2065. However, there is a major change for the period 2065-2090. The development of BECCS leads to negative values on *climate change*, which results in a decrease of the overall impact of biomass-based solutions (Fig. 82c, Fig. 83c and Fig. 84c). Even if the characteristic environmental impacts of biomass are still present, the negative impact of climate change compensates the other impacts. The biomass boiler solution becomes therefore the best-ranked solution for R1 and R2 with scores significantly lower than the other solutions (see appendix A4-6, A4-15 and A4-24).

V.4.2.2 Detailed analysis of the consequence of the period of time for R3

The non-dominated ranked solutions using method R3 for the different periods of time is presented in Fig. 85, Fig. 86 and Fig. 87, for electricity mix C1, C2 and C3 respectively. With this ranking method, negative *climate change* indicator does not overcompensate the other indicators and therefore, there is no major modifications in the non-dominated solutions for the three period of time for the C2 and C3 mix, dominated by MHP-based solution. On the other hand, there is a change in the C1 mix, with a gradual reduction in the share of gas and an increase in the share of MHP between each period for the best-ranked solutions. Furthermore, for the period 2065-2090, the first two best solutions only are different from the other periods, which requires further analysis. For C1 mix, two different trends emerge for the top 5 ranked solutions, but it has to be noticed that they all have a very similar score:

- (i) The 2 top-ranked solutions correspond to a mix of 2/3 gas and 1/3 biomass. This mix limits the impact on *resource use minerals and metals* to the detriment of *climate change*, *resource use fossils* and *particulate matter* (Appendix 8).
- (ii) The next top-ranked solutions are based on MHP with a gas share of about 10 %. This option performs better overall than the previous one except for a strong increase in *resource use minerals and metals* (Appendix 8).

Despite these differences between the 3 electric mix, the biomass-based solution is never well ranked with R3 for any period of time, because the weight of negative emissions is not outweighed compared with other environmental impacts, which is the aim of this ranking method. For the R3 ranking, the solutions with the highest rankings for the 2015-2040 and 2040-2065 periods remain the preferred solutions for the 2065-2090 period. Method R3 shows that installing technologies adapted to limiting impacts today is also adapted to limiting the exceedance of sustainable thresholds in the future, even if these solutions are not sustainable in all impact categories.

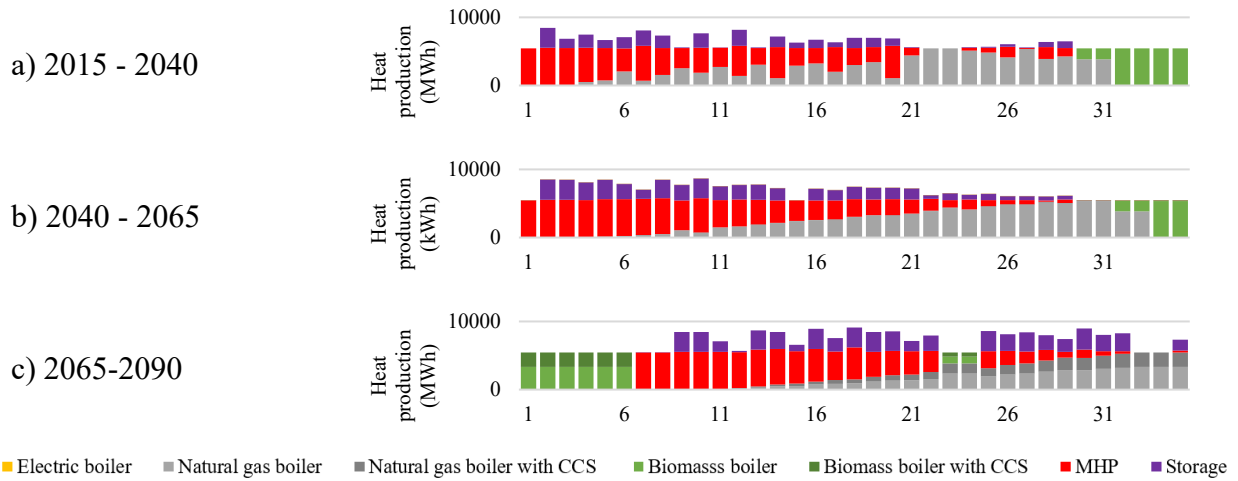


Fig. 82 - Pareto front solution's ranking for configuration C1, weekly, R1 for period a) 2015 – 2040, b) 2040 – 2065 and c) 2065-2090

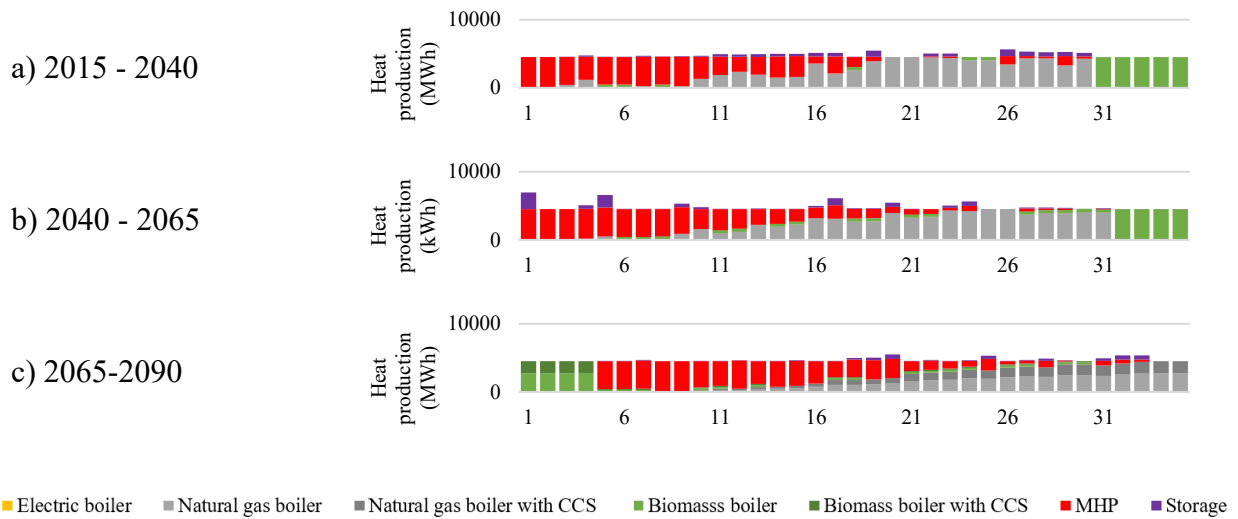


Fig. 83 - Pareto front solution's ranking for configuration C2, weekly, R1 for period a) 2015 – 2040, b) 2040 – 2065 and c) 2065-2090

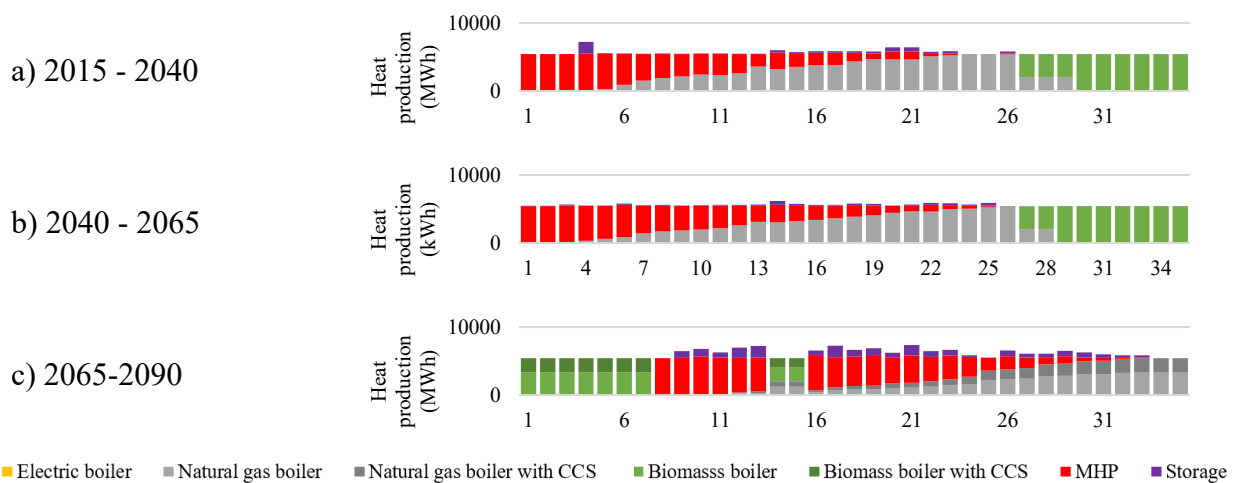


Fig. 84 - Pareto front solution's ranking for configuration C3, weekly, R1 for period a) 2015 – 2040, b) 2040 – 2065 and c) 2065-2090

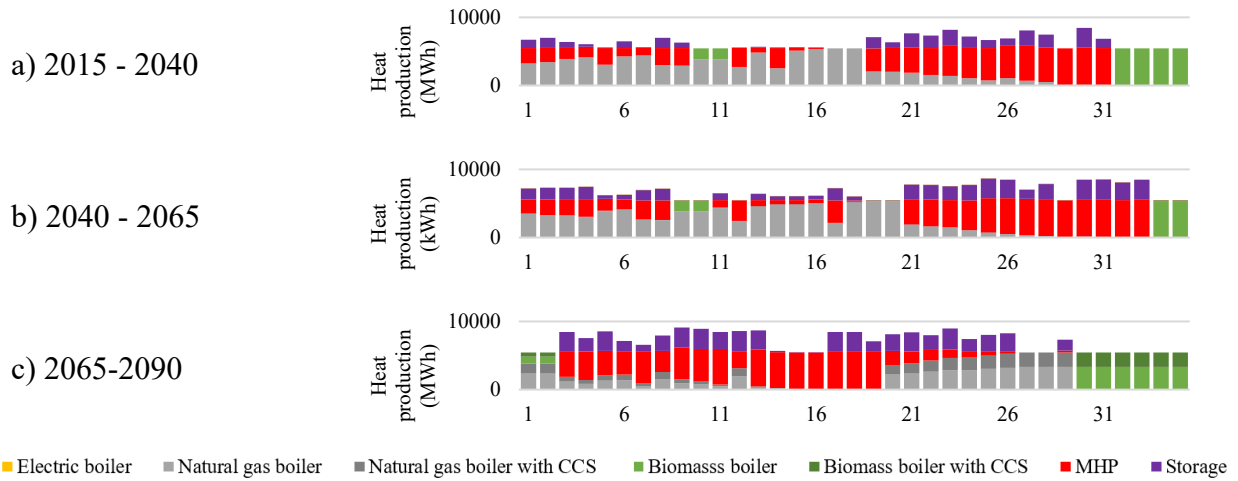


Fig. 85 - Pareto front solution's ranking for configuration C1, weekly, R3 for period a) 2015 – 2040, b) 2040 – 2065 and c) 2065-2090

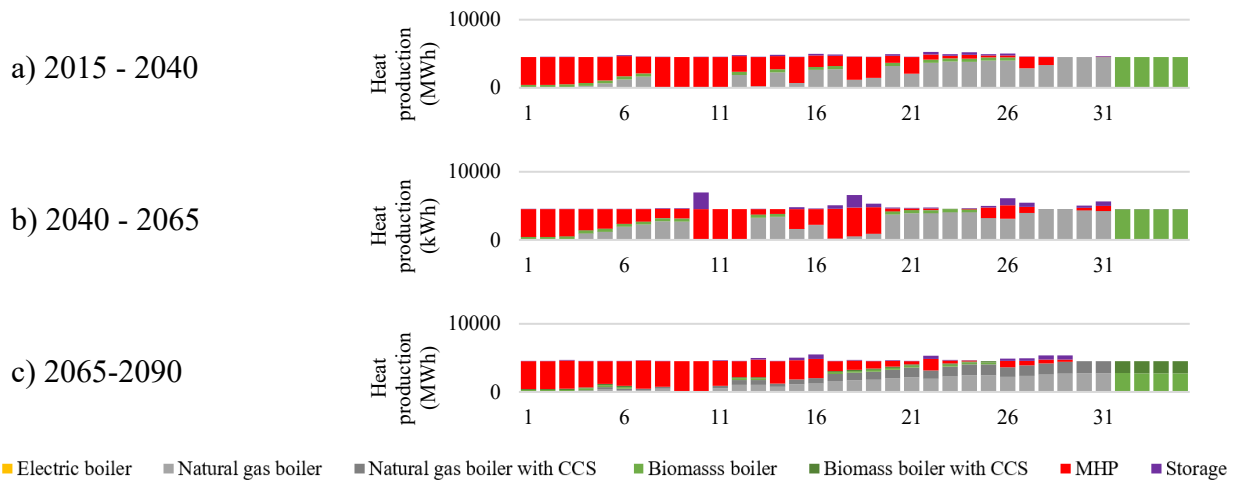


Fig. 86 - Pareto front solution's ranking for configuration C2, weekly, R3 for period a) 2015 – 2040, b) 2040 – 2065 and c) 2065-2090

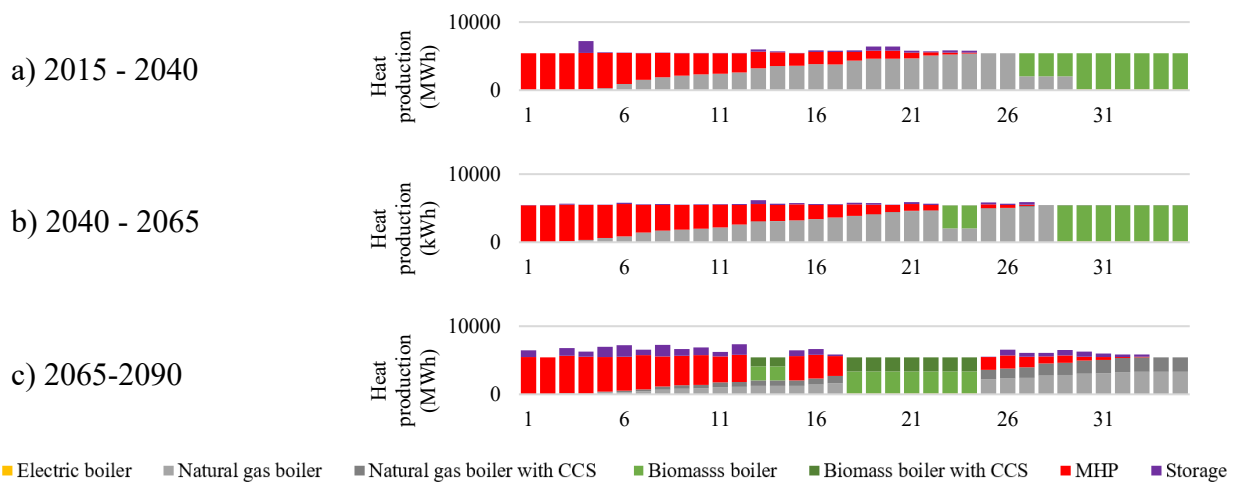


Fig. 87 - Pareto front solution's ranking for configuration C3, weekly, R3 for period a) 2015 – 2040, b) 2040 – 2065 and c) 2065-2090

V.4.2.3 Comparison of the scores with R1, R2 and R3

Fig. 88 presents the average scores for the three ranking methods, the three electric mix and the three periods of time for the top 5 non-dominated solutions. In the period 2065-2090, negative scores appear for R1 and R2, while score for R3 remains positive. These negative scores are not a guarantee of the sustainability of the solution, with impacts above sustainable levels in other impact categories.

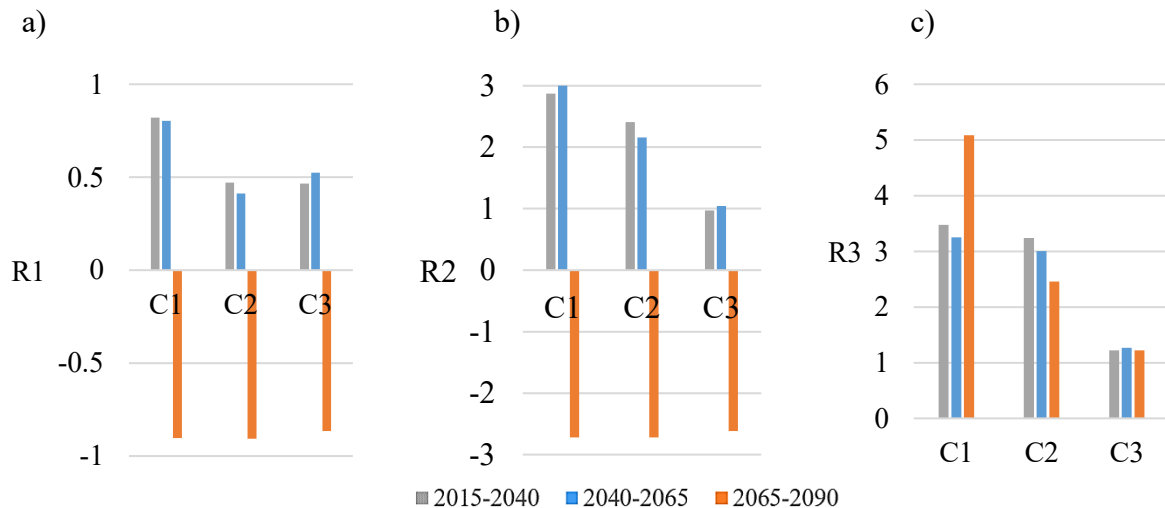


Fig. 88 - Average environmental score for the top 5 solutions according to the period studied for weekly process for ranking a) R1, b) R2 and c) R3

For R3, the score of the electric mix C1, which benefits the least from CCS, increases significantly due to the presence of gas which is largely penalised by the increase in the constraint on the *climate change* indicator. The R3 score of C2 and C3 mix are not affected by this constraint due to the presence of BECCS (from biomass boiler for C2 and in the electricity production for C3) which reduce the impact on *climate change* and consequently on the R3 score.

V.4.3 Overview of mitigation strategies

As presented in the previous sections, each electricity mix leads to different sustainable threshold exceedance, which result in different technology selection for the best solutions for R1 and R3 rankings. To limit the exceedance of sustainable thresholds with the R1 method, the use of MHP is the solution that emerges for all the mix. The performance of this solution is highly dependent on the amount of waste heat available, which is assumed in this work to be sufficient to power the process, but the benefits of electrification are reduced if there is little or no waste heat available (Appendix 6). As presented in Fig. 89, for the 5 electricity mix, significant exceeding of sustainability thresholds is mainly linked to the resource supply for ranking R1 for the periods 2015-2040 and 2040-2065. By penalising solutions that excessively exceed sustainable limits, ranking method 3 tends to distribute impacts more evenly across different categories, which leads to different consequence depending on the electricity mix:

- For electricity mix based on renewable energies, gas boilers account for a growing share, to the detriment of MHPs. This technology change limits the overshoot of *resource consumption, minerals and metals* but leads to an increase in *resource consumption, fossils* and *climate change*. The sensitivity of the results is strongly linked to the performance of the batteries, which account for most of the impact of indicator *resource consumption, minerals and metals*

(Appendix 6). A 50 % increase in the energy density of batteries results in a 46 % reduction in exceeding the sustainable threshold. In the event of a significant improvement in electricity storage efficiency, the proportion of gas required to reduce resource consumption would fall and led to a better R1 and R3 scores.

- For the nuclear-based C2 mix, the mitigation strategy introduces a share of biomass boiler in place of MHP to limit *resource consumption, fossils*. This nevertheless leads to an unsustainable level for *particulate matter*.
- For the C3 mix, the best solution is the same for R1 and R3 rankings. This solution allows a homogeneous distribution between *resource consumption, minerals and metals* and *resource consumption, fossils*. With the level of development of CCS, for both biomass and gas, and a third of thermal energy providing by biomass, it is possible to respect the sustainable level for the climate change impact category despite a large share of gas in the mix. On the other hand, if the development of CCS is slower than in the scenario used, the *climate change* indicator is exceeded (Appendix 6). The sensitivity study shows that, for the gas/biomass share used in this study, it is necessary to have at least 50 % of installations equipped with CCS.

Mix	Electricity mix		Unsustainable impact category of best ranked solutions for R1	Mitigation strategies (R1→R3)	Unsustainable impact category of best ranked solutions for R3
C1			1. Resource use, minerals and metals	Gas boiler MHP	1. Resource use, fossils 2. Resource use, minerals and metals 3. Climate change
C2	<ul style="list-style-type: none"> Dammed hydro Geothermal plants Offshore wind 		1. Resource use, fossils	Biomass boiler MHP	1. Resource use, fossils 2. Particulate matters
C3	<ul style="list-style-type: none"> Onshore wind River hydro Biomass 		1. Resource use, fossils 2. Resource use, minerals and metals	None	1. Resource use, fossils 2. Resource use, minerals and metals
C4	<ul style="list-style-type: none"> Gas Nuclear 		1. Resource use, minerals and metals	Gas boiler MHP	1. Resource use, fossils 2. Resource use, minerals and metals 3. Climate change
C5			1. Resource use, minerals and metals	Gas boiler MHP	1. Resource use, fossils 2. Resource use, minerals and metals 3. Climate change

Fig. 89 - Mitigation strategies summarised by electricity mix

For the period 2065-2090, the analysis is different because the negative value on the *climate change* indicator of on-site biomass boiler production makes this solution the best for R1 and R2. This solution has the advantage of having a negative contribution from the *climate change* indicator, but at the expense of other impacts such as *land use* and *particulate matter*. Biomass-based solutions are heavily penalised by the R3 ranking because it does not allow for too much compensation. This solution is therefore poorly ranked using this method, which best ranks the same technologies as the ones of the previous periods.

Defining the best strategy for an industrial process depends on the objectives being pursued, but also on the strategies implemented more generally. The top-ranked solutions for the R1 ranking help to reduce environmental damage compared to present impacts (GHG emission reduction

playing an important role, accounting for over 20 % of the total score). It is therefore a viable strategy for industries planning to reduce their GHG emissions. This strategy recommends focusing on MHP in the short term, then on biomass once the development of BECCS is sufficient to have carbon capture over the life cycle. As the problem is the same for all industrial processes and even for other sectors, there is a risk that all strategies will be based on the same decarbonisation principles and this would lead to shifting the burden to other impacts. More specifically in the cases studied, the development of decarbonisation strategies may be hampered by the resource availability if the strategy of all the world's industries moves in the same direction. There might then be a shift in the problematic impacts from those we know today to other impacts, depending on strategic choices and electricity mix, as shown in Fig. 89. To avoid the transfer of impacts, R3 ranking helps to avoid solutions that exceed sustainable thresholds by encouraging a greater diversity of energy sources to reduce the pressure on resource supplies.

V.5 Environment energy and economy crossover approach

V.5.1 Cross approach to environmental impact with energy and exergy

The objective of this section is to highlight the evolution of the energy and exergy indicators according to the different scores of the proposed ranking methods. The energy and exergy efficiencies over the entire life cycle of the technologies are defined in equation V-5 for energy and V-6 for exergy and presented in Table 46.

$$\text{Eff}_{\text{energy}} = \frac{E_{\text{out}}}{E_{\text{in}} + E_{\text{out,MHP}} \cdot (\text{COP} - 1)} \quad \text{V-5}$$

$$\text{Eff}_{\text{exergy}} = \frac{E_{\text{out}} \cdot \left(1 - \frac{T_0}{T_{\text{up}}}\right)}{E_{\text{in}} + E_{\text{out,MHP}} \cdot (\text{COP} - 1) \cdot \left(1 - \frac{T_0}{T_{\text{rec}}}\right)} \quad \text{V-6}$$

Table 46 - Energy and exergy efficiencies of several technologies considered in the analysis

	Gas boiler	Biomass boiler	MHP C1	MHP C2	MHP C3	MHP C4	MHP C5
Exergy efficiency	29 %	16 %	68 %	32 %	44 %	53 %	53 %
Energy Efficiency	84 %	51 %	94 %	67 %	78 %	85 %	86 %

Fig. 90 presents the results for a weekly process, similar to the continuous process, over the period 2015 – 2040 for ranking R1 and R3. Several observations can be made for the exergy indicator (Fig. 90 a and c):

- For solutions with a high biomass boiler share - identified by the red dotted lines in Fig. 90a - as the biomass boiler solutions have a low exergy efficiency and score very high for both R1 and R3, an improvement in exergy efficiency due a small share of another technology results also in a rapid reduction in these scores.
- For solutions with gas boilers and MHP, a clear negative correlation with exergy efficiency is observed for ranking method R1. Therefore, all solutions with higher exergy efficiency tend to perform better with this ranking method. The improvement in the exergy efficiency of mix C1, C4 and C5 results in a smaller gain (R1 reduction of 0.2 for an improvement of 30 %)

than that of mix C3 (R1 reduction of 0.2 for an improvement of 10 %), which in turn is smaller than that of C2 (R1 reduction of 0.2 for an improvement of 2 %).

- For solutions with gas boilers and MHP ranked with method R3, the analysis is more complex and depends on the electric mix:
 1. For the C1, C4 and C5 mix - which rely heavily on renewable energies - an optimum is present for an exergy efficiency of about 30 %. This optimum is due to the fact that R3 favours solutions with an intermediate composition based on approximately half MHP and half gas (as presented in part V.4.1). R3 scores for these mixed solutions are lower than the scores for the two solutions alone, as can be seen in Fig. 90c.
 2. For the C2 electricity mix there is no trend with an overall exergy efficiency near 30 % for all configuration due to the same exergy efficiency for both gas and MHP (Table 46). For this mix, it is therefore difficult to link the R3 score to the variation in exergy efficiency.
 3. For the C3 mix, based on a high fossil or biomass fired production share, an increase in exergy efficiency improves the R3 score. This trend is explained by the composition of the electricity mix, composed of gas and biomass. By improving the exergy efficiency, the consumption of these resources is reduced and as a consequence the overshoot of the sustainable limits.

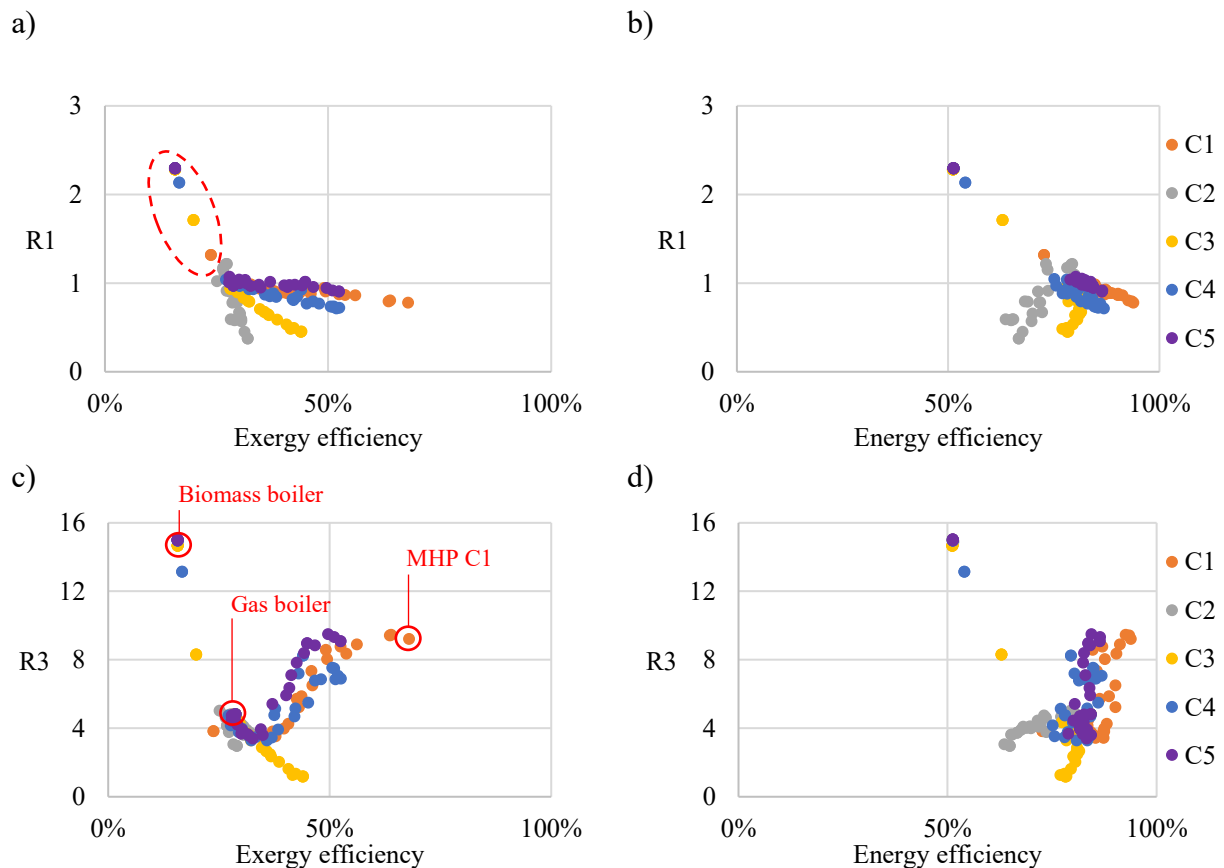


Fig. 90 - Comparison between environmental scores and CExD and CED efficiencies for configuration Weekly, 2015-2040 for ranking a) R1 function of exergy efficiency, b) R1 function of energy efficiency, c) R3 function of exergy efficiency, c) R3 function of energy efficiency. The red dotted circle identifies solutions composed mainly of biomass.

Concerning the energy efficiencies (Fig. 90 b and d), the trends are less clear. Different evolutions are observed depending on the electrical mix for R1. For the C1, C4 and C5 mix based on renewables, the trend is the same as for exergy, with an improvement in the R1 score when energy efficiency increases. On the other hand, the evolution is opposite for the C2 mix and there is no trend for the C3 mix. For R3 ranking, there is not a strong trend and a wide dispersion, but paradoxically, energy-efficient solutions tend to exceed more sustainable thresholds than less efficient ones.

For the period 2065-2090, the same overall trends are found: the solutions with the highest exergy efficiency are also those with the best R1 score (Fig. 91). The only difference is for mix C1, C4 and C5 ranked by method R3 with an optimum observed with a higher exergy efficiency of 40 % (Fig. 91c) compared to the previous period of time. This change is due to an increase in the proportion of MHP in the optimal solution to reduce the *climate change* indicator overshoot.

Over the same period, a clear trend emerges with the R1 method, for which C2 and C3 mix see their overall environmental score deteriorate as energy efficiency increases, while the exact opposite is true for C1, C4 and C5 mix. For all these mix, the environmental score and the efficiency of the gas solution is similar around 84 % efficiency, which represents the convergence efficiency of all the mix, identified by a red dotted line on Fig. 91b. The MHP-based solutions (which perform better for R1 ranking) for mix C1, C4 and C5 have an energy efficiency higher than that of gas (between 85 % - 94 %) while the efficiency for mix C2 and C3 are below the gas efficiency (67 % and 78 % respectively).

We confirm here the conclusion put forward in part I.3.5: in a non-fossil-based energy mix the link between environmental impact and energy efficiency is specific to the type of electricity mix.

For the batch process, the results are presented in Appendix 5. The observations are more or less identical to those of continuous and weekly processes, even if the trends are less clear with more dispersions, due to the presence of storage and more technologies for each non-dominated solution.

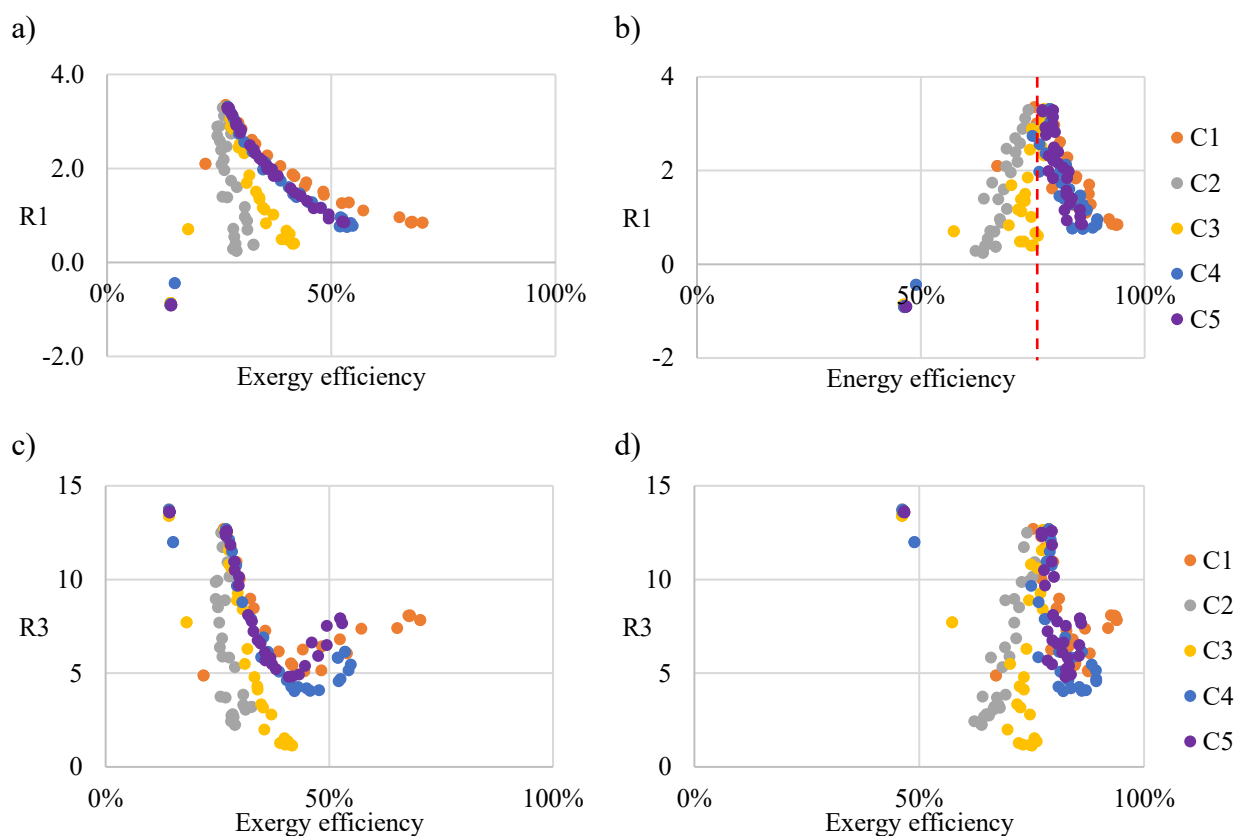


Fig. 91 - Comparison between environmental scores and CExD and CED efficiencies for weekly process for period 2065-2090 for ranking a) R1 function of exergy efficiency, b) R1 function of energy efficiency, c) R3 function of exergy efficiency, d) R3 function of energy efficiency. The red dotted line represents the efficiency of the gas solution.

V.5.2 Cross approach to environmental impact and economic

This section focuses only on the period 2015-2040, due to the uncertainties of the economic model. The total cost - which includes CAPEX, OPEX, energy prices and carbon taxes - is compared to the results of the environmental scores R1 and R3 (R2) (Fig. 92). The trends are slightly different between methods R1 and R3.

For R1, it is possible to separate the solutions with a high biomass content which are identified with the red circle from the solutions relying mainly on electricity and gas. On the whole life cycle, the biomass solution has the lowest economic cost but has a high environmental score as discussed in part V.4.1. For the renewable mix (C1, C4 and C5) there is very little change in the R1 score but a price variation ranging from 18 €/MWh to almost 60 €/MWh for the C4 mix. For the C2 mix, based on nuclear power, there is also a wide dispersion of total costs, but the solutions with the best environmental results also tend to be the cheapest. Finally, the C3 mix based on a large share of thermal electricity shows the lowest dispersion with total prices between 30 and 55 €/MWh with no correlation between price and R1 score. Technologies also behave differently in each mix, gas boiler solution is more economical than the MHP for some countries but offers a significant gain (2 times lower for C1) on the R1 score as presented in Fig. 92 and for other countries the result is the opposite with a MHP more cost-effective but a R1 score which is only

slightly improved (- 20 % for C1). For R3 (and R2 as presented in Appendix 5), there is no trends whatever the electricity mix, which all have a significant dispersion.

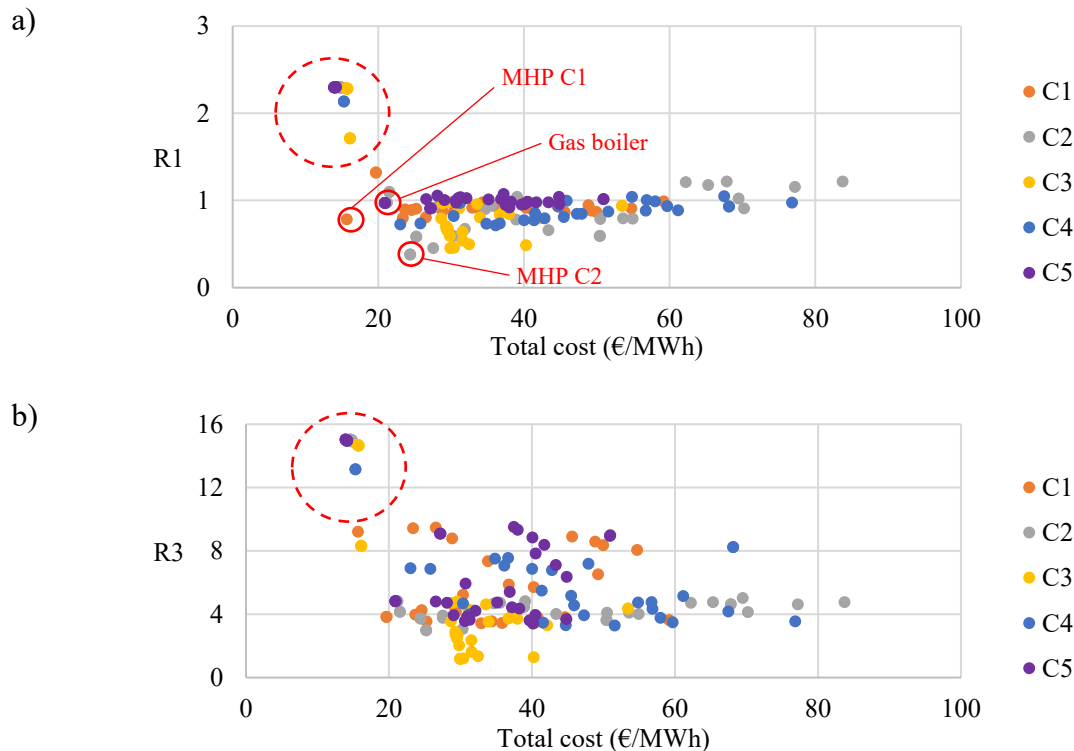


Fig. 92 - Comparison between environmental scores and the total cost to produce heat for a weekly process for the period 2015-2040, for ranking a) R1 and b) R3. The red circles represent the solutions dominated by biomass boiler.

The lack of clear trend between the solutions scores R1, R2 and R3 and the price of energy over the whole life cycle including carbon taxes can be explained by:

- The difference between electricity price and the type of electricity mix, with significant variations between the C1, C4 and C5 mix, despite a dominant share of renewable energies. However, this conclusion needs to be put into perspective because the calculations are performed in the context of 2019 data for energy prices, i.e., without considering the recent events that have led to a massive increase in energy prices in some countries which can lead to even greater variability.
- The share of CAPEX in total cost, which depends on the technology and the storage requirements.
- The level of GHG emissions from the solution, which has an impact on the level of carbon tax and in the scores R1, R2 and R3.
- The energy tax rates, which vary widely between countries.
- In addition to the cost of energy, it is useful to analyse the PayBack Period (PBP) of the different solutions of the Pareto front (Fig. 93). The time needed for cost savings to reimburse the investment in a new solution is estimated taking gas boiler as reference for business-as-usual operation. As explained in section II.5, industrial investors often ask for a small return time of less than 5 years to consider the installation of a new solution in order to lower the

financial risk. As the trends are similar for the C1, C4 and C5 mix, only the C1 mix is presented in this section to simplify the reading.

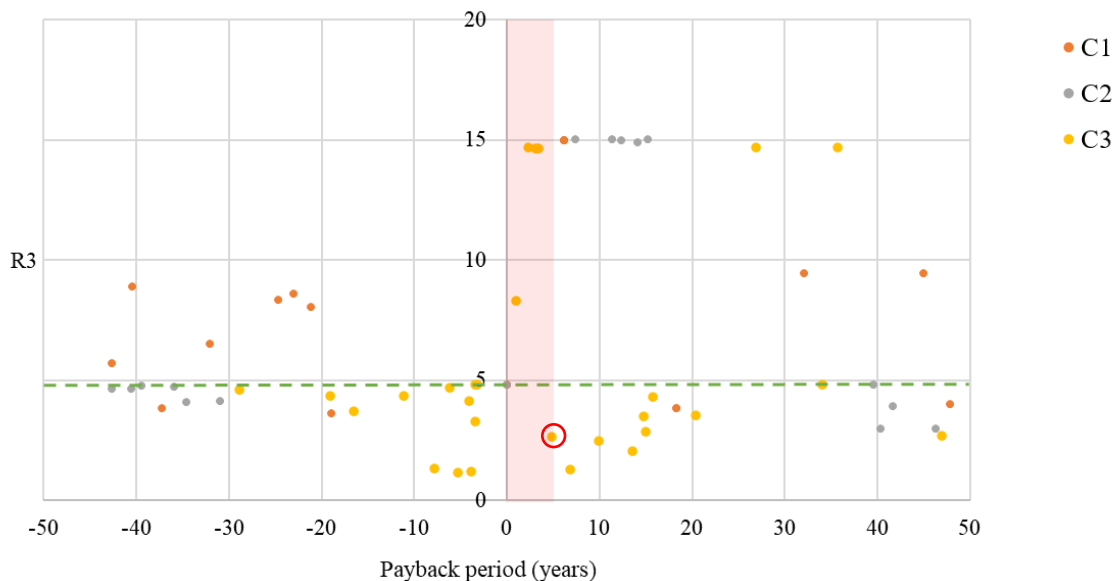


Fig. 93 - R3 scores versus payback period for electricity mix C1, C2 and C3, weekly process during the period 2015-2040. The red area represents the acceptable PBP for industries and the green dotted line the impact of the gas boiler reference scenario.

The red-shaded area represents the acceptable PBP for industrial development. The level of impact using the R3 ranking for the reference gas solution is represented by a dotted green line. The solutions with the best environmental scores have a PBP of more than 18 years for the C1 mix and it rises to 40 years for the C2 mix (Fig. 93). Only one solution (circled in red in the figure) based on a combination of MHP with gas boiler for the mix C3 respects the economic requirements and is lower than the current reference. Most of C1 and C3 value are negative which means that the solution is less cost-effective than the reference solution and that the industry is going to pay more each year as a result.

These poor economic results can be explained by:

- the higher share of investment costs for the most efficient solutions of the R3 score
- the presence of a still limited carbon tax (36.5 €/tCO₂)
- the lack of development of certain solutions allowing for economies of scale

They also stress out the need to diversify the economic models by including for example a sensitivity analysis to CAPEX variation, energy prices, taxes, etc. It would be also interesting to go a step further by including uncertainties in the optimisation model.

V.6 Conclusions

This chapter presented the results of the 45 configurations studied (5 countries, 3 processes and 3 time periods) for the environmental, energy and exergy, and economic approaches.

For the environmental analysis, the results show that the strategy chosen to limit GHG emissions has a strong impact on other impact categories, and that it is not possible to have solutions that respect sustainable levels for all impact categories. It is shown that there are several strategies for minimising environmental impacts of process heat, depending on the priorities that are set:

1. Select the solutions with the lowest overall impact, but which are likely to exceed certain limits significantly, in particular *resource use, minerals and metals*, by developing MHP in the short term, then biomass once the development of BECCS is sufficient to have carbon capture over the life cycle.
2. Select solutions with a higher overall impact, but which distribute the impacts more evenly across all categories, which means that the planet's boundaries are less exceeded. This strategy is based on diversifying the energy sources used.

The comparison between exergy and the other indicators shows that there is a correlation between exergy efficiency and minimisation of overall damage to the environment (ranking R1), but that no correlation has been found between exergy efficiency and the limitation of sustainable thresholds exceedance (ranking R2 and R3). The results also show that there is a wide dispersion of environmental damage for a given energy efficiency depending on the electricity mix (between 51 % and 94 %).

Finally, economic analysis shows that there is a very wide variation in costs for solutions with equivalent environmental scores, and that many other factors come into play (CAPEX, carbon and energy taxes), making any correlation with environmental criteria impossible. The economic analysis is therefore highly contextual compared to the energy, exergy and environmental assessments. However, a general trend emerges, which shows that there are a very limited number of solutions that can reduce environmental impact with a sufficiently low payback period to be adopted spontaneously by industry.

Conclusions

Decarbonisation of process heat is a key issue for the industry to meet its objective of GHG emission reduction. While a number of technologies are available to meet this need, choosing the best possible one is not an easy task, for a variety of reasons in addition to technical and economic issues. Indeed, the options may differ according to the characteristics of the heat demand, to the country's electricity mix if the new process is electricity-based, to the lifetime of the future installation, etc. What's more, while greenhouse gas reduction targets are clear at global level, this is no longer the case at sectoral level, either in terms of the criteria on which this reduction should be based (type of industry, current emissions, etc.) or the timeframes for this reduction. Installations have a relatively long lifespan, so choices must remain relevant throughout this period, which is not necessarily obvious, as shown by the first case study presented in Chapter III. Furthermore, decarbonisation leads to other environmental impacts, that can also be unsustainable from the planetary boundary perspective, and that also need to be quantified. The aim of this thesis was to answer all these questions through the development of a multi-objective optimisation method combining energy, energy efficiency, economic and environmental aspects, coupled to the development of environmental and economic indicators to analyse the results of the optimisation.

The literature review conducted in chapter I highlights the importance of the industrial sector in the global and European environmental footprint, and the various technical solutions available today to address it. The state of the art shows the evolution of the methods used to optimise or transform the systems, which were initially based on pure technical and economic studies, but to which carbon and even environmental issues in the broadest sense are now increasingly being added. However, the current methods are not sufficient to address all the issues outlined in the first paragraph, in particular the assessment of the environmental sustainability of the solutions, which requires the use of a multi-objective approach.

The methodological framework for this multi-objective optimisation model is developed in Chapter II. The first stage is the energy modelling, which is based on input data specific to the heat production systems considered in the study and the dynamic electricity mix specific to the studied country. Using this data, the energy consumption of each technology can be calculated on an hourly basis to meet the industrial requirements. This energy model incorporates the operating constraints - in particular the dynamic phenomena like the limited load ramp-up of biomass boiler or the loss of efficiency under partial load - of the technologies in order to have a realistic integration and to take account of price variability and the environmental impact of energy. This energy model is then used as input data for:

- Life Cycle Assessment (LCA), which benefits from fine hourly modelling to calculate environmental impacts
- Simplified economic model to calculate the cost of each solution over its lifecycle (based on energy consumption, CAPEX and OPEX)

The energy, economic and environmental models are then used within an optimisation model to find solutions that are non-dominated, i.e. there is no solution which dominates the others on all the criteria. One of the specific characteristics of this work is the optimisation of energy systems based on environmental criteria, while models of the literature tend to work in the other direction, i.e. optimising systems from an energy perspective and assessing their environmental impacts.

The output of the optimisation model does not provide a classification of the best solutions but only a set of non-dominated solutions. It is therefore necessary to classify these solutions to define which would be the best option to meet the industrial need. Two indicators are proposed for this purpose in this work:

- The environmental sustainability, based on the principle of downscaling total emissions in order to define a "right to impact" for each process.
- The level of contribution of the process, which penalises processes that are responsible for a large proportion of the environmental impact.

Based on this original approach, a first contribution consists in assessing the electrification of the food sector for France and Denmark. Given the potential for electrification of industrial processes, all the environmental impacts are calculated for both sectors. One of the conclusions of this study is the trade-offs between the different categories of environmental impact. While it is possible to achieve a sustainable level for the *climate change* indicator, this results in a number of other environmental impacts becoming unsustainable, i.e. *ecotoxicity* or *freshwater*. This environmental counterpart highlights the need for a global approach to reduce the transfer of impacts.

As for the multi-objective optimisation model, a genetic algorithm has been used. This method is well-suited for this type of configuration because it combines initial configurations that are well defined to quickly cover a wide combination of solutions. To reduce the size of the problem and limit computing time, the hourly data is clustered to reduce the problem to 100-time steps representative of the year. The optimisation model can then assess a large number of heat production modes by combining the different technologies and retaining the non-dominated solutions, which then need to be ranked. To do this, three ranking approaches are proposed: R1, which considers a reference approach using weightings derived from the LCIA, R2, which includes a comparison with global limits with a linear penalty for exceeding them, and R3, which also includes a comparison with global limits but with an exponential penalty, and also another specific feature of not allowing too much compensation linked to CO₂ capture.

This methodology is applied to 3 typical industrial processes over 1 year, for 5 countries with an electricity mix representative of one of the trajectories envisaged by 2050 in Europe. These different configurations are evaluated for 3 different periods (2015-2040, 2040-2065 and 2065-2090) in order to incorporate the increase in GHG emission reduction requirements.

One of the findings of this study is the absence of solutions that meet all the sustainable thresholds for all the technologies studied (electric boiler, gas boiler, biomass boiler and mechanical heat pump), whatever the electricity mix. Overshoot of sustainable limits concerns different impacts depending on the technologies:

- Electrification solutions using electricity from mix based mainly on renewable energies exceed the sustainable thresholds in *resource use, minerals and metals* impact by a factor 7 to 9, mix based on nuclear energy are above the sustainable limit for *resource use, fossils* indicator by a factor 5, and mix with a high proportion of biomass and fossil-fired electricity production are also above *resource use, minerals and metals* impact by a factor 1.5 and *resource use, fossils* by a factor 1.3.

- Gas boilers exceed the sustainable thresholds for *resource use*, *fossils* impact by a factor 5 and *climate change* impact by a factor 2 in 2015-2040 to a factor 13 in 2065-2090¹.
- Biomass boilers have very significant thresholds exceedance for indicators such as *land use* by a factor 5 and *particulate matter* by a factor 15.

As no single technology or combination of technologies is capable of achieving sustainable levels, a ranking system is used to highlight the solutions that have the smallest environmental impact.

For R1 ranking, which is based on standard weightings of LCA, the MHP solution appears to be the solution that limits damage the most for periods 2015-2040 and 2040-2065. This technology is sometimes combined with biomass or gas boilers to limit resource consumption, but this complementary technology remains limited. In 2065-2090, biomass boilers combined with CCS become the best solution because of carbon sequestration over the life cycle.

On the other hand, R2 and R3 rankings penalise technologies that exceeds too much the sustainable levels, as for example the lack of natural resources availability for some technologies. For these rankings, the best solutions are a combination of technologies having different impacts to limit the exceedance of sustainable thresholds. These higher-ranked solutions therefore often have more unsustainable categories, but with more limited overshoots. For renewable electricity mix, the strategy is to couple electricity solutions with gas (between 30 and 50 %) in order to limit exceedance of the *resource use*, *minerals and metals* indicator; for the nuclear mix, the compensation is done by using a share of biomass (5 to 10 %) in order to limit exceedance of the *resource use*, *fossils* indicator. Finally, for the mix based on biomass and fossil-fired electricity production, there is no compensation to reduce the impact with the technologies studied.

The R1 method selects solutions with the lowest overall impact, but authorises certain limits to be significantly exceeded, in particular those relating to minerals and metals resources, while the R3 ranking proposes a solution with a greater overall impact, but without exceeding planetary limits too significantly. There is therefore a significant risk of reaching an unacceptable limit if the R1 method were applied on a large part of the economy, whereas the R3 method would spread the impacts more evenly. Indeed, on a global scale, it may be possible for certain sectors to compensate for the impacts of others and vice versa, but if certain limits are too far exceeded, this compensation seems more difficult. The R3 method may therefore seem more robust.

The comparison of energy, exergy and economic indicators with environmental indicators of the non-dominated solutions shows also different results depending on the ranking methods. It shows a correlation between the R1 score and the exergy performance. For all the mix, exergy optimisation results in a reduction in environmental impacts. However, this trend is no longer valid for the R2 and R3 scores, for which there is an optimum depending on the mix. This reflects the fact that exergy efficiency is not necessarily relevant for assessing impact transfers and exceeding sustainable thresholds. The energy and economic analysis show that there is no correlation between the performance of a solution based on methods R1, R2 and R3 and the energy efficiency and cost of the solution. In other words, costs are not correlated to environmental indicators but to other specific factors like electricity costs, taxation, etc.

¹ Including CCS development

Perspectives

There are several ways in which this research can be followed up. To begin with, the model needs to be improved in the light of the many limitations identified throughout this manuscript as for example:

- Specific integration into a process to consider the constraints of integration in order to have a more accurate energy model
- The development of a more robust economic model to be able to really plan the impact on production and energy costs
- Updating the sustainable thresholds to incorporate current developments in this research sector, such as recycling for the consumption of mineral and metal resources
- Etc.

In addition to the improvements of the model itself, it is possible to imagine many possible applications of this method. For the energy sector, as the current heat production solutions are based on fossil fuels, the priority is given to the *climate change* indicator. In the case of a profound transformation of this sector, the environmental priorities may change as shown in part V.4.; it is important to ensure that this energy transformation is in line with current targets, but that the impact is transferred as little as possible to other impact categories. In other words, it is necessary to ensure that current problems are solved without compromising the future, which is the very definition of sustainability used by the UN's World Commission for Environment and Development "[...] meets the needs of the present generations without compromising the ability of future generations to meet their own needs". Therefore, the transformation of the industrial heat production cannot be thought of in isolation from other sectors.

A systemic approach is therefore needed to analyse all sectors and define how best to achieve this transformation. This approach requires a global assessment of all human activities in order to evaluate their performance and identify for each sector the impact categories that are above sustainable levels and those that are below sustainable levels. By integrating the results across all sectors, it is possible to analyse whether the compensation between each sector makes it possible to achieve an overall sustainable level for all impact categories. A major difficulty to be solved for this analysis is the lack of global data. This global approach can help determine whether human activities can be maintained as they are once the best solutions have been determined for transforming all these activities or whether, on the contrary, a more fundamental reflection on the "right to impact" of each sector needs to be undertaken.

For this last perspective, the analysis of this transformative change cannot be based solely on physical and technological sciences, but must involve an interdisciplinary approach with the sociological or political sciences. In this work, the share (τ_s) of each sector is based either on the current impacts or on its economic value. These approaches have the advantage to be easy to implement but raises a number of questions because the approach is currently based on unsustainable level of impact, which makes it problematic to consider them as a reference. A new type of distribution could be based on many other criteria that need to be defined today such as utility and needs. These notions being complex to define, they need to be studied within an interdisciplinary framework incorporating sociological, political and technical approaches. It is also possible to integrate other notions, like well-being or social justice, as highlighted by a new adaptation of planetary limits that integrates the notion of 'just' into sustainable limits [162].

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Appendix 1 - Energy supply clustering

Country TAG	Scenario	Dammed hydro	Geothermal plants	Offshore wind	Onshore wind	Photovoltaic	River hydro	Wave & tidal	Concentrated solar power	Biomass	Solid	Petroleum	Gas	Nuclear	Gr. clustering
AT	BL 2050	12%	10%	0%	59%	7%	2%	0%	0%	8%	0%	0%	2%	0%	4
AT	CD 2050	7%	2%	0%	41%	26%	1%	0%	0%	19%	0%	0%	5%	0%	4
AT	HRE 2050	7%	2%	0%	42%	25%	1%	0%	0%	18%	0%	0%	5%	0%	4
AT	E3M	10%	0%	0%	43%	37%	9%	0%	0%	0%	0%	0%	0%	0%	4
BE ²⁴	CORE-95	0%	4%	30%	21%	44%	0%	0%	0%	0%	0%	0%	0%	0%	1
	BEH	0%	4%	29%	24%	42%	0%	0%	0%	0%	0%	0%	0%	0%	1
	TECH	0%	10%	28%	20%	43%	0%	0%	0%	0%	0%	0%	0%	0%	1
BE	BL 2050	0%	1%	11%	8%	13%	0%	0%	0%	3%	0%	0%	63%	0%	3
BE	CD 2050	0%	1%	4%	11%	33%	0%	0%	0%	2%	0%	0%	50%	0%	3
BE	HRE 2050	0%	1%	4%	14%	31%	0%	0%	0%	2%	0%	0%	48%	0%	3
BE	E3M	0%	0%	27%	19%	24%	0%	0%	0%	1%	0%	0%	29%	0%	3
BG	E3M	0%	3%	13%	24%	36%	0%	0%	0%	3%	0%	0%	10%	0%	5
BG ²⁵	No target	0%	38%	0%	38%	25%	0%	0%	0%	0%	0%	0%	0%	0%	4
	Delayed	7%	20%	0%	47%	27%	0%	0%	0%	0%	0%	0%	0%	0%	4
	Decarbonized	7%	21%	0%	31%	41%	0%	0%	0%	0%	0%	0%	0%	0%	5
CY ²⁶	WEM	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	5
CY	E3M	0%	0%	0%	14%	81%	0%	0%	0%	0%	0%	0%	5%	0%	5
CZ	CD 2050	2%	2%	0%	37%	18%	0%	0%	0%	11%	2%	0%	28%	0%	4
CZ	HRE 2050	3%	2%	0%	36%	22%	0%	0%	0%	10%	1%	0%	26%	0%	4
CZ	BL 2050	6%	0%	0%	4%	32%	0%	0%	0%	4%	1%	0%	11%	42%	2
CZ ²⁷	Ref	1%	0%	0%	5%	9%	0%	0%	0%	12%	2%	0%	31%	40%	2
CZ	E3M	1%	11%	0%	33%	15%	1%	0%	0%	4%	1%	0%	10%	0%	4
DE	E3M	0%	0%	38%	37%	25%	1%	0%	0%	0%	0%	0%	0%	0%	1
DE	BL 2050	0%	2%	19%	11%	16%	0%	0%	0%	14%	0%	0%	38%	0%	3
DE	CD 2050	1%	2%	29%	23%	20%	0%	0%	0%	7%	0%	0%	18%	0%	1
DE ²⁸	RNS	4%	11%	39%	27%	19%	0%	0%	0%	0%	0%	0%	0%	0%	1
DE	HRE 2050	1%	2%	29%	23%	21%	0%	0%	0%	6%	0%	0%	18%	0%	1
DK ²⁹	Ref	0%	0%	71%	0%	0%	0%	0%	0%	25%	0%	0%	4%	0%	1
	Bio+	0%	0%	63%	0%	0%	0%	0%	0%	32%	0%	0%	5%	0%	1
	Wind	0%	0%	99%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	1
DK	E3M	0%	0%	16%	65%	16%	0%	0%	0%	2%	0%	0%	0%	0%	4
EE	E3M	0%	0%	51%	27%	15%	0%	0%	0%	4%	0%	0%	2%	0%	1
EL	E3M	0%	5%	15%	47%	29%	3%	0%	0%	0%	0%	0%	1%	0%	4
ES	E3M	0%	0%	0%	49%	46%	1%	0%	0%	2%	0%	0%	1%	0%	4
ES	BL 2050	4%	0%	15%	32%	18%	0%	0%	0%	15%	0%	1%	14%	0%	4
ES	CD 2050	2%	0%	0%	10%	26%	0%	0%	20%	21%	0%	1%	19%	0%	3
ES	HRE 2050	2%	0%	4%	8%	25%	0%	0%	21%	19%	0%	1%	18%	0%	3
FI	BL 2050	17%	0%	7%	37%	10%	0%	0%	0%	0%	0%	0%	0%	29%	2
FI	CD 2050	8%	0%	0%	15%	0%	0%	0%	0%	0%	0%	0%	0%	77%	2
FI ³⁰	Base	4%	0%	31%	31%	19%	0%	0%	0%	10%	0%	0%	5%	0%	1

²⁴ <https://climat.be/doc/climate-neutral-belgium-by-2050-report.pdf>

²⁵ <https://www.tandfonline.com/doi/full/10.1080/14693062.2018.1532390>

²⁶ https://energy.gov.cy/assets/entipo-iliko/SRSS-C2018-070-Impact_Assessment_13Dec2019_en.pdf

²⁷ https://www.mpo.cz/assets/en/energy/electricity/2022/5/Assessment-of-resource-adequacy-of-the-Czech-electricity-system-_2021_-.pdf

²⁸ https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/energieziel_2050_kurz.pdf

²⁹ https://www.sdu.dk/-/media/files/om_sdu/centre/lifecycleengineering/student_reports_2017/17m33_buhl+hegelundand+simonsenroadmapto2050.pdf

³⁰ <https://tem.fi/documents/1410877/3437254/Energy+and+Climate+Roadmap+2050+14112014.pdf>

	Change	9%	0%	0%	51%	39%	0%	0%	0%	0%	0%	0%	0%	0%	4
FI	HRE 2050	4%	0%	30%	29%	18%	0%	0%	0%	13%	0%	0%	6%	0%	1
FI	E3M	0%	0%	13%	50%	3%	0%	0%	0%	5%	0%	0%	2%	0%	4
FR	BL 2050	10%	3%	5%	33%	29%	0%	0%	0%	7%	0%	0%	5%	7%	4
FR	CD 2050	3%	0%	0%	47%	17%	0%	7%	0%	16%	0%	0%	10%	0%	4
FR ³¹	RTE M0	4%	0%	34%	21%	39%	0%	1%	0%	0%	0%	0%	0%	0%	1
	RTE N1	5%	0%	31%	21%	28%	0%	0%	0%	0%	0%	0%	0%	15%	1
	RTE N3	6%	0%	17%	17%	19%	0%	0%	0%	0%	0%	0%	0%	40%	2
FR	HRE 2050	3%	0%	1%	46%	18%	0%	8%	0%	15%	0%	0%	10%	0%	4
FR	E3M	2%	0%	13%	60%	21%	1%	0%	0%	2%	0%	0%	1%	0%	4
HR ³²	ESEK2050	2%	4%	0%	60%	23%	0%	0%	0%	1%	0%	0%	11%	0%	4
	NC2	3%	2%	0%	33%	44%	0%	0%	0%	1%	0%	0%	17%	0%	5
	NC1.5	2%	3%	0%	38%	41%	0%	0%	0%	1%	0%	0%	15%	0%	4
HR	E3M	4%	3%	7%	48%	26%	5%	0%	0%	2%	0%	0%	5%	0%	4
HU	BL 2050	0%	12%	0%	23%	13%	0%	0%	0%	7%	0%	0%	16%	29%	2
HU	CD 2050	0%	3%	0%	44%	20%	0%	0%	0%	10%	0%	0%	23%	0%	4
HU	HRE 2050	0%	3%	0%	42%	20%	0%	0%	0%	11%	0%	0%	24%	0%	4
HU	E3M	0%	0%	41%	51%	7%	0%	0%	0%	0%	0%	0%	0%	34%	2
IE	E3M	0%	0%	49%	38%	5%	0%	0%	0%	1%	0%	0%	6%	0%	1
IE ³³	WEM	0%	0%	41%	51%	7%	0%	0%	0%	0%	0%	0%	0%	0%	1
	WAM	0%	0%	65%	31%	2%	0%	1%	0%	0%	0%	0%	1%	0%	1
IT	BL 2050	6%	4%	0%	21%	24%	0%	0%	0%	13%	0%	0%	32%	0%	3
IT	CD 2050	3%	0%	0%	12%	39%	1%	0%	11%	10%	0%	0%	24%	0%	3
IT	HRE 2050	3%	0%	0%	13%	39%	1%	0%	11%	10%	0%	0%	23%	0%	3
IT ³⁴	DEIT	8%	8%	0%	25%	60%	0%	0%	0%	0%	0%	0%	0%	0%	5
	LT	9%	8%	0%	42%	41%	0%	0%	0%	0%	0%	0%	0%	0%	4
IT	E3M	1%	2%	1%	26%	55%	4%	0%	0%	3%	0%	0%	8%	0%	5
LT	E3M	0%	0%	0%	54%	27%	3%	0%	0%	15%	0%	0%	2%	0%	4
LU	E3M	0%	0%	0%	36%	64%	0%	0%	0%	0%	0%	0%	0%	0%	5
LV	E3M	0%	0%	35%	38%	4%	20%	0%	0%	3%	0%	0%	1%	0%	1
MT	E3M	0%	0%	0%	0%	31%	0%	0%	0%	0%	0%	0%	68%	0%	3
NL	BL 2050	0%	4%	55%	10%	16%	0%	0%	0%	0%	0%	0%	5%	8%	1
NL	CD 2050	0%	0%	42%	18%	11%	0%	1%	0%	2%	0%	0%	26%	0%	1
NL	HRE 2050	0%	0%	50%	13%	11%	0%	1%	0%	2%	0%	0%	22%	0%	1
NL ³⁵	Regional	6%	0%	43%	17%	33%	0%	0%	0%	0%	0%	0%	0%	0%	1
	International	3%	0%	59%	14%	24%	0%	0%	0%	0%	0%	0%	0%	0%	1
	European	6%	0%	60%	13%	22%	0%	0%	0%	0%	0%	0%	0%	0%	1
NL	E3M	0%	0%	37%	42%	21%	0%	0%	0%	0%	0%	0%	0%	0%	1
PL	BL 2050	5%	0%	2%	37%	15%	0%	0%	0%	0%	0%	0%	0%	39%	2
PL	CD 2050	2%	2%	16%	40%	17%	0%	0%	0%	5%	3%	0%	15%	0%	4
PL	HRE 2050	2%	2%	8%	44%	17%	0%	0%	0%	6%	4%	0%	17%	0%	4
PL	E3M	0%	0%	32%	17%	9%	1%	0%	0%	1%	1%	0%	3%	0%	1
PT	E3M	4%	0%	2%	50%	32%	10%	0%	0%	2%	0%	0%	0%	0%	4
RO ³⁶	Baseline	17%	0%	0%	25%	6%	0%	0%	0%	11%	3%	0%	37%	1%	3
	Green	30%	0%	0%	35%	14%	0%	0%	0%	2%	0%	0%	6%	13%	4
	Super Green	21%	0%	0%	27%	10%	0%	0%	0%	0%	0%	0%	0%	42%	2
RO	BL 2050	3%	0%	3%	9%	6%	0%	0%	0%	15%	4%	0%	55%	5%	3
RO	CD 2050	0%	0%	0%	51%	23%	0%	0%	0%	5%	1%	0%	19%	0%	4

³¹ <https://www.rte-france.com/analyses-tendances-et-prospectives/bilan-previsionnel-2050-futurs-energetiques>

³² <https://www.b2green.gr/el/post/75687/stratigiki-exoikononisis-energeias-sta-ktiria-eos-to-2050-to-plires-keimeno-kelyfos-thermansii-energeia>

³³ https://energy.ec.europa.eu/system/files/2020-08/ie_final_necp_main_en_0.pdf

³⁴ https://download.terna.it/terna/Documento_Descrizione_Scenari_2022_8da74044f6ee28d.pdf

³⁵ <https://www.gasunie.nl/en/expertise/energy-system/ii3050/the-four-future-scenarios>

³⁶ <https://openknowledge.worldbank.org/server/api/core/bitstreams/4207e5a3-34a6-57a6-a345-c0e868ca5c01/content>

RO	HRE 2050	0%	0%	0%	49%	23%	0%	0%	0%	6%	2%	0%	21%	0%	4
RO	E3M	0%	0%	0%	43%	24%	6%	0%	0%	1%	0%	0%	4%	0%	4
SE	E3M	0%	0%	0%	80%	7%	0%	0%	0%	10%	0%	0%	3%	0%	4
SE	BL 2050	11%	0%	29%	29%	12%	0%	0%	0%	0%	0%	0%	0%	19%	1
SE	CD 2050	4%	0%	0%	63%	15%	0%	0%	0%	14%	0%	0%	4%	0%	4
SE	HRE 2050	5%	0%	1%	64%	15%	0%	0%	0%	12%	0%	0%	4%	0%	4
SI	E3M	18%	0%	0%	6%	37%	1%	0%	0%	4%	1%	0%	33%	0%	3
SK	E3M	4%	0%	0%	24%	17%	2%	0%	0%	7%	0%	0%	2%	0%	4

Appendix 2 - Heat demand distribution for industrial food processing

The breakdown of industrial demand by type of process and temperature level is shown for Denmark in Fig. 93 using data from the Danish Energy Agency (Energistyrelsen) [156] and for France in Fig. 94 using data from the French statistical office (INSEE) [157].

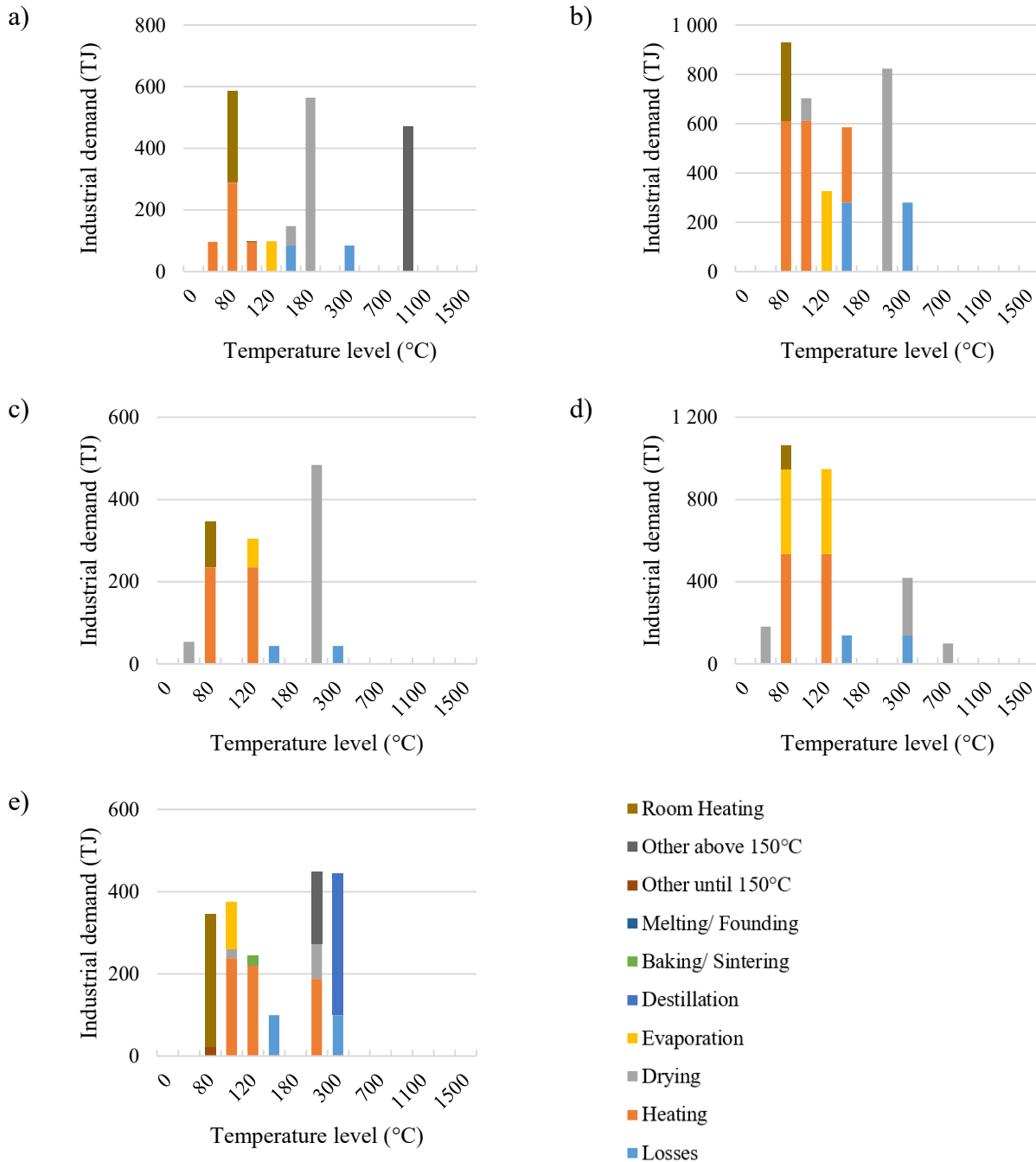


Fig. 94 - Industrial heat demand by temperature range and type of process for process in Denmark from the Danish Energy Agency (Energistyrelsen) [156] for sector a) Slaughterhouse, b) Dairy Processing, c) Production of compound feed, d) Production of Sugar and e) Other food industry.

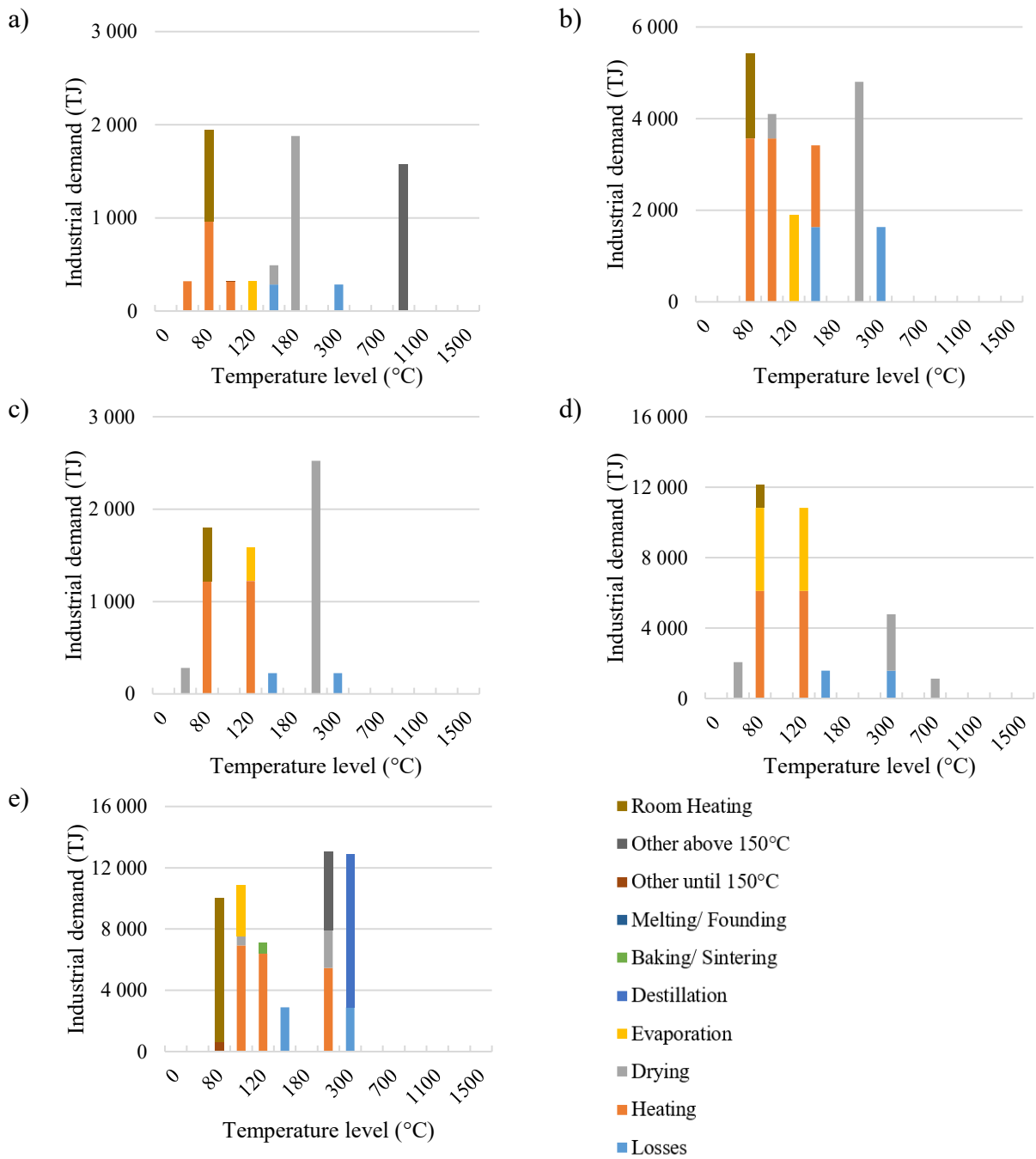


Fig. 95 - Industrial heat demand by temperature range and type of process for process in France from the French statistical office (INSEE) [157] for sector a) Slaughterhouse, b) Dairy Processing, c) Production of compound feed, d) Production of Sugar and e) Other food industry.

Appendix 3 - Storage loss factor

To calculate the hourly loss ϵ_{sto} , a so-called unit configuration is used to solve the balance. This configuration charges homogeneously for 8 hours (0.125 MWh per time step) to reach a value of 1 MWh, then empties the homogeneous storage (0.0625 MWh per time step) for 16 hours to empty it completely. The balance is solved in such a way that :

1. The balance of the configuration with losses (ϵ_{sto} real) is the same energy available at the storage outlet as the version without losses ($\epsilon_{sto} = 1$), i.e. once the losses have been removed the configuration (ϵ_{sto} real) has the same energy available.
2. All the losses represent 5% of the final energy consumed to fill the storage in the lossy configuration.

In the unit configuration presented in Table 47, the resolution find a $\epsilon_{sto} = 0.996$ makes it possible to obtain the balance so that the two conditions are met:

1. The total output energy available when removing the losses (0.63MWh are lost during the 24 hours cycle) is 12 MWh as for the configuration without losses.
2. The losses are equal to the 5 %, as found by Koçak et al. [33], of the final energy consumed to fill the stock on a typical day ($\frac{12.63-12}{12.63} = 5\%$).

Table 47 - Storage level for the unit configuration with the configuration without loss ($\epsilon_{sto} = 1$) and the configuration with the loss value ($\epsilon_{sto} = 0.996$) used to solve the balance [45].

time step	Storage without losses $\epsilon_{sto} = 1$	Storage with losses (ϵ_{sto} real)
1	0.125	0.125
2	0.250	0.251
3	0.375	0.378
4	0.500	0.504
5	0.625	0.632
6	0.750	0.759
7	0.875	0.888
8	1.000	1.016
9	0.938	0.957
10	0.875	0.898
11	0.813	0.838
12	0.750	0.779
13	0.688	0.719
14	0.625	0.658
15	0.563	0.598
16	0.500	0.538
17	0.438	0.477
18	0.375	0.416
19	0.313	0.354
20	0.250	0.293
21	0.188	0.231
22	0.125	0.169
23	0.063	0.107
24	0.000	0.045
Total	12	12.63

Appendix 4 - Life cycle assessment methodology

The following methodology is based on ISO 14040/14044 standards [56], [125] and the present section follows the different steps of the methodology.

Goal

The goal of the environmental model is to assess the impact of different industrial heat production technologies using life cycle assessment. These results are compared to environmental thresholds to assess their sustainability. The study generates a large number of possible heat production technologies combination to meet industrial needs. The environmental assessment will be coupled with an economic and energy analysis of the process. This study is in a decision contexts which can be describe as a macro-level decision support (Situation B) which is defined by Hauschild et al. as the assessment of a process “expected to cause structural changes in one or more processes of the systems that the studied product system interacts with.” [57]

The main limitations due to methodological choices are:

- (i) This study does not consider increased or decreased of process need
- (ii) The environmental threshold need to be adapted for every process to consider his specificity.
- (iii) The solutions proposed in this study are a set of non-dominated solutions and there is no single dominant solution.

Scope

The goal of this study is to assess the environmental impact of industrial heat production technologies for different configuration i.e. for different countries, type of process, temperature, years. The LCA will be used in the optimisation model to highlight the set of non-dominated solutions. As a result, for each configuration the LCA will be performed on a large number of configurations varying the share of each energy on each time step. Therefore, the impact is calculated at each time step for the elements that are likely to vary (impact of electricity, system efficiency, etc.). For this matter, the functional unit used is the heat production to meet the demand of the industrial processes described in part II.2.4 with an hourly discretisation over 1 year in the 5 selected country as representative in part II.2.3.1, for the three different period of time 2015-2040, 2040-2065 and 2065-2090.

Life Cycle Inventory Analysis

This study is considering consequential modeling as it wants to evaluate the change induces by the system transformation. The environmental data are from Ecoinvent database v3.7.1 [88]. Consequential modeling is defined by Hauschild et al. as the “aim to describe the changes to the economy caused by the introduction of the studied product system” [57]. There are no multifunctional processes in the life cycle inventory (LCI) modelling framework. The system boundary is presented in Fig. 95, with the detail of every considered and excluded processes from the LCA. The two main processes not considered in the study are (i) the connection with the process due to this high level of specificity and minor environmental impact compared to the process itself and its energy consumption and (ii) the process requirement in material, chemical, consumable. It is possible to adapt the method to integrate a process as a whole i.e. not only the energy part, but this would require a level of information on the process that is difficult to obtain in order to subsequently determine the level of impact that can be considered sustainable. The last element not considered in this study is the benefice from the gas avoided by the new system compared to the current one (which is mainly gas-based). The choice was made in order to assess the level of impact from a technical solution compared to an

acceptable level of impact and not to compare the benefice to change with the proposed solution compared to the current energy system.

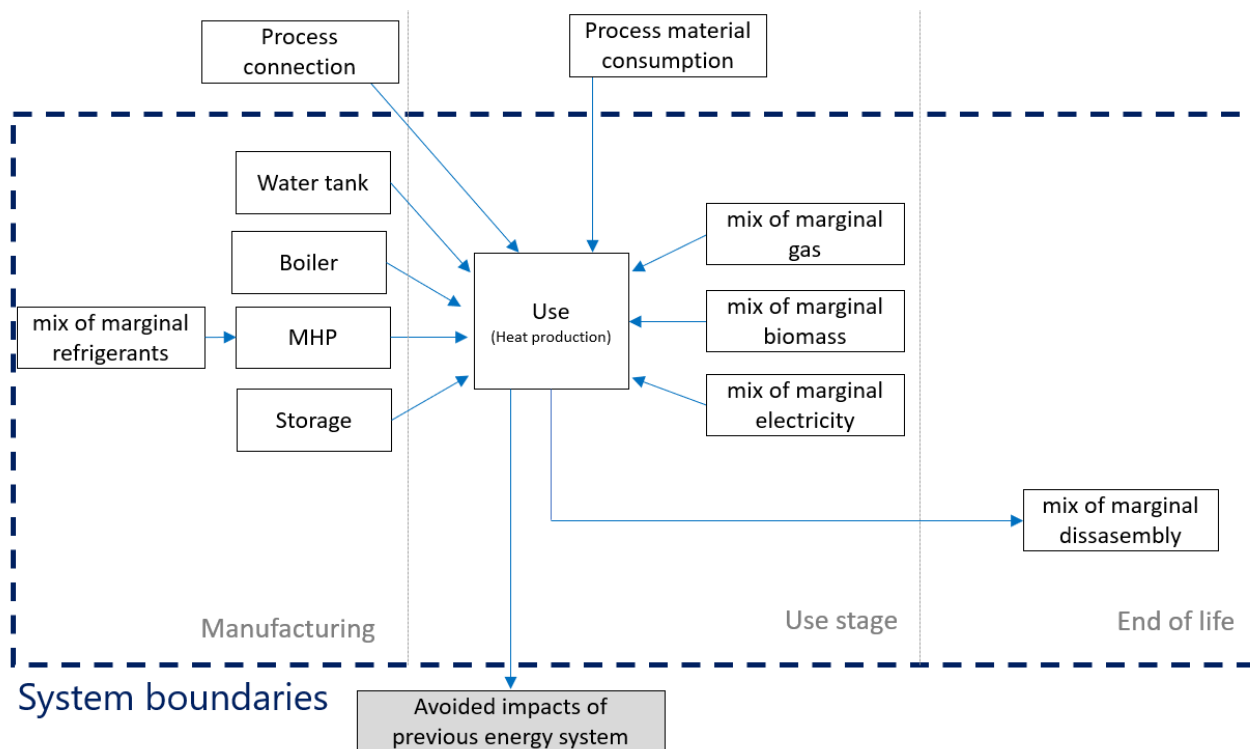


Fig. 96 - Flow diagram. The blue line indicates the system boundaries; all processes outside of the line are not considered in this study. The grey box represents the avoided energy consumption due to the change of the heat production system.

Geographical, temporal and technological scopes

The modelling is based on five representative electricity scenarios for Europe over three typical time periods, 2015-2040, 2040-2065 and 2065-2090, using the method presented in II. The scenario is constructed using the current available LCA data which are corrected using the available energy scenarios (Fig. 96). It is assumed here that the impact of biomass and gas at industry scale will be sufficiently similar that the typical countries are based on the five electricity mix presented in Part II.2.3.1. This choice is made because there is only one value in the database for Europe for these two processes of gas and biomass, so it would not have been possible to run scenarios like those run for electricity. One of the assumptions is that the development of new electricity generation is sufficiently constant to assume that the distribution of new generation remains the same over the three periods and that the evolution will be progressive following the electrification of the processes. This hypothesis implies that the share of each energy resulting from electrification is the same over the three periods. Finally, on the technological choice, the technologies considered in this study are those with a high level of maturity with a TRL of 8 or 9. This study therefore does not consider any disruptive technology as well as potential improvements in efficiency. On the other hand, the developments considered in the analysis are the development of CCS in electricity production and directly on industrial sites as defined in part II.2.3.3.

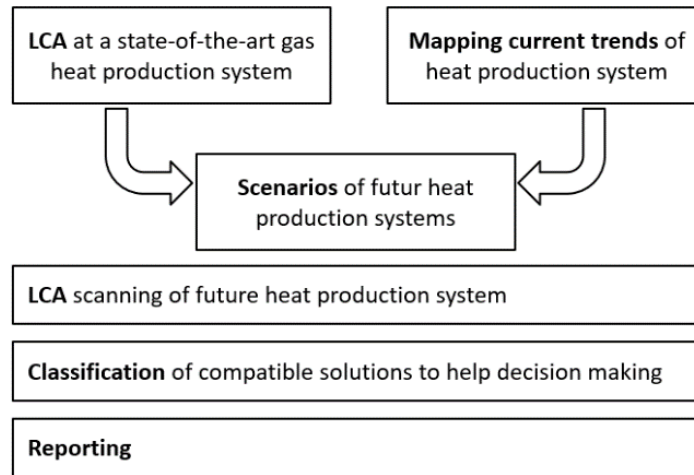


Fig. 97 - Modelling of heat production with future trends, figure adapted from Anderson et al. work [163]

Life Cycle Impact Assessment

Selection of impact categories, classification and characterisation are done using EF 3.0 methodology developed with the Joint Research Center from European commission [126] for the environmental analyses and the method named cumulative energy demand (CED) [127] and cumulative exergy demand (CExD) [127]. The impact categories used with their description are presented in the Table 48.

Table 48 - Environmental and energy Impact categories with description from SIMAPRO software

Source	Impact category	Units	Description
EF 3.0	Climate change	kg CO2 eq	Radiative forcing as Global Warming Potential GWP100 Baseline model of the IPCC 2013 with some factors adapted from EF guidance
	Ozone depletion	kg CFC11 eq	Ozone Depletion Potential calculating the destructive effects on the stratospheric ozone layer over a time horizon of 100 years.
	Ionising radiation	kBq U-235 eq	Ionizing Radiation Potentials: Quantification of the impact of ionizing radiation on the population, in comparison to Uranium 235.
	Photochemical ozone formation	kg NMVOC eq	Expression of the potential contribution to photochemical ozone formation.
	Particulate matter	disease incidence	Disease incidence due to kg of PM2.5 emitted. The indicator is calculated applying the average slope between the Emission Response Function (ERF) working point and the theoretical minimum-risk level. Exposure model based on archetypes that include urban environments, rural environments, and indoor environments within urban and rural areas.
	Human toxicity, non-cancer	CTUh	Comparative Toxic Unit for human. Using USEtox consensus multimedia model. It spans two spatial scales: continental scale consisting of six compartments (urban air, rural air, agricultural soil, natural soil, freshwater and costal marine water), and the global scale with the same structure but without the urban air.
	Human toxicity, cancer	CTUh	
	Acidification	mol H+ eq	Accumulated Exceedance characterising the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit.
	Eutrophication, freshwater	kg P eq	
	Eutrophication, marine	kg N eq	Nitrogen equivalents: Expression of the degree to which the emitted nutrients reach the marine end compartment (nitrogen considered as limiting factor in marine water).
	Eutrophication, terrestrial	mol N eq	Accumulated Exceedance characterising the change in critical load exceedance of the sensitive area, to which eutrophying substances deposit.
	Ecotoxicity, freshwater	CTUe	Comparative Toxic Unit for ecosystems. Using USEtox consensus multimedia model. It spans two spatial scales: continental scale consisting of six

			compartments (urban air, rural air, agricultural soil, natural soil, freshwater and costal marine water), and the global scale with the same structure but without the urban air.
	Land use	Pt	Soil quality index Calculated by JRC starting from LANCA® v 2.2 as baseline model.
	Water use	m3 deprivation	User deprivation potential (deprivation-weighted water consumption) Relative Available Water REMaining (AWARE) per area in a watershed, after the demand of humans and aquatic ecosystems has been met. Blue water consumption only is considered, where consumption is defined as the difference between withdrawal and release of blue water. Green water, fossil water, sea water and rainwater are not to be characterised with this methodology.
	Resource use, fossils	MJ	Abiotic resource depletion fossil fuels; based on lower heating value ADP for energy carriers, based on van Oers et al. 2002 as implemented in CML, v. 4.8 (2016).
	Resource use, minerals and metals	kg Sb eq	Abiotic resource depletion (ADP ultimate reserve) ADP for mineral and metal resources, based on van Oers et al. 2002 as implemented in CML, v. 4.8 (2016).
Ecoinvent	Cumulative energy demand	MJ	Method to calculate Cumulative Energy Demand (CED), based on the method published by Ecoinvent version 2.0 and expanded by PRé Consultants for raw materials available in the SimaPro 7 database. The method is based on higher heating values (HHV)
	Cumulative exergy demand	MJ	In this method exergy is used as a measure of the potential loss of "useful" energy resources.

In this work we are not using the optional normalisation developed by the method EF 3.0 to compare the impact with current impact level but we propose to compare the level of impact with sustainable level which are defined in the chapter II.6.3. Concerning the weighting, the value from EF 3.0 [164] are used in this work and are presented in Table 49. The weighting is not used in the optimisation model but for the proposed ranking method afterward. Weighting is an element which is both optional and subject to much debate in LCA community [165] but which gives a weighting for the different criteria. This weighting will be used in the ranking of the solutions but it is necessary to specify that these weightings reflect the current impacts and that a transformation of our energy model could lead to a modification of these values.

Table 49 - Weighting factor from EF 3.0

	Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals
Weighting EF 3.0 (Ws)	21%	6%	5%	5%	9%	2%	2%	6%	3%	3%	4%	2%	8%	9%	8%	8%

Appendix 5 - Result of environment energy and economy crossover approach

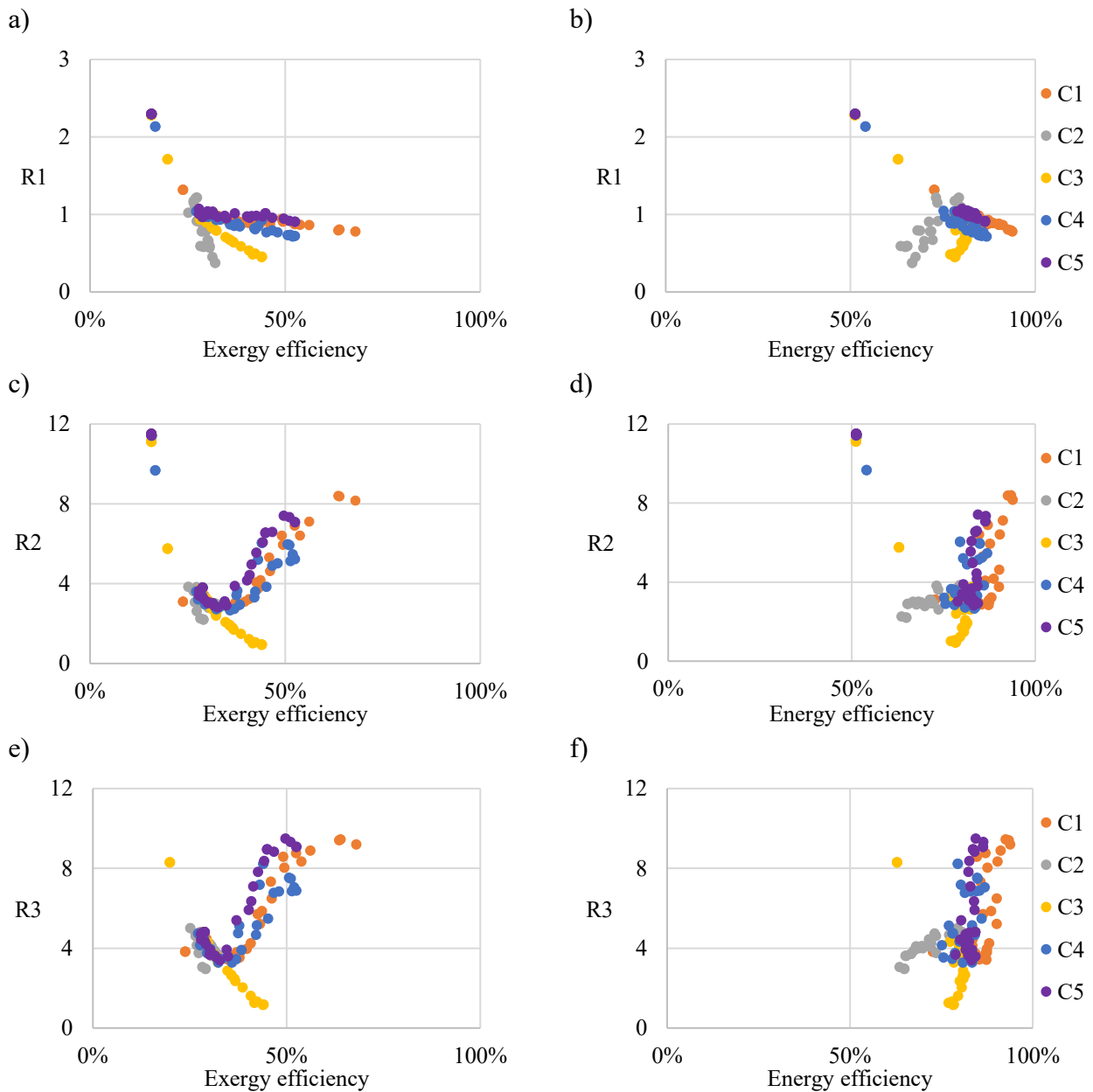


Fig. 98 - Correlation between environmental score and CExD and CED efficiency for configuration Weekly, 2015-2040 for ranking a) R1 function of exergy efficiency, b) R1 function of energy efficiency, c) R2 function of exergy efficiency, d) R2 function of energy efficiency, e) R3 function of exergy efficiency, f) R3 function of energy efficiency. The red dotted circle identifies solutions composed mainly of biomass.

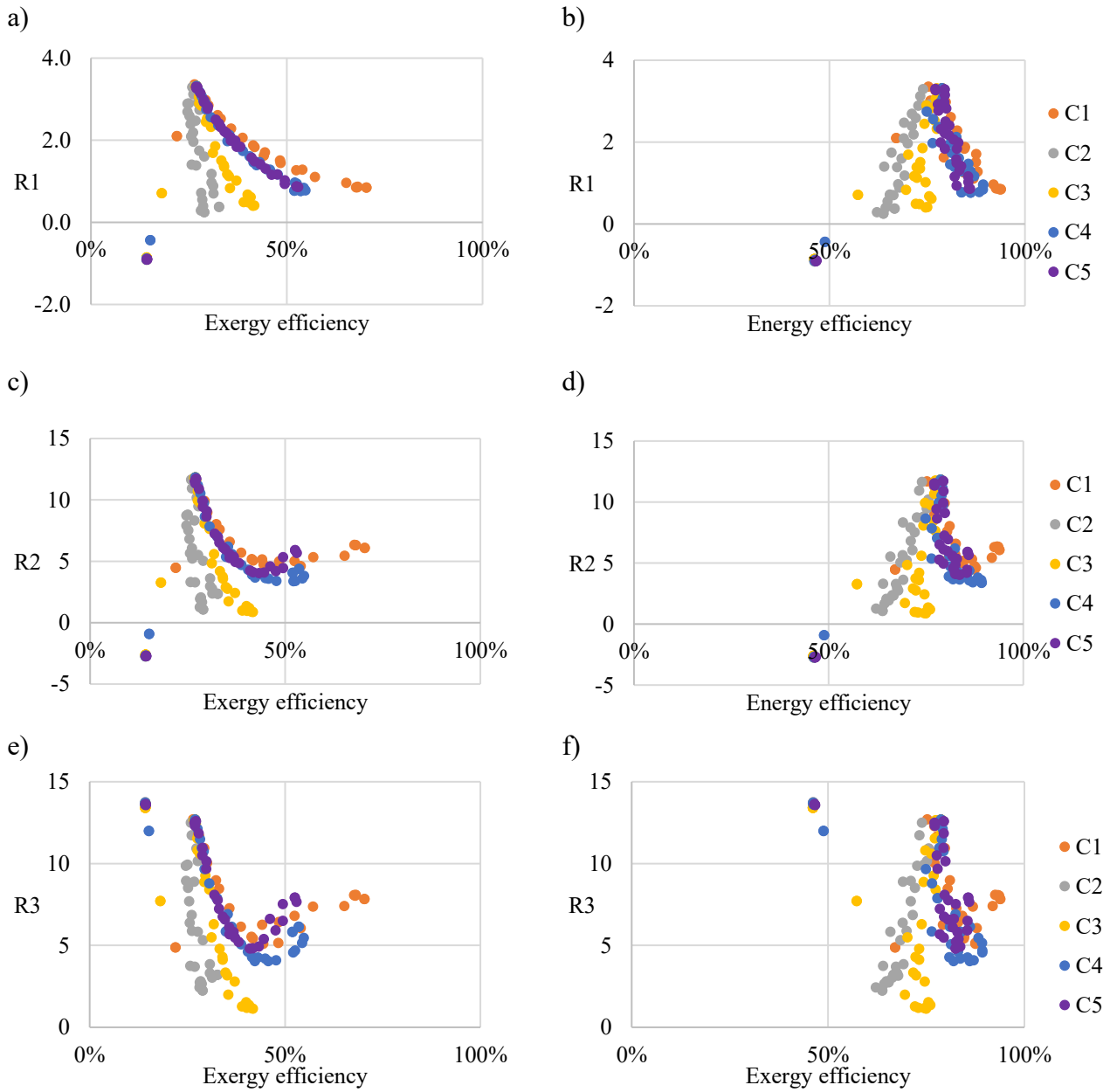


Fig. 99 - Correlation between environmental score and CExD and CED efficiency for weekly process for period 2065-2090 for ranking a) R1 function of exergy efficiency, b) R1 function of energy efficiency, c) R2 function of exergy efficiency, d) R2 function of energy efficiency, e) R3 function of exergy efficiency, f) R3 function of energy efficiency. The red dotted line represents the efficiency of the gas solution.

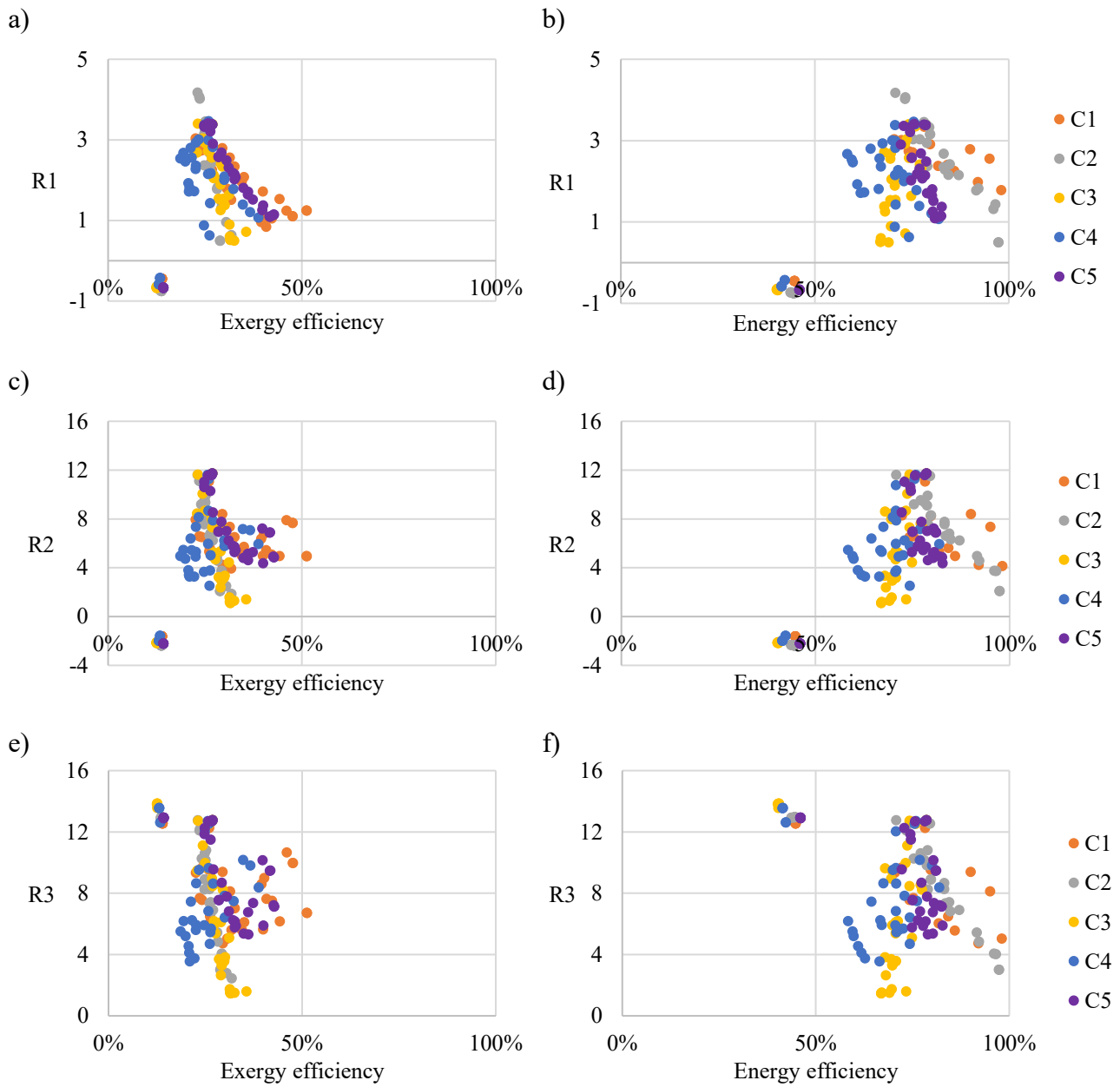


Fig. 100 - Correlation between environmental score and CExD and CED efficiency for batch process, 2065-2090 for ranking a) R1 function of exergy efficiency, b) R1 function of energy efficiency, c) R2 function of exergy efficiency, d) R2 function of energy efficiency, e) R3 function of exergy efficiency, f) R3 function of energy efficiency. The red dotted line represents the efficiency of the gas solution.

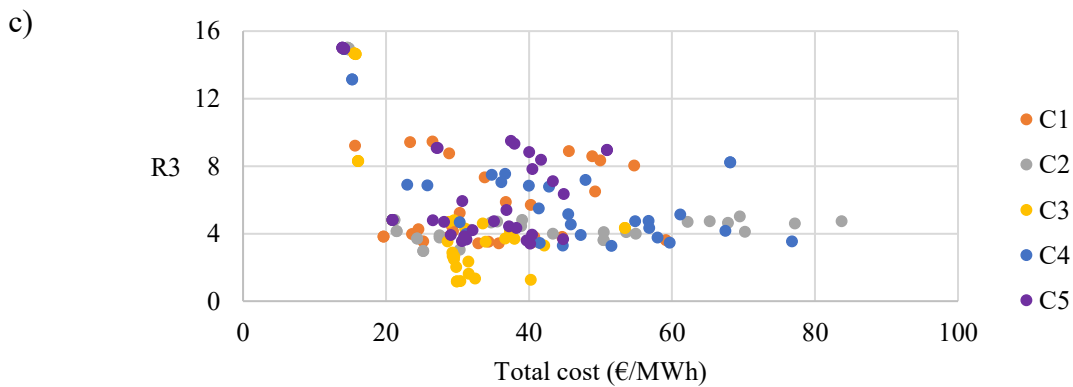
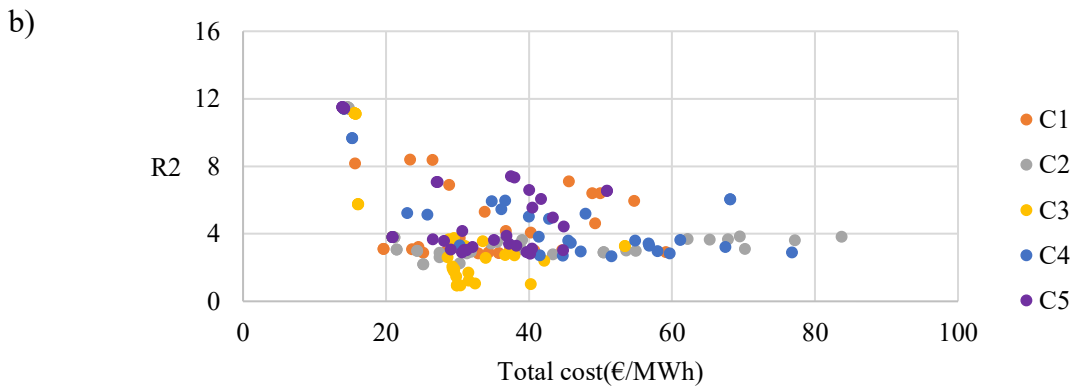
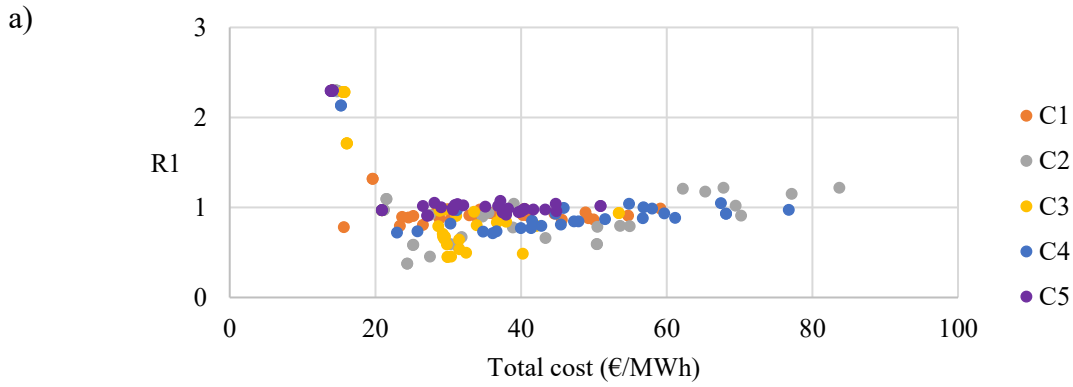


Fig. 101 - Correlation between environmental score and the total cost to produce heat for weekly process for the period 2015-2040, for ranking a) R1, b) R2 and c) R3. The red circle represents the solution dominated by biomass boiler.

Appendix 6 – Sensitivity analysis

Batteries efficiency

The evolution of battery performance in recent years shows that the sector is evolving and that the current environmental impact is not necessarily representative of what can be achieved in a few decades (Fig. 101). The gain can be based on either an increase in battery efficiency, i.e. the increase in energy stored per kilo of metal, or by using new resources. The latter option is more difficult to assess as environmental data is not available in the databases. The study will therefore focus on a parametric study of storage efficiency with an efficiency factor improvement β . The value $\beta = 1$ is the reference value presented in part II.2.5.3 when $\beta = 0.8$ represent the impact if the batteries mass required for a given unit of energy is reduce by 20 % compared to the reference scenarios. The different scenarios are tested on cluster C1 which has the lowest rate of controllable electricity, and therefore the highest share of batteries in its mix over the period 2065-2090.

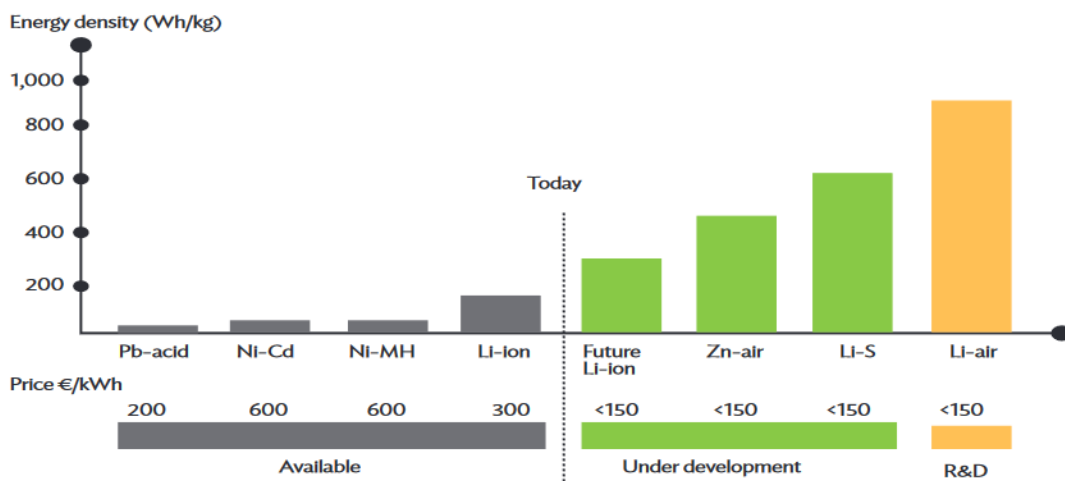


Fig. 102 – Projection of energy density evolution from [121]

In the configuration of improved efficiency of the amount of energy stored per unit mass, the solution with only the MHP installation approaches the sustainable level for cluster C1 (Fig. 102), and consequently for clusters C4 and C5. This is reflected in a reduction of the share of gas in the best ranked solutions of the R3 ranking, for $\beta = 0.8$, there is on average 12 % gas in the 3 best solutions, this value drops to 9 % for $\beta = 0.6$ and to 1 % for $\beta = 0.4$. Batteries are the main contributor to “resource use, minerals and metals” for mix based on intermittent generation sources.

Reducing the impact of these batteries is therefore the main issue for these electricity mix, and this can be done by improving the batteries, but also by other factors such as reducing demand, aligning demand with production, and trade between countries.

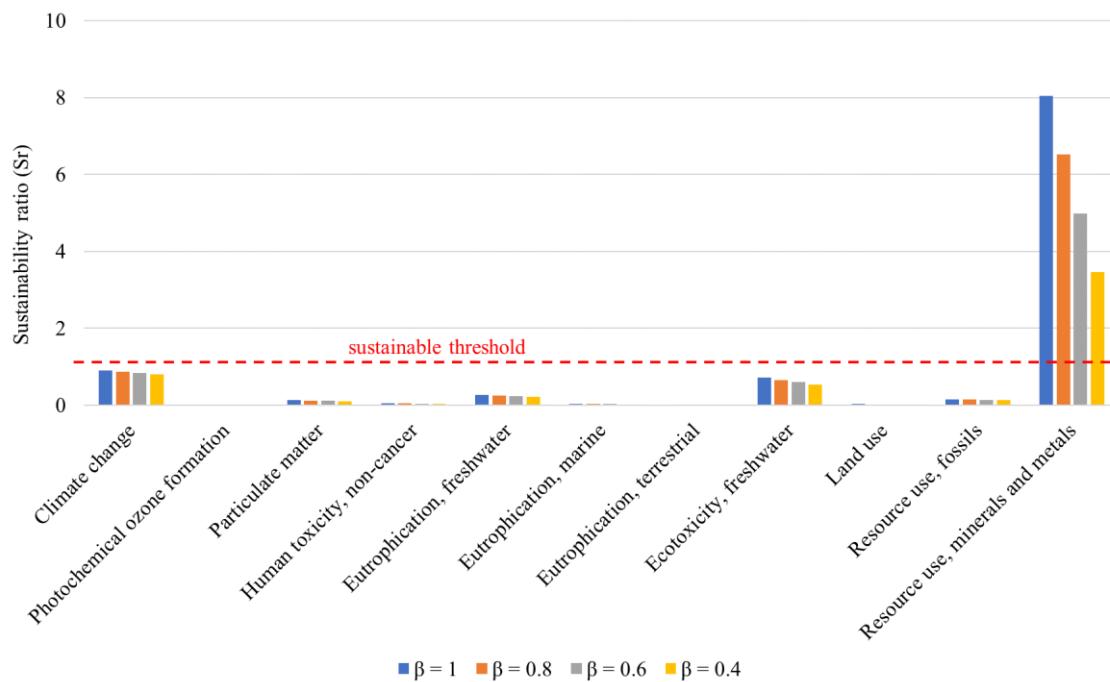


Fig. 103 - Sustainability ratio assessing four different mass factors by unit of energy, for the weekly process of the C1 mix over the period 2065-2090

Fatal heat and MHP up-time: Rate of recovery of waste heat

The presence of MHP is dependent on the available waste heat, in the initial configuration a high rate of heat is considered accessible. The idea of the parametric study is to show the impact of the rate of accessible waste heat for the process. The variations studied give the impact of a decrease of 50 % compared to reference accessible waste heat. This value is chosen because it limits the available power of the MHP with a production of about 50% of the need in a constant need configuration, this value decreases even more during periods of increased load.

The main difference in the configuration with less waste heat available compared to the reference case is the increase of the gas share in the highest ranked electric based solutions (Fig. 103). This increase coupled with the integration of electric boiler strongly increases the R3 score, so that there is no longer a solution with a score similar to the couple composed of 2/3 gas and 1/3 biomass. This is due to a much higher “climate change” threshold overshoot than in the reference configuration (factor of 6 to 8 for the solutions ranked 3 to 7 (Fig. 103b) against a factor of 2 to 5 for the reference case (Fig. 103a).

Accessibility to a sufficient supply of waste heat is a key condition for the development of MHP, especially since in the absence of waste heat, the electric alternative (electric boiler) will exacerbate the environmental impacts presented previously for MHP. The generalisation of this solution is therefore by no means guaranteed and relies on synergies specific to each industry. The solutions presented in the initial configuration are therefore favourable to the development of this technology, which risk to further increases the difficulty of limiting the impact below sustainable thresholds, which is largely based on the deployment of MHP.

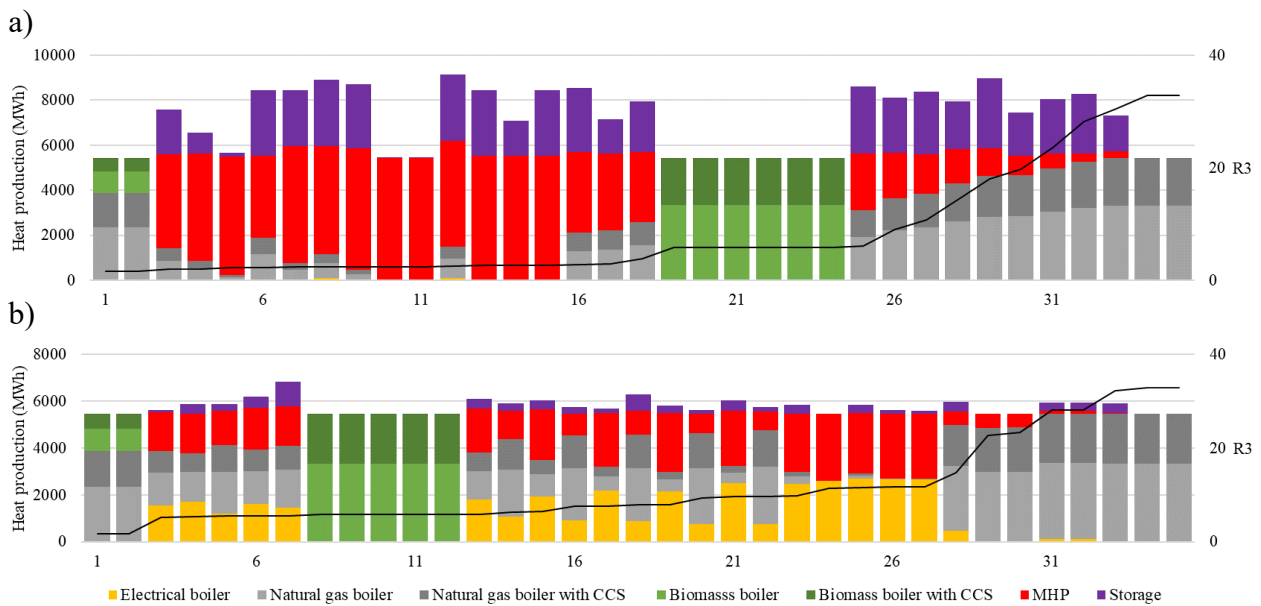


Fig. 104 – Ranking R3 for solution of cluster C1 for weekly process during the period 2065-2090 for
a) reference case b) waste heat available reduce by 50%

Refrigerants

The choice of refrigerants is also a major issue to allow the MHP to meet high temperature levels. The study will focus on 3 refrigerants available in the Ecoinvent database [88], the R744 (CO₂) studied in the initial configuration, R134a which has a high GWP of 1430 and is widely used today for temperature levels around 100 °C and R1336mzz(Z) which has a GWP of 2 and a critical temperature of 171 °C. The latter refrigerant is one of the preferred options of current market of very high temperature MHP [30]. Note that the loss of efficiency of the MHP associated with the change of refrigerant is not considered here, as the regimes of the three fluids are very different and it is decided in this section to compare them for the same energy efficiency.

The difference between R1336mzz(Z) and R744 is always below 0.11 % (Fig. 104), the impact of the refrigerant is very limited on all impact categories. For R134a and R744, the impact is even more limited with the exception of *climate change* for which there is a 1.5 % increase. R744 scores better for all impact categories studied, only a slightly higher value for the impact of *ionising radiation* is present (up to 0.01%). For the R744 configuration, the energy share is higher than 98 % for all impact categories. The choice of refrigerant will impact the COP by more than 10 % in some configurations [30] and this evolution will have a greater impact than the evolution of the environmental impact of these refrigerants.

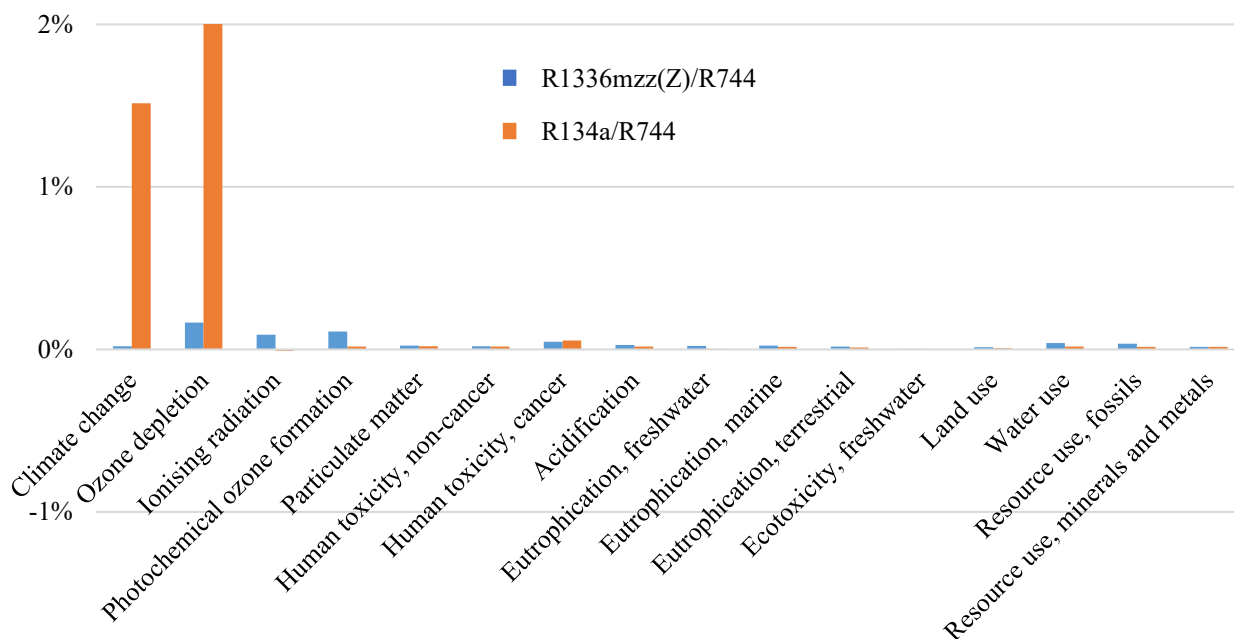


Fig. 105 – Environmental impact evolution for refrigerants R1336mzz(Z) and R134a compared to the reference used R744 (CO₂)

Sensitivity on CCS development rate

The development of CCS is currently subject to considerable uncertainty, so much so that the latest report "Energy, transport and GHG emissions - Trends to 2050" from European commission states that the cost has had to be revised upwards due to the current low level of development [35]. The rate of development will have a highly variable impact depending on the mix, and in this section the aim is to test the impact that this development may have on the conclusions presented so far.

The sensitivity study is applied to the mix that is most reliant on CCS, i.e. the C3 mix, as CCS is applied to both on-site and thermal power generation in this mix. To assess the impact of its development, two scenarios are tested to evaluate the impact that a faster or slower development could have compared to the baseline scenario (Table 50). As presented in part II.2.3.3, the periods 2015-2040 and 2040-2065 have similar trends and to simplify the reading the results will only be presented for the year 2015-2040 and 2065-2090.

Table 50 - CCS development scenario for 3 configurations, the reference scenario, a slow development scenario and a fast development scenario.

		2015-2040	2065-2090
Reference	CCS electricity production	8 %	71 %
	CCS on-site installation	0 %	39 %
Slow development	CCS electricity production	0 %	35 %
	CCS on-site installation	0 %	20 %
Fast development	CCS electricity production	15 %	90 %
	CCS on-site installation	5 %	60 %

The development of CCS has very little impact over the period 2015-2040 as industrial scale development has not yet started, the variation between fast and slow development has very little impact on climate change with a 20 % reduction on *climate change*, a 3 % increase on *resource consumption*,

fossils and a 1 % increase in *resource consumption, minerals and metals* between the fast and slow CCS development configurations (Fig. 105 a). On the other hand, for the period 2065-2090, the development of CCS will have a significant impact on the climate change indicator for the MHP-based solutions (Fig. 105b). The level is unsustainable in the case of a slow development of CCS technology and exceeds this limit by a factor of 2.7, when it becomes sustainable for the reference configuration. For the mix relying on a significant share of thermal energy, the presence of CCS is essential to avoid an overshoot of the climate change indicator, which would strongly penalise the solution (the solution with a slow development already considers 35 % of the installations equipped with CCS). On the other hand, the deployment of CCS results in a slight increase in resource consumption (+10 % for fossil fuels and +3 % for minerals and metals). The development of CCS limits the overshoot of one of the three limits at the expense of an increase in the other two. The others impact categories increase very marginally as soon as the CCS rate rises, these values are not presented here as they are not exceeding the sustainable threshold.

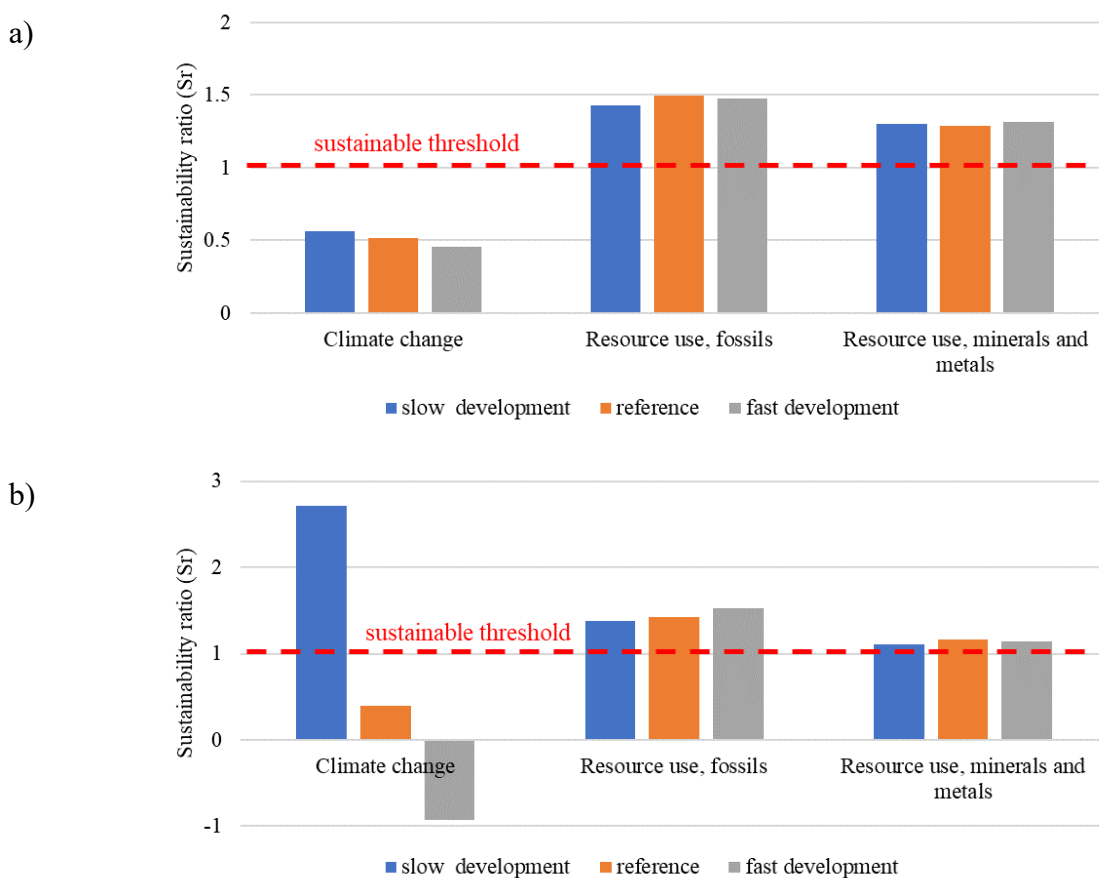


Fig. 106 - Sustainability ratio for climate change and resource consumption of the best solution for configuration C3, Weekly, a) 2015-2040 and b) 2065-2090. The solution is the best ranked for rankings R1, R2 and R3.

The results presented above are reflected in the R3 score for the three technologies (Fig. 106). For the period 2015-2040, the score of the different solutions is close enough that the development of CCS does not lead to a difference between the technologies. For the period 2065-2090, there is an interest in developing a sufficient rate of CCS in this type of mix to avoid exceeding the threshold of *climate change* with a value close to 50 % for the configuration presented here. On the other hand, above this threshold, the interest is limited because the gain is made on *climate change* which is already at a sustainable level at the expense of categories that are not. The CCS rate to be targeted may change

slightly depending on the electricity mix and the share of fossil or biomass fired energy. For a more carbon intensive mix, it will be necessary to target a higher CCS rate to meet this sustainable limit.

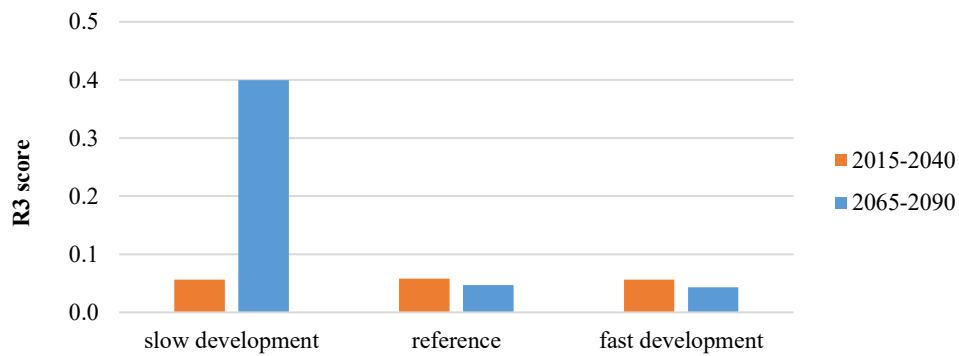


Fig. 107 - R3 score of the best solution for the weekly process of the C3 mix over the period 2015-2040 and 2065-2090. The solution is the best ranked for rankings R1, R2 and R3.

Appendix 7 - Industrial heat decarbonisation by electrification: can energy indicators be useful as a screening environmental indicator?

Introduction

Industrial heat accounts for two-thirds of industrial energy demand and nearly one-fifth of global energy consumption [1]. In the context of the transition to a low carbon economy, electrification is seen as a major path to decarbonise industrial heat that is primarily generated by fossil fuel (gas) combustion today [2]. Despite a huge potential for decarbonisation, this sector is often overlooked when compared to mobility and building ones as highlighted by Sorknæs et al. [3]. Furthermore, according to the same authors, insufficient insight is given to this transformation in most of the reported studies with for example non-easily duplicable scenarios assessed. In consequence, the overall environmental impact due to the change in the electricity generation because of the resulting increase in electricity demand is often not considered, the focus being put on the technology used (e.g. refrigerant choice for industrial heat pumps in [4]), the change in demand [5], [6], or on techno-economic criteria (e.g. Mallapragada et al. [7] for the chemical sectors, Lincoln et al. [8] for the dairy one). On the other hand, as illustrated for example by Slorach and Stanford [9] for the Building sector, environmental assessment is required to have a fair picture of the impacts and hence make informed decisions.

Life cycle assessment (LCA) analysis is a widely used environmental assessment method that can be applied to evaluate the environmental impact of switching process heat production from fossil fuel combustion to electrification. The integration of LCA in energy systems assessment leads to now well established 4E (energy, exergy, economic and environmental) or 3E (i.e. 4E without economic aspects) methodology that has been successfully applied to various cases, e.g.: primary copper production [166], Power-to-Methane [167], waste recovery in CHP plant [168].

While powerful and meaningful, the implementation of a full LCA approach increases the complexity of the problem to be solved with potential issues to be addressed as highlighted by Blanco et al. [167]. Simplification strategies most notably focus on reducing the number of impact categories in an effort to better communicate the results to a non-expert audience without affecting the results of the study [72]–[74]. Hence, methods for simplifying LCA analyses have been widely proposed over the past 20 years [73], [75], [76]. From a systematic review of the LCA simplification state of the art, Beemsterboer et al. [73] identified five simplifying strategies: exclusion, inventory data substitution, qualitative expert judgment standardisation and automation. For each of these strategies, the author outlines the main concerns linked to these simplifications. Simplification methods based on the exclusion of certain impact categories are among the most common approaches [75], [76]. Many studies have examined the effectiveness of a limited number of indicators to best reflect the environmental impact of a product or process [72], [74], [77]–[80]. The most radical of these approaches consists in adopting only one environmental indicator such as the carbon footprint [74], [81] or an energy indicator like Cumulative Energy Demand (CED) or Cumulative Exergy Demand (CExD) [77], [78], [82], [83].

Using cumulative energy demand as a single proxy for environmental performance was the title of one of the first papers related to LCA simplification [77], which is still widely cited in the literature today. Indeed, most of the current processes - especially industrial heat production as outlined previously - are driven by fossil fuels as shown by Huijbregts et al. [77], with a correlation between fossil fuel consumption, global warming and resource depletion indicators. Therefore, as concluded by the authors, “the use of fossil fuels is an important driver of several environmental impacts and thereby

indicative for many environmental problems. It may therefore serve as a screening indicator for environmental performance”. However, these conclusions - which are still valid today for fossil fuel energy intensive process as the energy transition is still struggling to get off the ground - could change abruptly if ambitious transition scenarios are put in place. Therefore, the consequences in terms of environmental impacts of a massive electrification of industrial heat production are relevant and deserve to be analysed and quantified.

Given the importance of industrial heat production in the global energy mix, the electrification of this sector will necessarily lead to an increase in global electricity production and the commissioning of new power generation facilities. Electricity can be used directly in electric boilers or - if waste heat is available - through a mechanical heat pump (MHP) to raise the temperature level to the process temperature . At constant delivered heat, these two technologies have very different impacts in terms of electricity consumption and environmental footprint even at for the system itself, e.g. the use of refrigerants in MHP. Hence, the analysis of the environmental consequences of such a choice in the frame of energy transition requires a coupled energy and environmental approach such as the one presented for the food industry by Jovet et al. [169]. To complement such approaches, the present paper focuses on questioning the existence of correlations between LCA indicators in the frame of energy transition and hence of large deployment of new power generation facilities that can radically change the environmental footprint of an electricity mix depending on the roadmap chosen by the country policymakers. This clearly distinguishes the present work compared to the previous reference contributions discussed in the introduction as they were mainly based on an electricity mix which environmental footprint was driven by fossil fuel use.

For this purpose, the proposed methodology aims to assess if a single energy indicator like CED or CExD is relevant as a screening environmental indicator for the production of electricity in the context of industrial heat electrification. Several pairs of energy used to produce electricity (e.g. nuclear/wind power) are then considered to assess whether the difference in value between their energy indicator can be correlated to the resulting difference for the LCA environmental indicators. The existence of two possible correlations is questioned:

1. If similar trends exist across all sources of energy, for a given environmental and energy indicators,
2. If similar trends exist between all environmental and energy indicators, for two different sources of energy,

To illustrate the proposed methodology, the assessment of current electricity generation with their characteristics for France is taken as an example.

1. Methods and Material

1.1 Overall methodology

The steps of the methodology are described in Fig. 1, for the pair of energy (A;B). The first step is to carry out an LCA for all the energy sources considered in the study - including sources A and B - with an assessment of one environmental impact indicator identified with the index i as well as one energy indicator identified with the index j . The impact I for energy A and impact category i is identified as $I_i(A)$.

The second step is to assess the absolute and relative changes of both the energy and the environmental impacts when switching from energy source A to energy source B to produce 1 kWh of electricity.

This shift can be characterized by the absolute change $\Delta I_i(A;B) = I_i(A) - I_i(B)$ for each indicator I_i , which is dimensional, or the relative change $Rc_i(A;B) = \Delta I_i(A;B)/ref(I_i)$, which is non dimensional, $ref(I_i)$ being the reference value usually taken at $I_i(A)$. In the frame of this assessment, as it is planned to compare the shift in each indicator, it is necessary to use a non-dimensional formula, i.e. the relative change. However, using $I_i(A)$ as the reference for the calculation of the relative change has several drawbacks. As the reference is linked to the substituted energy, it differs for all the studied energy pairs. Furthermore, within the same (A;B) pair, the result is not symmetrical if we substitute B for A. Finally, if for energy A the indicator is close to zero, the relative variation tends towards infinity. Therefore, it is more convenient to use a common reference for all the source of energy to calculate the relative change. Hence, the chosen reference for this study is the range of indicators I_i for all the source of energy: $I_{i \max} - I_{i \min}$. Thus, the relative change of indicator I_i when switching from energy source A to energy source B to produce 1 kWh of electricity is expressed as:

$$Rc_i(A; B) = \frac{\Delta I_i(A; B)}{I_{i \max} - I_{i \min}} = \frac{I_i(A) - I_i(B)}{I_{i \max} - I_{i \min}} \quad (1)$$

If $Rc_i(A;B)$ is close to 0, it implies that the shift from energy A to energy B does not have a significant impact on the I_i indicator. On the contrary, a value close to 1 indicates a significant impact on the I_i indicator.

The third and final step is to compare the two relative changes associated to each impact category, i.e. the environmental impact i and the energy indicator j :

$$Rc_{i/j}(A; B) = \frac{Rc_i(A; B)}{Rc_j(A; B)} \quad (2)$$

This ratio enables to assess, for a shift from source A to source B, how the variation in the energy indicator deviates from that of the environmental indicator. Thus, when comparing the relative change of indicators I_i and I_j when shifting from energy source A to energy source B, it is both possible to know whether this shift leads to a variation of the same sign for all the indicators and in similar proportions compared to the maximum achievable with all the considered sources of energy. If $Rc_{i/j}(A; B)$ is positive, both the indicator i and j point in the same direction, i.e. an improvement (or a degradation) in one indicator leads to an improvement (or a degradation) of the second. If, on the other hand, $Rc_{i/j}(A; B)$ is negative, changing the source of energy production will lead to an improvement in one of the criteria and a deterioration in the other.

One can note that $Rc_{i/j}$ is the same for the pair of energy sources A/B and B/A and inversely proportional between the indicator pairs j/i and i/j :

$$Rc_{i/j}(A; B) = Rc_{i/j}(B; A) = \frac{1}{Rc_{j/i}(A; B)} \quad (3)$$

Therefore, using indicator pair j/i instead of i/j leads to a result of the same sign but with an inverse value so that on a log scale, the ratio is symmetrical with respect to 1 or -1, i.e. the difference between the two indicators is the same between 1 and 0.1 as between 1 and 10. If $0 < Rc_{i/j}(A; B) < 1$, the relative improvement (degradation) of indicator i is lower than the relative improvement (degradation) of indicator j and the opposite is true if $Rc_{i/j}(A; B) > 1$.

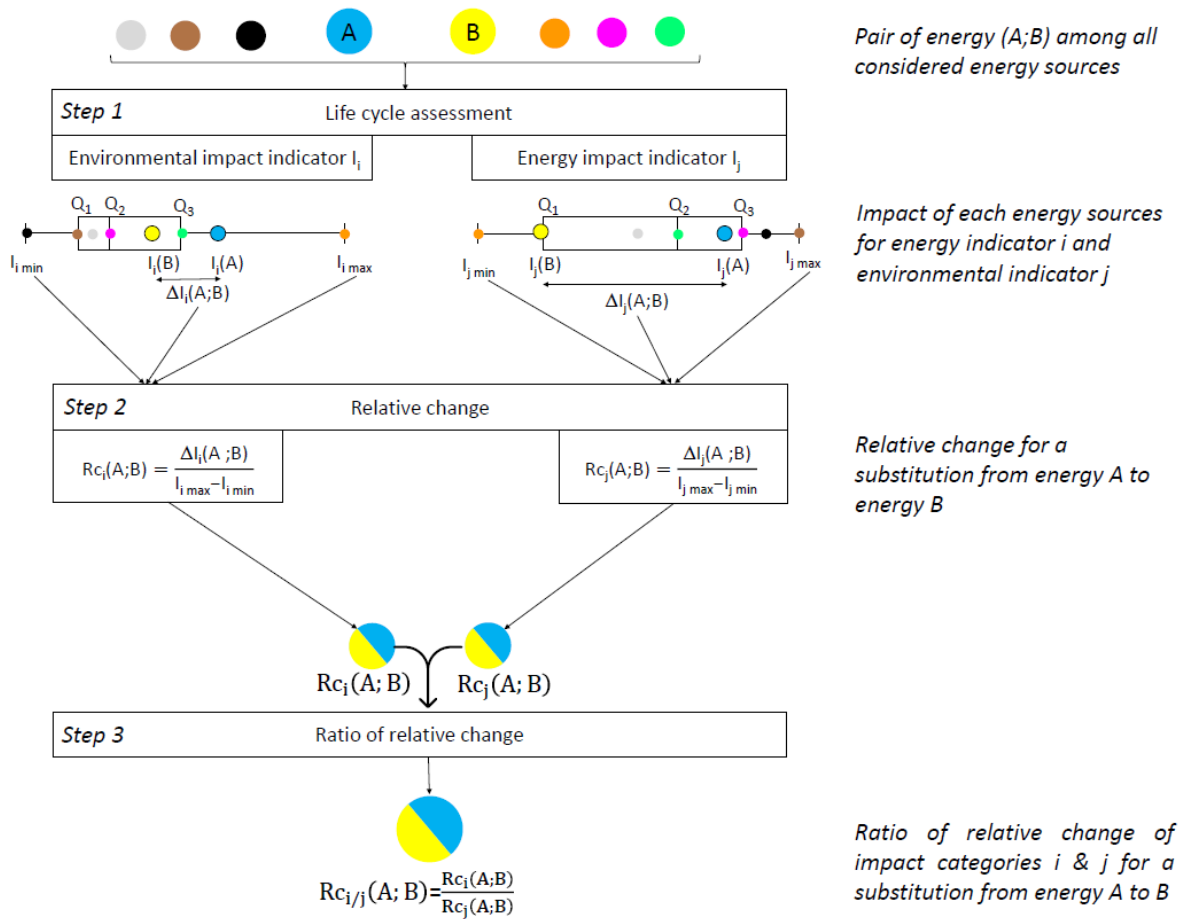


Fig. 1 - Proposed assessment framework

1.2 LCA model description

1.2.1. Goal and scope definition

The life cycle assessment follows the ISO 14044:2006 standards (ISO, 2006). The goal of this study is to evaluate the evolution of the environmental impacts of electricity generation when changing the energy sources. The functional unit, which is the basis of the assessment, is defined as the average generation of 1 kWh of electricity in France. The average performance of installations in France for each of the following energy sources are considered: coal, deep geothermal, gas combined cycle, hydro river, nuclear, solar, wind 1-3 MW and wood. Solar energy is not considered as the study focuses only on high voltage electricity production, for which the share of solar energy is negligible.

The analysed system considers a full life cycle assessment, encompassing the necessary resource extraction, the erection of the power plant, its use or operations (electricity generation) and its final decommissioning and disposal as described in Fig. 2.

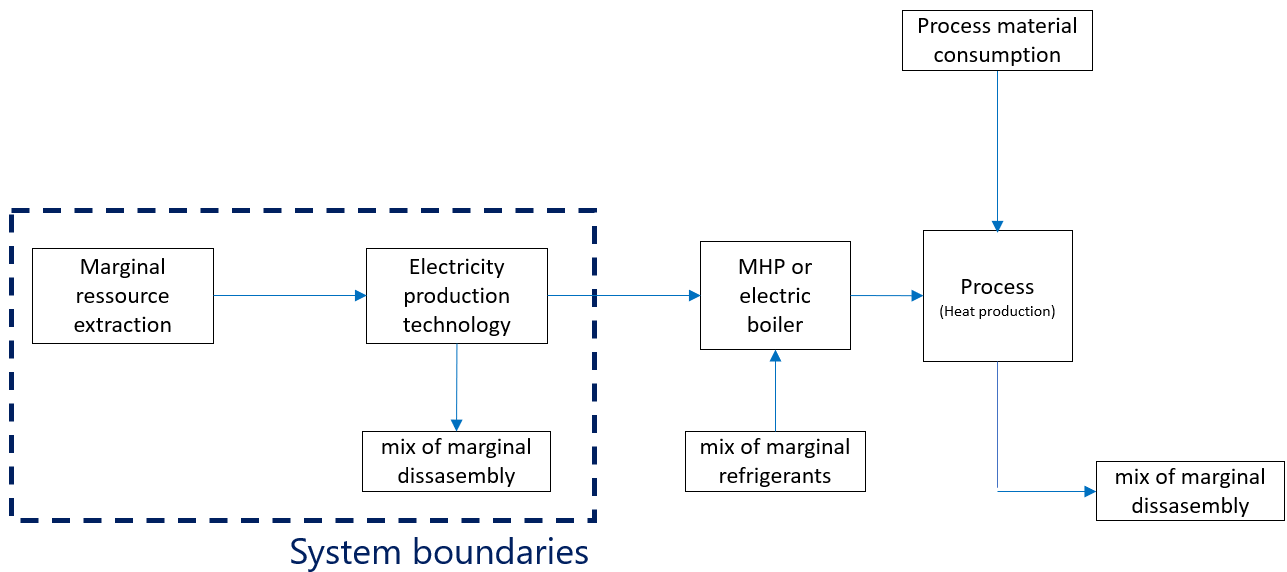


Fig. 2 – LCA system boundaries, the elements inside the dotted box are considered in the study.

1.2.2. Life cycle inventory modelling and impact assessment

The study adopts a consequential modelling, with the view to investigate the environmental consequences of the changes in the system, i.e. the change induced by the power system transformation, rather than the current state of the system, following the approach described in Hauschild et al. [4]. Data are based on the life cycle inventory (LCI) database ecoinvent, which gathers inputs and output flows (e.g. energy, materials, waste, emissions, resources, etc.) for thousands of individual process or activities [23]. Data from Ecoinvent consequential LCI database (version v.3.7.1) [23] were used, with as much specificity to the French energy supply systems, where available. The data used for the conversion of primary energy to electricity are taken from the French electricity generation mix database from the same database [23]. The production sources are compared with each other in order to see the environmental evolution.

The Life Cycle Impact Assessment (LCIA) was performed using the Environmental Footprint (EF) 3.0 LCIA methodology [24]. It enables quantification of approx. 16 impact categories, presented in Table A in SI1. These 16 environmental indicators are compared with two energy indicators, viz. cumulative energy demand (CED) and cumulative exergy demand (CExD), for electricity generation from different primary energy sources (fossil fuel, renewable energies, nuclear). For the sake of simplicity, it was chosen to not consider oil and concentrated solar power as significant contributors in new electricity facility development, oil being dedicated to mobility (only 2.77% of electricity production and still declining according to IEA³⁷) and CSP being seen as still marginal in the future in the European based mix³⁸.

³⁷ IEA, World electricity generation mix by fuel, 1971-2019, IEA, Paris <https://www.iea.org/data-and-statistics/charts/world-electricity-generation-mix-by-fuel-1971-2019>, IEA. Licence: CC BY 4.0

³⁸ IEA (2010), Technology Roadmap - Concentrating Solar Power, IEA, Paris <https://www.iea.org/reports/technology-roadmap-concentrating-solar-power>, License: CC BY 4.0

2. Results

2.1 Influence of energy choice for electricity production on energy and environmental criteria

This section presents the relative change (R_c) calculated for each pair of energy and all the environmental and energy indicators for the production of 1 kWh of electricity. Even if decarbonation of heat production by electrification implies that electricity production is also decarbonized, fossil fuel resources are also considered in this study, in order to broaden the scope of the comparison.

As an example, R_c is calculated for the pair of energy gas/wind for CExD and climate change (CC) indicators. To produce 1 kWh of electricity, 9.2 MJ and 4.3 MJ of cumulative exergy are required from gas and wind power while the CC indicator is equal to 0.55 kgCO₂-eq and 0.024 kgCO₂-eq, respectively. The two values of R_c are thus:

- $R_{CExD}(\text{gas/wind}) = \frac{9.2-4.3}{14.3-1.3} = 38\%$
- $R_{CC}(\text{gas/wind}) = \frac{0.55-0.024}{1.079-0.009} = 49\%$

By switching from gas to wind power, relative change for cumulative exergy demand falls by 38% while climate change impacts fall by 49%. The results for each source of energy are reported in Table 1. The first column of the tables contains the reference energy A and the first row, the alternative energy B used to produce the same amount of electricity. The symmetry between the pairs A/B and B/A, highlighted in equation 1, is reflected in the tables.

Table 1 – Relative change in (a) CExD, and (b) CC indicators. A negative value implies an increase in the considered impact indicators compared to the reference energy (A).









(a)

CExD A ↔ B	coal	deep geothermal	gas combined cycle	hydro river	nuclear	solar	wind 1-3 MW	wood
coal		90%	28%	69%	-10%	60%	66%	9%
deep geothermal	-90%		-61%	-21%	-100%	-30%	-23%	-81%
gas combined cycle	-28%	61%		40%	-39%	32%	38%	-20%
hydro river	-69%	21%	-40%		-79%	-8%	-2%	-60%
nuclear	10%	100%	39%	79%		70%	77%	19%
solar	-60%	30%	-32%	8%	-70%		6%	-51%
wind1-3 MW	-66%	23%	-38%	2%	-77%	-6%		-57%
wood	-9%	81%	20%	60%	-19%	51%	57%	

(b)

Climate change (CC) A ↔ B	coal	deep geothermal	gas combined cycle	hydro river	nuclear	solar	wind 1-3 MW	wood
coal		94%	49%	100%	100%	92%	99%	97%
deep geothermal	-94%		-45%	6%	6%	-2%	5%	3%
gas combined cycle	-49%	45%		51%	51%	42%	49%	48%
hydro river	-100%	-6%	-51%		0%	-8%	-1%	-3%
nuclear	-100%	-6%	-51%	0%		-8%	-1%	-3%
solar	-92%	2%	-42%	8%	8%		7%	5%
wind1-3 MW	-99%	-5%	-49%	1%	1%	-7%		-2%
wood	-97%	-3%	-48%	3%	3%	-5%	2%	

Fig. 3 summarizes the relative change calculated for each environmental and energy indicator and for the 28 energy pairs studied in this paper. This graph provides two major insights: i) it shows whether the distribution of benefits is similar across all environmental and energy categories and ii) it shows whether this change leads to environmental trade-offs, positive values having benefits and negative

values having negative impacts. For the first insight i), the smaller the height of the plot box, the closer the relationship between all environmental impact categories. Therefore, pairs with a narrow distribution are more likely to be correlated with each other. For insight ii), it can be noticed that some pairs lead to relative change always positive or negative, regardless of the environmental or energy indicators. This is the case for 6 pairs out of 18, namely coal/geothermal , coal/hydro , gas/hydro , solar/hydro , nuclear/hydro  and wind/hydro . One of the two energies has therefore less impact than the other regardless of the impact categories. For all other pairs of energy, there are always trade-offs when shifting from source A to source B. Furthermore, the more the distribution is spread out, the more the counterparts will be important. It is possible to see that some pairs have an equivalent number of positive and negative values i.e. gas/deep geothermal  or nuclear/deep geothermal . This means that there are as many impact categories that are improved as there are categories that are negatively affected.

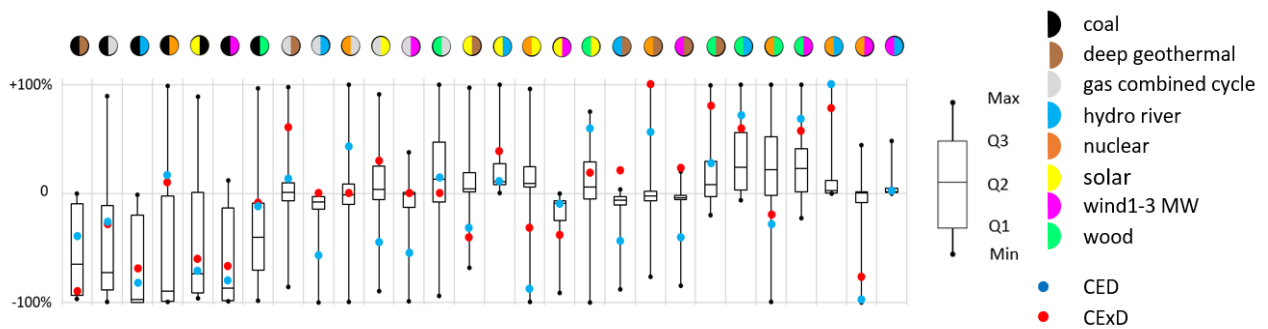


Fig. 3 – Relative change (R_{ci}) of the 28 energy pairs. The color on the left of the bicolor circle is the reference energy A and the color on the right the alternative energy B. Negative values imply a reduction of impact after the energy change for the impact category. The evolution of the energy indicators CED and CExD are presented in blue and red respectively.

Apart from deep geothermal, CED and CExD have very similar values. The difference for geothermal energy comes from the way the ground energy is accounted for, as the heat of the earth is not considered by the CExD method unlike the CED method. In the case of CED, the energy indicator is outside the environmental quartile Q1 and Q3 for 18 pairs among the 28 studied, while 19 pairs are outside this range for the CexD. The response of the energy indicators to a shift of energy is therefore generally different from that of the environmental indicators.

2.2 Correlation between energy-related and environmental impact indicators

To assess the existence of a correlation between energy, exergy and environmental indicators, the ratio of relative change (Eq. 2) is used. The goal being to compare environmental indicators to energy indicators, I_i is any of the 16 environmental indicators, while I_j is the cumulative exergy demand. Using the example of the wind/gas pair, we obtain for the climate change indicator and for the cumulative exergy demand:

$$R_{CC/CExD}(gas/wind) = \frac{49\%}{38\%} = 1.31$$

This result shows that a variation of 1 on the indicator CExD leads to a variation of 1.31 on the indicator CC, when switching from gas to wind power.

The results presented in Table 2 show both negative and positive values. Negative values indicate that an improvement in one of the indicators leads to a deterioration of the other. Out of 28 possible pairs of energy, 10 are negative and 18 are positive. For the latter, changing from energy A to energy B to produce 1 kWh of electricity improve or deteriorate both CExD and CC indicators.

Table 2 - Ratio of the relative change between the climate change indicator and cumulative exergy demand for different energy sources.

$R_{CC/CExD}(A; B)$	coal	deep geothermal	gas combined cycle	hydro river	nuclear	solar	wind 1-3 MW	wood
coal		1.05	1.73	1.46	-9.69	1.52	1.49	10.95
deep geothermal	1.05		0.73	-0.29	-0.06	0.07	-0.20	-0.04
gas combined cycle	1.73	0.73		1.27	-1.31	1.34	1.31	-2.42
hydro river	1.46	-0.29	1.27		0.00	0.99	0.63	0.06
nuclear	-9.69	-0.06	-1.31	0.00		-0.12	-0.02	-0.16
solar	1.52	0.07	1.34	0.99	-0.12		1.13	-0.10
wind1-3 MW	1.49	-0.20	1.31	0.63	-0.02	1.13		0.03
wood	10.95	-0.04	-2.42	0.06	-0.16	-0.10	0.03	

The ratios vary from a factor -10 for coal to nuclear substitution to a factor of +11 for coal to wood substitution. Even if some of the values are relatively close such as coal/geothermal or gas/geothermal, no general correlation can be found due to the disparity of values across the different energy sources. This shows that the CExD indicator is not a suitable proxy for estimating variations of the climate change indicator. This is particularly true for one third of the energy pairs for which the ratio is negative.

2.1.1. Classification of each ratio of relative change by environmental impact category

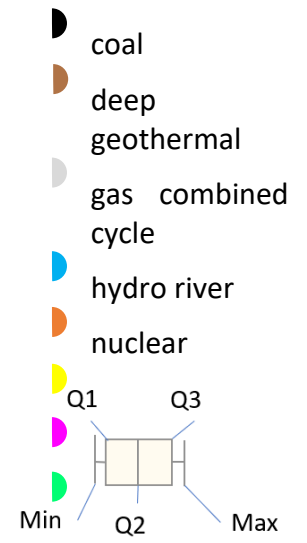
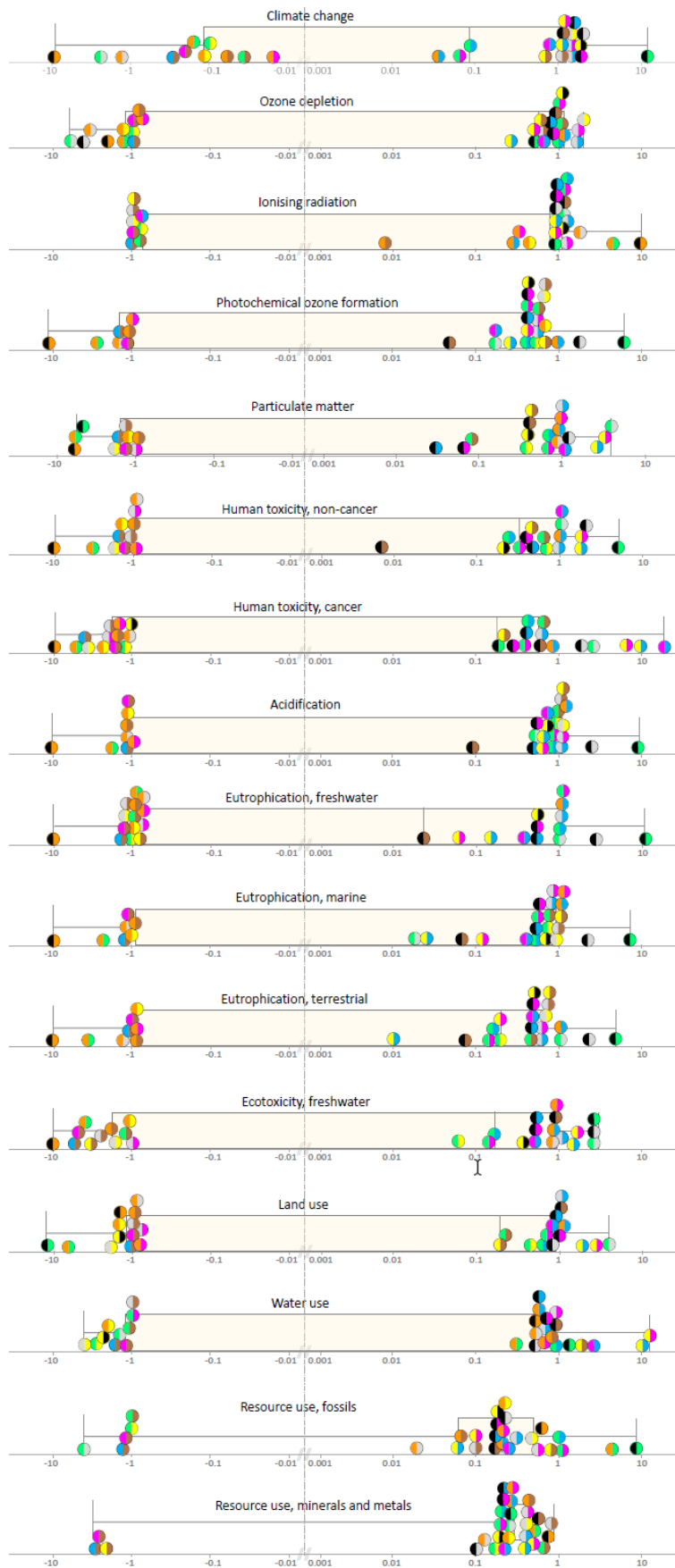
The ratios of relative change for CExD and the 16 environmental impacts are reported in Fig.4. The more pairs with a positive value, the more the CExD is an indication of the direction of change of the environmental impact.

A wide dispersion for all the impact categories is observed. Categories for which the first quartile is negative i.e. 13 of the 16 environmental categories have at least 25 % of the energy pairs evolving in opposite directions between the CExD and the considered environmental indicator. With a large disparity of values and above all, a significant share for both positive and negative values, there is no valid correlation for all energy pairs whatever the considered environmental impact category. This observation can also be confirmed using the difference between the first quartile (Q1) and the third (Q3), which is always higher than 1 except for the indicators “Ionising radiation” (0.9), “water use” (0.8) and “resource use, fossils” (0.7). Even for the two latter, the dispersion remains important for some energy pairs.

Focusing on the coal/gas pair, most of the indicators are positive excl. ozone depletion, which is in accordance with results reported by Huijbrets et al. [77], [78]. The scale width – from 0.1 (resource consumption metals and minerals) to 2.5 (fresh water eutrophication) leads to an average value of 1.52. For ozone depletion it has to be noticed that the contribution of the energy sector is low (Gebara et al., [170]), and this is to remain as it, natural gas being the main contributor with a global trend to decrease gas consumption.

It is possible to identify very different behaviors for the energy sources: nuclear shows many negative values, indicating an opposite evolution of exergy and environmental impacts, while on the contrary, many positive values are observed for hydro-river energy. Finally, some energy sources show a huge variability according to the impact categories, such as wind, wood and deep geothermal energy. As an example, wood energy consumes a lot of space but has a low consumption of mineral and metal resources.

(a)



Q1: 1st quartile

Q2: median

Q3: 3rd quartile

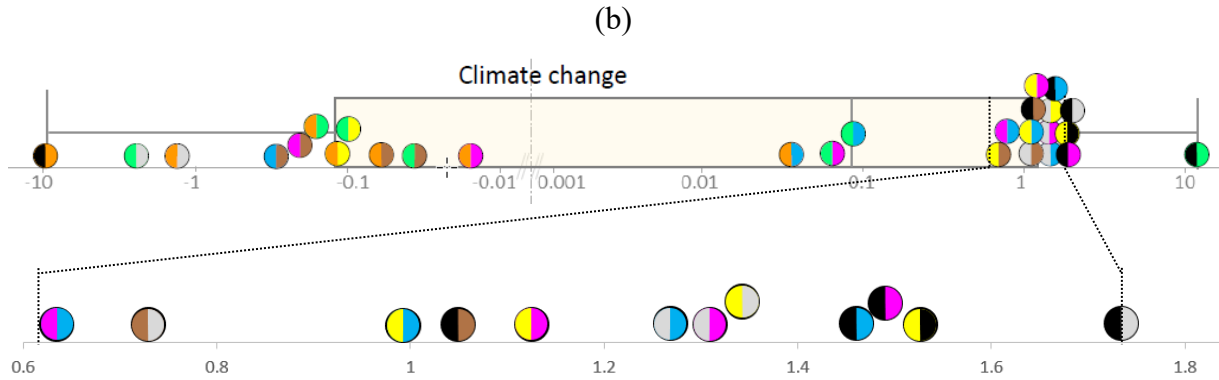


Fig. 4 – (a) Ratios of relative change for CExD and the 16 environmental impacts (log scale); for each pairs (bicolor circle) the left colour represents the energy with the maximal CExD, (b) focus on the cluster around 1 for CC indicator. For positive values, the energy on the left has the highest environmental impact, while for negative values the energy with the highest environmental impact is on the right.

While it can be concluded that there is no general correlation for all environmental impact categories with the CExD energy indicator, it is however possible, for each environmental category, to identify a few clusters of energy pairs having similar ratios. For example, for the climate change indicator, it is possible to identify a group of 13 out of the 28 energy pairs having values in the range 0.6 – 1.8. Among this cluster of 12 pairs of energy, *Fig. 4* shows that they are however quite dispersed except for three energy pairs around a similar ratio of 1.35 and 1.5. Furthermore, while it is possible to identify some groups of energy pairs for each impact category, these groups differ for each impact category, so there is no overall trend.

2.1.2. Classification of each ratio of relative change by energy pairs

In addition to the previous analysis, it may also be interesting to analyse whether similar trends exist for a particular energy pair among all environmental indicators (*Fig. 5*). Two main information need to be evaluated: i) whether the distribution of benefits is similar across all environmental and energy categories and ii) whether this change leads to environmental trade-offs, positive values having benefits and negative values having negative impacts.

For the first item i) if the ratio of relative change is positive, both environmental and energy indicators follow the same pattern i.e. improvement or degradation, whereas the opposite is true when the sign is negative. Six pairs of energy have only positive value, and none of them have only negative value. The hydro river/geothermal pair has only one positive value for indicator “Ressource use, minerals and metal”, which shows that the improvement of the CExD indicator leads to a deterioration of most of the environmental indicators for this pair of energy. Nonetheless, for most indicators, the ratios of relative change spreads among both positive and negative value depending on the impact category. For these pairs of energy, trade-offs must be considered between energy and environmental categories, but also between environmental categories themselves. It is therefore necessary to carry out a more detailed study, including sector specificities, to examine what are the counterparts.

For the second item ii), the analysis focuses on the distribution of ratios of relative change for each pair. For some energy pairs, a high concentration of the ratios can be observed as for example for coal/deep geothermal, coal/hydro river or gas/hydro river. For these pairs, the relative

reduction in environmental impacts is of the same order of magnitude as that of the energy indicator CExD. However, most of the other pairs have a widespread distribution as for example coal/solar, coal/wood, wood/gas. A detailed analysis of each of the impact categories is therefore necessary to assess the impact of using one energy over another to produce 1 kWh of electricity.

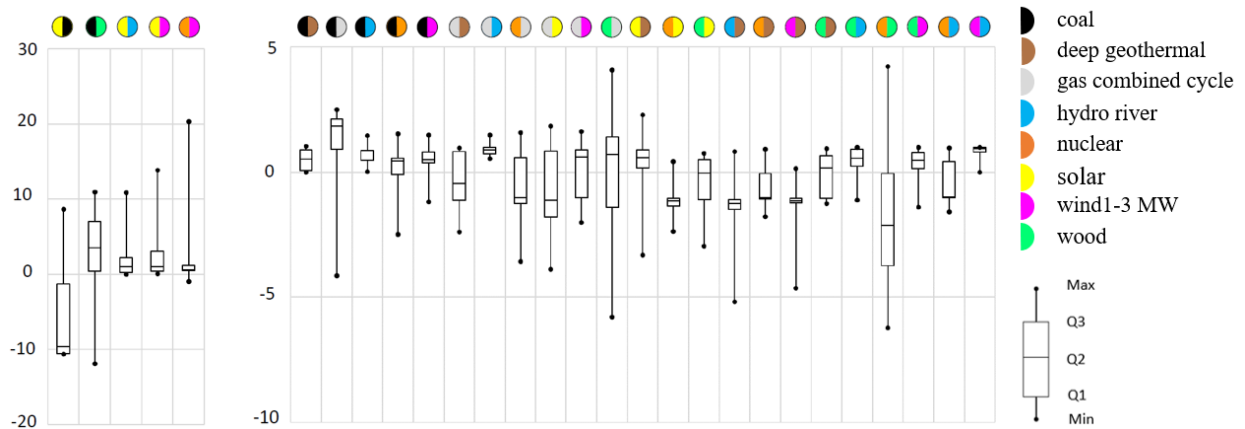


Fig. 5 – Ratios of relative change with CExD reference and the 16 environmental indicators. The color on the left of the bicolor circle is the energy with the higher CExD.

3. Discussion

From the previous results, no general trends are observed between the CED or CExD indicators and the 16 environmental impact categories when shifting the energy source for electricity production in France.

For all the other studied shifting pairs, the larger the observed differences in the ratio of relative changes, the more cautious the assessment needs to be. Energy pairs such as coal/deep geothermal ●, coal/hydro ●, gas/hydro ● or wind/hydro ● show very similar behaviour for all impact categories and it is possible in these configurations to use the CExD proxy. For other energy pairs, it is necessary to be more cautious in the use of proxies as there are significant differences between some energy sources, it is preferable to carry out detailed assessment that goes well beyond energy/exergy efficiency and climate change impact when it comes to the consequence of the deployment of new means of electricity production. The conclusions from Huijbregts et al. [77] remains valid for the energy pair gas/coal for which the pattern presented strong correlation for all impact categories with the exception of ozone depletion and to a lesser extent the resource use (land, water, minerals, fossils).

This was highlighted by [77] for case of nuclear power concerning the indicator “ionising radiation”, the present work extending the discussion to the consequence of electrification of industrial heat that can deeply impact the electricity generation portfolio. Therefore, this energy transition will lead to a shift of the impact that is today mainly climate change (gas boiler being by far the main mean to produce industrial heat) to other categories. It is then necessary to consider these new issues when thinking about the resulting transformation of the electricity system. Although the study does not compare the impact of electricity with that of a gas boiler, it is possible to compare the new generation sources on the grid with each other to identify what the weak points of each technology are. The impact categories which are likely to increase, when looking to relative change, are resource use for wind power, land use for wood energy or toxicity

for wood and geothermal. It is then necessary to have a reflection on the compatibility of these transformations on the earth's capacity to absorb them.

This conclusion is most certainly applicable to global electricity production as the differences for an impact category between the different means of production are more important than the differences between the portfolio of production processes between the countries. Table 3 presents the coefficient of variation (ratio of the standard deviation to the mean) calculated from the available data by country in the Ecoinvent database [88]. The disparity for energy sector mainly comes from the differences in efficiency for fossil power plants and in the load factor for wind power. Although there are sometimes significant variations between countries, it is possible to see in Fig. 6 that the distribution of all the means of production for France (red dot) is generally around the first quartile, except for gas which is close to the mean so that it can be seen as reasonably representative.

Table 3 - Coefficient of variation for all countries with available data in Ecoinvent database using an energy source present in the study for the 17 impacts category of methodology EF 3.0. Wood case not presented because of the worldwide scope.

Coefficient of variation for the ECOINVENT impact categories (%)	Coal	Geothermal	Gas	Hydro river	Nuclear	Oil	Wind
Climate change	18	7	27	3	7	28	46
Ozone depletion	35	8	45	3	5	27	48
Ionising radiation	56	20	458	17	6	27	63
Photochemical ozone formation	30	8	31	3	6	32	47
Particulate matter	110	10	63	3	6	64	47
Human toxicity. non-cancer	37	7	49	3	5	76	44
Human toxicity. cancer	30	3	50	5	5	48	45
Acidification	39	11	37	7	7	35	44
Eutrophication. freshwater	45	13	126	5	8	36	47
Eutrophication. marine	30	10	30	4	6	35	46
Eutrophication. terrestrial	32	11	31	3	6	35	46
Ecotoxicity. freshwater	36	16	61	9	6	27	46
Land use	27	9	47	125	8	28	60
Water use	46	8	58	6	52	47	44
Resource use. fossils	25	8	27	3	6	27	47
Resource use. minerals and metals	67	-6	57	-25	6	28	45

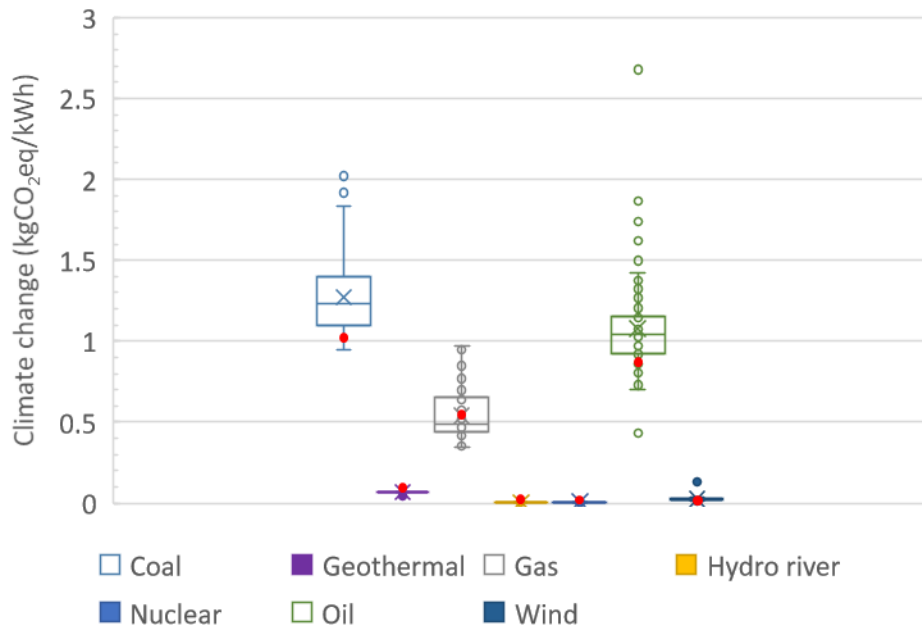


Fig. 6 – Distribution of the Climate Change impact related to different energy sources as a function of the considered country (Ecoinvent database)

Hence, while CED and CExD were relevant screening indicators in a context of fossil fuel driven electricity production such proxies are outdated in the context of a wide diversity in resources for electricity generation. Therefore, the environmental impacts have to be compared to a sustainable level such as the planetary boundaries from the Stockholm resilience center [11]. The comparison of the environmental assessment with these thresholds makes it possible to distinguish between a solution that reduces the environmental impact for different environmental categories like greenhouse gases (GHG) and a solution that stays below a sustainable level for these categories. A study from Jovet et al. [159], assessing the impact of the electrification of the food industry, shows that a reduction of the climate change impact towards a sustainable level leads to the overtaking of the earth boundary limits for other indicators, implying trade-offs between the different environmental indicators. Thus, an exhaustive approach of any environmental assessment in the frame of the current energy transition should be based on a multi-criteria analysis combining energy, exergy, economic and environment, such as the 4E methodologies.

In consequence, process heat electrification will lead to fully reconsider the impact of goods production. Indeed, coal and gas being the main energy resource used worldwide for these applications, the final environmental content of the product is independent of the plant location at the first order, while with electrification, the final impact will depend heavily of the chosen path of electricity decarbonisation, leading to significant variations in indicator values. Then, it is an important change in paradigm. Therefore, it may be interesting to extend the scope of the study to other sectors of activity. Laurent et al. [81] studied the relationship between the carbon footprint and other indicators of environmental impact categories for about 4000 products from the Ecoinvent LCI database [88]. It was found that correlations are highly biased when looking at the product level. Their study shows that some impact categories have high deviations compare to the others, such as toxicity to ecosystems and humans, depletion of resources, and land use. Their

conclusions are therefore similar to those of this study and show that for any complex system, it is necessary to maintain a multi-criteria approach.

4. Conclusions and recommendations

The electrification of industrial heat is identified as a powerful way to foster the decarbonisation of the processes. However, it implies to massively deploy new means of electricity production which will heavily impact the energy transition roadmaps. To help with decision making, this study proposes to investigate the existence of correlations between different energy and exergy indicators in relation to the environmental impact of an LCA and hence determine whether energy indicators coupled with climate change includes enough information to make informed decision as it is the case for shifting between fossil fuels. For each possible shifting of means of production of electricity, the proposed approach consists in estimating the relative change for each LCA indicator and their ratio.

For the use case of France, no general correlation is found between energy and environmental indicators. Indeed, for 28 studied pairs, 19 pairs have a relative change for the exergy indicator falling beyond quartiles Q1 and Q3 for the relative change in environmental indicators. For example, shifting from nuclear to gas leads to evenly positive and negative changes in environmental indicators while an increase by 100% is found for the exergy demand. As for ratio in relative changes, a large number of impact categories evolves in a non-proportional way and even sometimes in opposite way, i.e. the reduction of the impact of one category leads to the increase of another category. Nevertheless, in some limited cases, a behaviour close to correlation is identified (for coal/gas shifting for example), which confirms the results obtained in previous work but in other contexts (e.g. [77]). For most of the other shifting possibilities, using a single energy indicator as a relevant proxy for all environmental impacts is clearly not appropriate. Furthermore, it is also shown that the distribution of the ratios of relative change is highly dependent of the considered environmental indicator so that a multi-criteria approach is therefore necessary for a comprehensive analysis of the consequence of decarbonation of industrial heat generation by electrification.

The need to integrate a wide set of environmental parameters into energy and exergy studies increases the number of parameters and therefore the difficulty of assessing the strengths and weaknesses of each solution. It is therefore necessary to be able to arbitrate between different technical solutions despite these differences. In order to address this additional complexity, methodological work on the classification of solutions and the categories of impact to be prioritised for each sector is required.

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SII – Environmental and energy Impact categories with description from SIMAPRO software

Source	Impact category	Units	Description
EF 3.0	Climate change	kg CO ₂ eq	Radiative forcing as Global Warming Potential GWP100 Baseline model of the IPCC 2013 with some factors adapted from EF guidance
	Ozone depletion	kg CFC11 eq	Ozone Depletion Potential calculating the destructive effects on the stratospheric ozone layer over a time horizon of 100 years.
	Ionising radiation	kBq U-235 eq	Ionizing Radiation Potentials: Quantification of the impact of ionizing radiation on the population, in comparison to Uranium 235.
	Photochemical ozone formation	kg NMVOC eq	Expression of the potential contribution to photochemical ozone formation.
	Particulate matter	disease incidence	Disease incidence due to kg of PM2.5 emitted. The indicator is calculated applying the average slope between the Emission Response Function (ERF) working point and the theoretical minimum-risk level. Exposure model based on archetypes that include urban environments, rural environments, and indoor environments within urban and rural areas.
	Human toxicity, non-cancer	CTUh	Comparative Toxic Unit for human. Using USEtox consensus multimedia model. It spans two spatial scales: continental scale consisting of six compartments (urban air, rural air, agricultural soil, natural soil, freshwater and costal marine water), and the global scale with the same structure but without the urban air.
	Human toxicity, cancer	CTUh	
	Acidification	mol H+ eq	Accumulated Exceedance characterizing the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit.
	Eutrophication, freshwater	kg P eq	
	Eutrophication, marine	kg N eq	Nitrogen equivalents: Expression of the degree to which the emitted nutrients reach the marine end compartment (nitrogen considered as limiting factor in marine water).
	Eutrophication, terrestrial	mol N eq	Accumulated Exceedance characterizing the change in critical load exceedance of the sensitive area, to which eutrophying substances deposit.
	Ecotoxicity, freshwater	CTUe	Comparative Toxic Unit for ecosystems. Using USEtox consensus multimedia model. It spans two spatial scales: continental scale consisting of six compartments (urban air, rural air, agricultural soil, natural soil, freshwater and costal marine water), and the global scale with the same structure but without the urban air.
	Land use	Pt	Soil quality index Calculated by JRC starting from LANCA® v 2.2 as baseline model.
	Water use	m ³ deprivation	User deprivation potential (deprivation-weighted water consumption) Relative Available WATER REMaining (AWARE) per area in a watershed, after the demand of humans and aquatic ecosystems has been met. Blue water consumption only is considered, where consumption is defined as the difference between withdrawal and release of blue water. Green water, fossil water, sea water and rainwater are not to be characterized with this methodology.
	Resource use, fossils	MJ	Abiotic resource depletion fossil fuels; based on lower heating value ADP for energy carriers, based on van Oers et al. 2002 as implemented in CML, v. 4.8 (2016).
Resource use, minerals and metals	kg Sb eq	Abiotic resource depletion (ADP ultimate reserve) ADP for mineral and metal resources, based on van Oers et al. 2002 as implemented in CML, v. 4.8 (2016).	
Ecoinvent	Cumulative energy demand	MJ	Method to calculate Cumulative Energy Demand (CED), based on the method published by ecoinvent version 2.0 and expanded by PRé Consultants for raw materials available in the SimaPro 7 database. The method is based on higher heating values (HHV)
	Cumulative exergy demand	MJ	In this method exergy is used as a measure of the potential loss of "useful" energy resources.

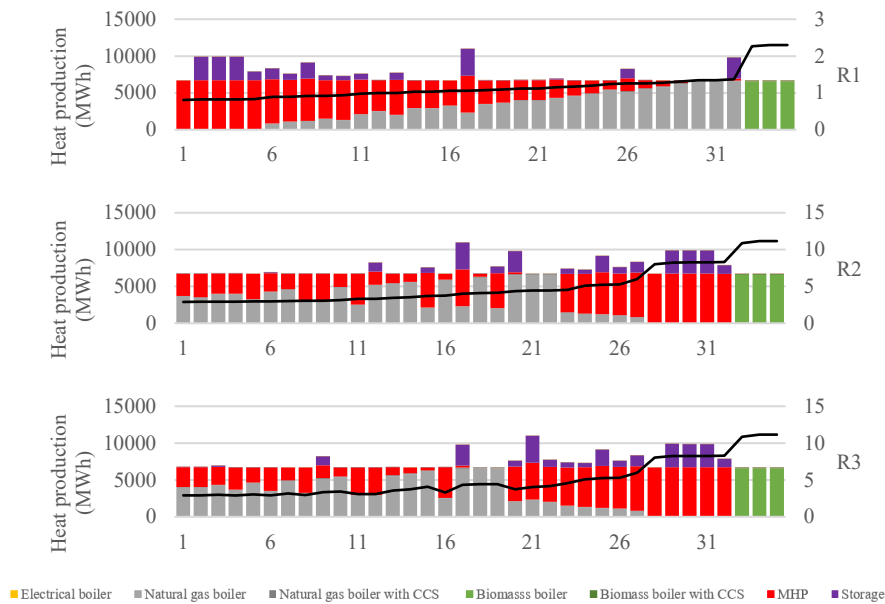
Appendix 8 – Pareto front solutions for 45 reference cases

The results of the different Pareto fronts are presented in this appendix. The organisation of the results follows the following logic:

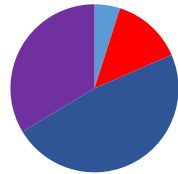
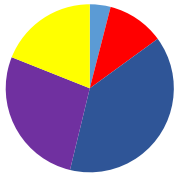
C1	Continuous	2015-2040	A1
		2040-2065	A2
		2065-2090	A3
	Weekly	2015-2040	A4
		2040-2065	A5
		2065-2090	A6
	Batch	2015-2040	A7
		2040-2065	A8
		2065-2090	A9
C2	Continuous	2015-2040	A10
		2040-2065	A11
		2065-2090	A12
	Weekly	2015-2040	A13
		2040-2065	A14
		2065-2090	A15
	Batch	2015-2040	A16
		2040-2065	A17
		2065-2090	A18
C3	Continuous	2015-2040	A19
		2040-2065	A20
		2065-2090	A21
	Weekly	2015-2040	A22
		2040-2065	A23
		2065-2090	A24
	Batch	2015-2040	A25
		2040-2065	A26
		2065-2090	A27
C4	Continuous	2015-2040	A28
		2040-2065	A29
		2065-2090	A30
	Weekly	2015-2040	A31
		2040-2065	A32
		2065-2090	A33
	Batch	2015-2040	A34
		2040-2065	A35
		2065-2090	A36
C5	Continuous	2015-2040	A37
		2040-2065	A38
		2065-2090	A39
	Weekly	2015-2040	A40
		2040-2065	A41
		2065-2090	A42
	Batch	2015-2040	A43
		2040-2065	A44
		2065-2090	A45

A4 2 - C1 Germany - 2040-2065 - Continuous process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

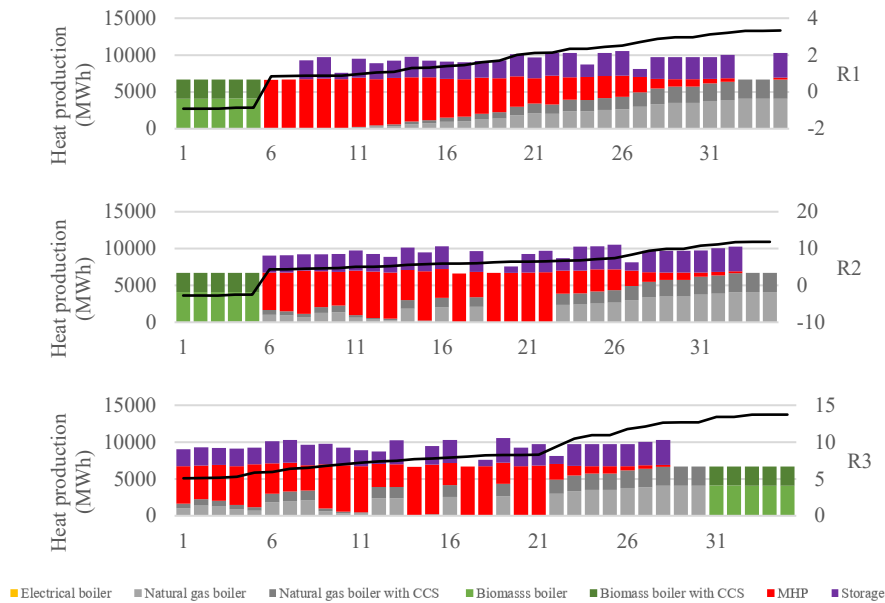
- Dammed hydro
- Geothermal plants
- Offshore wind
- Onshore wind
- Photovoltaic
- River hydro
- Biomass
- Solid
- Petroleum
- Gas
- Nuclear

Optimisation results

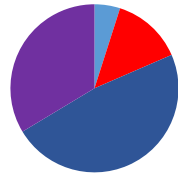
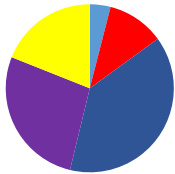
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.3	0.0	0.0	0.8	0.0	0.0	0.2	9.4	69%	93%	17	1	28	28
0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.3	0.0	0.0	0.8	0.0	0.0	0.2	9.6	67%	93%	17	2	29	29
0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.3	0.0	0.0	0.8	0.0	0.0	0.2	9.6	67%	93%	17	3	30	30
0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.3	0.0	0.0	0.8	0.0	0.0	0.2	9.6	67%	93%	17	4	31	31
0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.0	0.0	0.8	0.0	0.0	0.2	9.7	67%	92%	17	5	32	32
0.7	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.3	0.0	0.0	0.7	0.0	0.0	0.9	8.4	57%	90%	21	6	27	27
0.8	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.3	0.1	0.0	0.7	0.0	0.0	1.1	7.8	56%	91%	22	7	26	26
0.9	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.0	0.0	1.2	7.9	54%	89%	23	8	25	25
1.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.3	0.1	0.0	0.6	0.0	0.0	1.4	7.2	52%	91%	24	9	23	23
0.9	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.3	0.1	0.0	0.7	0.0	0.0	1.3	7.8	53%	90%	24	10	24	24
1.4	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.0	0.0	2.0	6.3	48%	89%	27	11	15	20
1.6	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.0	0.0	2.3	5.6	45%	90%	29	12	11	16
1.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.0	0.0	1.9	6.9	47%	89%	27	13	19	22
1.9	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.0	0.0	2.6	5.1	43%	89%	31	14	8	11
1.9	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.0	0.0	2.6	5.1	43%	89%	31	15	9	12
2.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.0	0.0	2.9	4.7	41%	89%	32	16	5	8
1.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.6	0.0	0.0	2.1	6.8	44%	83%	30	17	17	21
2.2	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.0	0.0	3.1	4.3	40%	89%	34	18	2	6
2.3	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.0	0.0	3.3	4.1	39%	88%	35	19	1	4
2.5	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.0	0.0	3.5	3.7	37%	88%	36	20	3	1
2.5	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.0	0.0	3.5	3.7	37%	88%	36	21	4	2
2.6	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.0	0.0	3.8	3.4	36%	86%	38	22	6	3
2.8	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	4.0	2.8	35%	87%	39	23	7	5
3.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	4.3	2.4	34%	86%	41	24	10	7
3.3	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	4.7	1.7	32%	86%	44	25	13	10
3.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	4.6	2.4	32%	83%	43	26	12	9
3.4	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	4.9	1.5	32%	85%	45	27	14	13
3.5	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.1	1.1	31%	85%	46	28	16	14
3.7	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.5	0.5	30%	84%	48	29	18	15
3.9	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.0	29%	84%	50	30	21	18
3.9	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.0	29%	84%	50	31	22	19
3.9	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.4	28%	81%	50	32	20	17
0.7	0.0	0.0	0.3	16.0	1.2	0.0	0.1	0.6	0.6	0.1	4.1	5.6	0.0	0.6	0.5	16%	52%	20	33	33	33
0.6	0.0	0.0	0.3	16.4	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.5	16%	51%	20	34	35	35
0.6	0.0	0.0	0.3	16.4	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.5	16%	51%	20	35	34	34

A4 3 - C1 Germany - 2065-2090 - Continuous process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

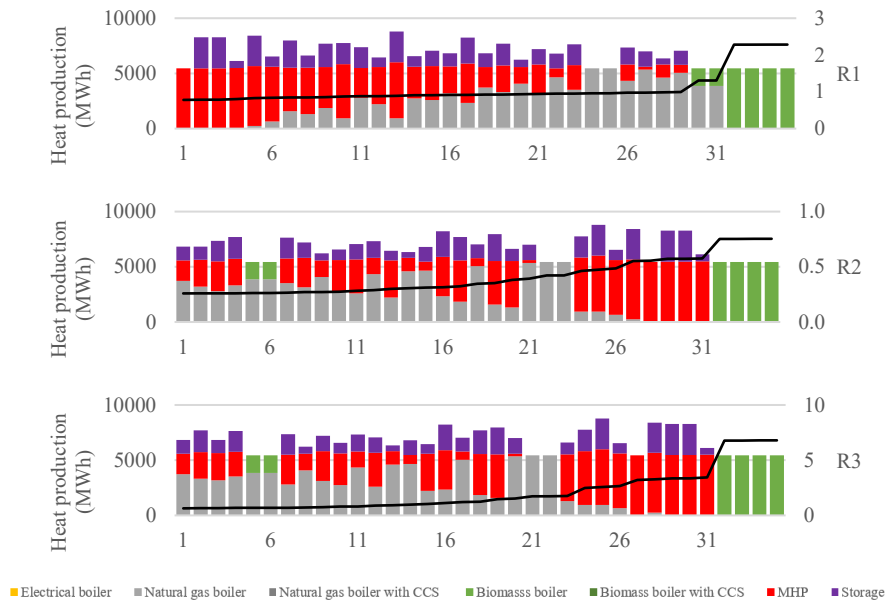
- Dammed hydro
- Onshore wind
- Biomass
- Gas
- Geothermal plants
- Photovoltaic
- Solid
- Nuclear
- Offshore wind
- River hydro
- Petroleum

Optimisation results

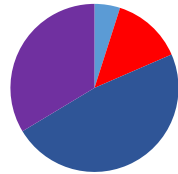
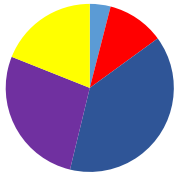
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3			
Sustainable ratio																			14%	46%	24	1	1	34
-14.5	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.5	0.0	0.6	0.8	14%	46%	24	2	2	35			
-14.5	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.5	0.0	0.6	0.8	14%	46%	24	3	3	33			
-14.1	0.0	0.0	0.3	15.5	1.2	0.0	0.1	1.0	0.7	0.1	4.1	5.3	0.0	0.7	0.8	14%	47%	23	4	4	31			
-14.1	0.0	0.0	0.3	15.5	1.2	0.0	0.1	1.0	0.7	0.1	4.1	5.3	0.0	0.7	0.8	14%	47%	23	5	5	32			
0.9	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.3	0.0	0.0	0.7	0.0	0.0	0.2	7.9	71%	95%	25	6	17	14			
0.9	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.3	0.0	0.0	0.7	0.0	0.0	0.2	8.3	69%	93%	26	7	19	17			
0.9	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.3	0.0	0.0	0.7	0.0	0.0	0.2	8.4	67%	93%	27	8	21	20			
0.9	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.3	0.0	0.0	0.7	0.0	0.0	0.2	8.5	67%	92%	27	9	22	21			
0.9	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.3	0.0	0.0	0.7	0.0	0.0	0.2	8.4	68%	92%	27	10	20	18			
1.3	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.3	0.0	0.0	0.7	0.0	0.0	0.3	8.2	63%	90%	28	11	15	15			
1.8	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.3	0.0	0.0	0.7	0.0	0.0	0.5	7.8	61%	91%	29	12	13	11			
2.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.3	0.0	0.0	0.7	0.0	0.0	0.6	7.7	59%	90%	29	13	12	10			
2.8	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.0	0.0	0.7	0.0	0.0	0.9	7.9	52%	86%	33	14	11	9			
3.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.3	0.1	0.0	0.6	0.0	0.0	1.1	7.0	53%	88%	32	15	8	5			
3.6	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.0	0.0	1.3	6.5	51%	90%	33	16	7	4			
3.9	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.0	0.0	1.4	6.2	50%	90%	33	17	6	1			
4.6	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.6	0.0	0.0	1.7	6.1	46%	86%	36	18	9	3			
5.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.0	0.0	1.9	5.6	45%	87%	36	19	10	2			
6.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.5	0.0	0.0	2.5	5.0	39%	82%	41	20	14	6			
7.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.0	0.0	2.8	4.2	38%	84%	42	21	18	8			
7.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.5	0.0	0.0	2.8	4.8	38%	80%	43	22	16	7			
8.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.0	0.0	3.2	3.8	35%	81%	45	23	24	13			
8.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.0	0.0	3.2	4.0	35%	81%	45	24	23	12			
8.7	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.0	0.0	3.4	3.7	34%	79%	47	25	25	16			
9.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.0	0.0	3.6	3.5	33%	79%	47	26	26	19			
10.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	4.0	2.6	31%	79%	49	27	27	22			
11.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	4.5	1.7	30%	80%	51	28	28	23			
11.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	4.7	1.3	29%	80%	52	29	29	24			
11.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	4.7	1.3	29%	80%	52	30	30	25			
12.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.0	0.8	28%	79%	54	31	31	26			
12.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.2	0.7	28%	78%	55	32	32	27			
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.1	27%	79%	56	33	34	29			
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.1	27%	79%	56	34	35	30			
13.3	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.4	27%	77%	57	35	33	28			

A4 4 - C1 Germany - 2015-2040 - Weekly process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

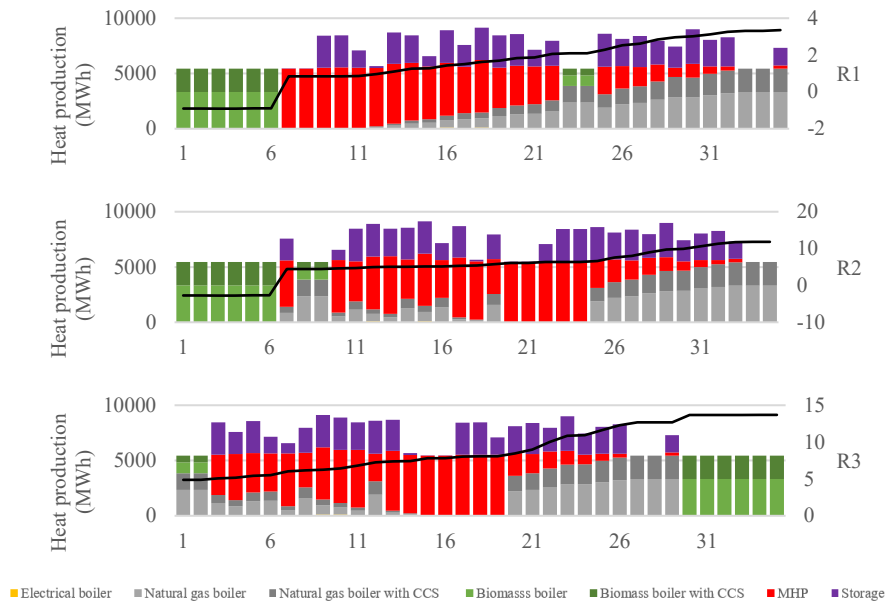
- Dammed hydro
- Geothermal plants
- Offshore wind
- Onshore wind
- Photovoltaic
- River hydro
- Biomass
- Solid
- Petroleum
- Gas
- Nuclear

Optimisation results

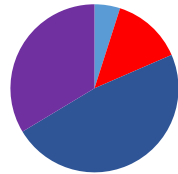
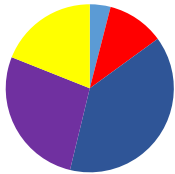
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.3	0.0	0.0	0.8	0.0	0.0	0.2	9.3	68%	94%	16	1	29	29
0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.0	0.0	0.8	0.0	0.0	0.2	9.5	64%	93%	23	2	31	30
0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.0	0.0	0.8	0.0	0.0	0.2	9.5	64%	93%	27	3	30	31
0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.4	0.1	0.0	0.8	0.0	0.0	0.7	9.0	56%	91%	46	4	28	28
0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.4	0.1	0.0	0.8	0.0	0.0	1.0	8.6	54%	90%	50	5	26	25
0.9	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.0	0.0	2.3	6.0	43%	90%	30	6	17	19
0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.0	0.0	0.9	8.9	52%	87%	29	7	27	27
0.7	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.0	0.0	1.8	7.1	46%	90%	49	8	22	22
1.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.0	0.0	2.8	5.2	41%	88%	25	9	14	14
0.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.6	0.0	0.0	2.1	6.6	44%	89%	37	10	21	21
1.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.0	0.0	3.0	4.9	40%	87%	24	11	10	12
0.6	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.0	0.0	1.6	7.8	46%	86%	34	12	23	23
1.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.0	0.0	3.4	4.3	38%	87%	25	13	3	5
0.5	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.4	0.1	0.0	0.8	0.0	0.0	1.3	8.4	49%	88%	55	14	24	24
1.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.5	0.0	0.0	3.2	4.7	38%	87%	41	15	8	9
1.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.0	0.0	3.6	4.0	36%	87%	33	16	1	1
0.9	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.0	0.0	2.3	6.5	43%	86%	40	17	20	20
1.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.0	0.0	3.3	4.7	37%	87%	45	18	9	8
1.4	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.0	0.0	3.8	3.9	35%	85%	36	19	2	2
0.5	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.4	0.1	0.0	0.8	0.0	0.0	1.3	8.9	49%	85%	49	20	25	26
1.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	4.8	2.1	32%	84%	28	21	7	7
2.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.1	29%	84%	21	22	18	17
2.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.1	29%	84%	21	23	19	18
2.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.5	0.8	29%	84%	29	24	15	15
1.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.2	1.5	30%	84%	29	25	13	13
1.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	4.5	2.9	32%	83%	34	26	4	4
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.4	29%	83%	30	27	16	16
1.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.0	0.0	4.3	3.5	33%	84%	41	28	5	3
1.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.3	0.0	0.0	4.7	2.6	31%	85%	59	29	6	6
1.6	0.0	0.0	0.1	4.6	0.4	0.0	0.0	0.3	0.3	0.0	1.2	1.6	0.0	4.3	0.3	24%	73%	20	30	11	10
1.6	0.0	0.0	0.1	4.6	0.4	0.0	0.0	0.3	0.3	0.0	1.2	1.6	0.0	4.3	0.3	24%	73%	20	31	12	11
0.4	0.0	0.0	0.3	16.5	1.2	0.0	0.1	0.7	0.7	0.1	4.2	5.8	0.0	0.5	0.7	16%	51%	14	32	34	34
0.4	0.0	0.0	0.3	16.5	1.2	0.0	0.1	0.7	0.7	0.1	4.2	5.8	0.0	0.5	0.7	16%	51%	14	33	35	35
0.4	0.0	0.0	0.3	16.5	1.2	0.0	0.1	0.7	0.7	0.1	4.2	5.8	0.0	0.5	0.7	16%	51%	14	34	32	32
0.4	0.0	0.0	0.3	16.5	1.2	0.0	0.1	0.7	0.7	0.1	4.2	5.8	0.0	0.5	0.7	16%	51%	14	35	33	33

A4 6 - C1 Germany - 2065-2090 - Weekly process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

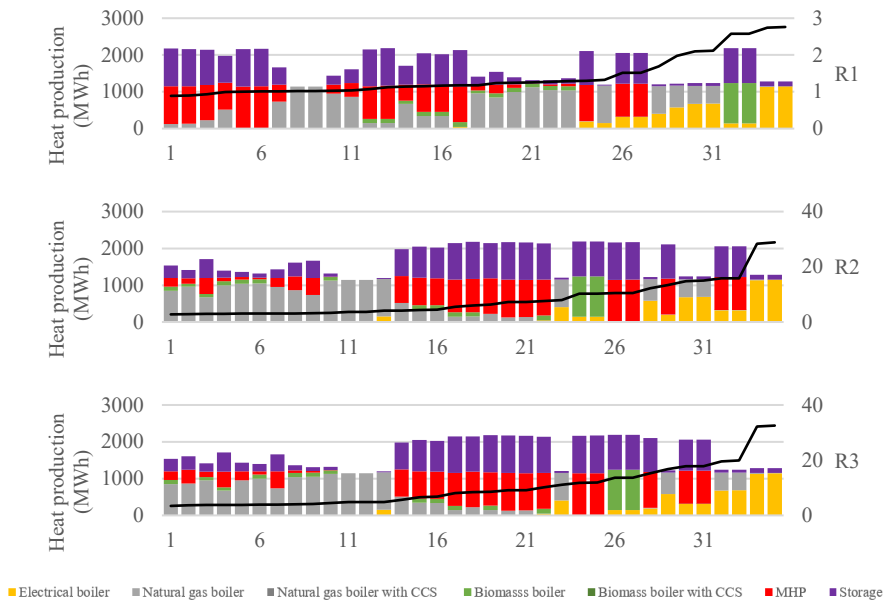
- Dammed hydro
- Geothermal plants
- Offshore wind
- Onshore wind
- Photovoltaic
- River hydro
- Biomass
- Solid
- Petroleum
- Gas
- Nuclear

Optimisation results

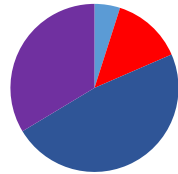
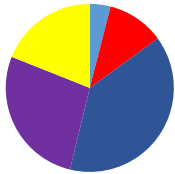
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3		
Sustainable ratio																							
-14.5	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	0.9	14%	46%	24	1	1	34		
-14.5	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	0.9	14%	46%	24	2	2	35		
-14.5	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	0.9	14%	46%	24	3	3	33		
-14.5	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	0.9	14%	46%	24	4	4	32		
-14.4	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	0.9	14%	46%	24	5	5	30		
-14.4	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	0.9	14%	46%	24	6	6	31		
0.9	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.3	0.0	0.0	0.7	0.0	0.0	0.1	8.0	70%	94%	25	7	7	15		
0.9	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.3	0.0	0.0	0.7	0.0	0.0	0.1	8.0	70%	94%	25	8	20	16		
0.8	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.0	0.0	0.6	0.0	0.0	0.1	8.2	68%	94%	26	9	23	17		
0.8	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.0	0.0	0.6	0.0	0.0	0.1	8.3	68%	93%	26	10	24	18		
0.9	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.3	0.0	0.0	0.7	0.0	0.0	0.1	8.3	68%	93%	26	11	22	19		
1.4	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.3	0.0	0.0	0.7	0.0	0.0	0.4	7.8	65%	92%	27	12	18	14		
1.9	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.3	0.0	0.0	0.6	0.0	0.0	0.6	8.0	57%	87%	30	13	17	13		
2.7	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.3	0.0	0.0	0.6	0.0	0.0	0.9	7.8	52%	84%	32	14	13	11		
2.9	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.3	0.0	0.0	0.7	0.0	0.0	1.0	7.2	54%	88%	32	15	10	7		
3.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.0	0.0	1.2	7.7	48%	83%	35	16	12	10		
4.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.3	0.1	0.0	0.6	0.0	0.0	1.5	6.3	48%	88%	34	17	7	4		
4.1	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.0	0.0	1.5	7.7	44%	79%	38	18	15	9		
5.2	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.0	0.0	2.0	5.4	44%	88%	36	19	11	3		
5.7	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.0	0.0	2.2	5.3	42%	85%	38	20	14	5		
6.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.0	0.0	2.3	5.2	41%	85%	39	21	16	6		
6.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.5	0.0	0.0	2.6	4.8	39%	83%	42	22	19	8		
5.5	0.0	0.0	0.1	4.5	0.3	0.0	0.0	0.4	0.3	0.1	1.3	1.5	0.0	4.0	0.3	22%	67%	38	23	8	1		
5.5	0.0	0.0	0.1	4.5	0.3	0.0	0.0	0.4	0.3	0.1	1.3	1.5	0.0	4.0	0.3	22%	67%	38	24	9	2		
8.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.0	0.0	3.2	3.8	36%	83%	44	25	25	12		
9.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.0	0.0	3.7	3.1	33%	81%	47	26	26	20		
9.7	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	3.9	2.7	32%	81%	48	27	27	21		
10.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	4.3	2.4	30%	77%	52	28	28	22		
11.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	4.7	1.4	29%	80%	52	29	30	24		
11.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	4.6	2.0	29%	76%	54	30	29	23		
12.3	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.0	1.1	28%	78%	55	31	31	25		
13.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.2	0.7	27%	77%	56	32	32	26		
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.1	27%	79%	56	33	34	27		
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.1	27%	79%	56	34	35	28		
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.6	26%	75%	58	35	33	29		

A4 7 - C1 Germany - 2015-2040 - Batch process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

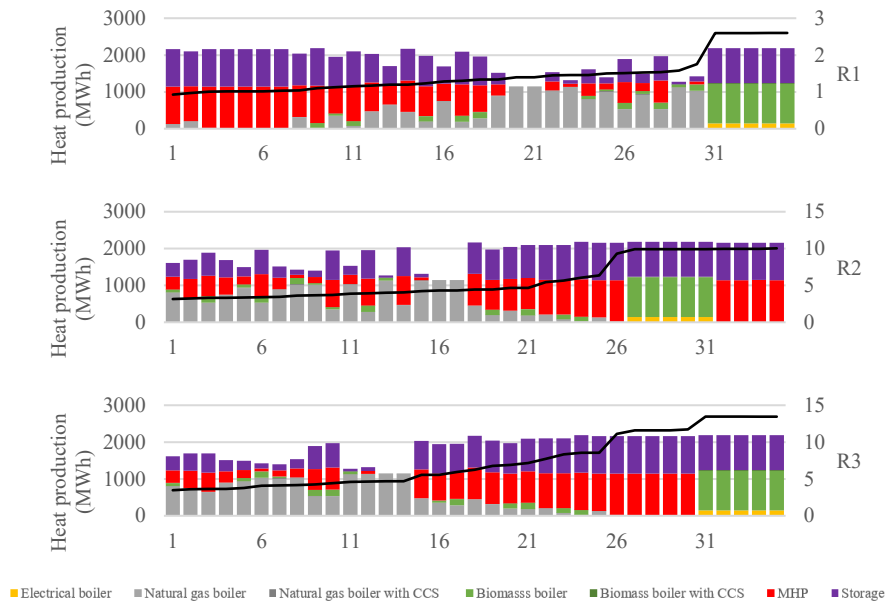
- Dammed hydro
- Onshore wind
- Biomass
- Gas
- Geothermal plants
- Photovoltaic
- Solid
- Nuclear
- Offshore wind
- River hydro
- Petroleum

Optimisation results

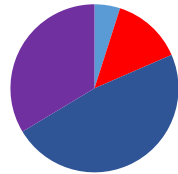
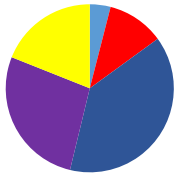
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3																		
Sustainable ratio																																							
0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.8	0.0	0.0	0.8	9.2	53%	158%	42	1	20	20																		
0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.4	0.1	0.0	0.8	0.0	0.0	0.9	9.3	53%	158%	43	2	21	21																		
0.5	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.8	0.0	0.0	1.3	8.8	48%	142%	44	3	19	18																		
1.0	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.0	0.0	2.8	6.7	38%	113%	46	4	14	14																		
0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.4	0.1	0.0	1.0	0.0	0.0	0.2	11.9	50%	155%	53	5	26	24																		
0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.4	0.1	0.0	1.0	0.0	0.0	0.2	11.9	50%	155%	53	6	27	25																		
1.4	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.5	0.0	0.0	3.8	4.7	33%	101%	47	7	9	7																		
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.9	0.7	29%	84%	26	8	11	11																		
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.9	0.7	29%	84%	26	9	12	12																		
1.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	5.0	2.7	29%	90%	61	10	7	5																		
1.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.0	0.0	4.5	3.7	31%	93%	44	11	8	2																		
0.4	0.0	0.0	0.1	1.7	0.2	0.0	0.0	0.5	0.1	0.0	1.2	0.6	0.0	1.0	8.6	42%	130%	59	12	17	17																		
0.4	0.0	0.0	0.1	1.8	0.2	0.0	0.0	0.5	0.1	0.0	1.3	0.6	0.0	1.0	9.1	38%	126%	97	13	18	19																		
1.4	0.0	0.0	0.1	1.3	0.1	0.0	0.0	0.4	0.1	0.0	0.8	0.4	0.0	3.6	4.8	29%	95%	85	14	3	4																		
0.8	0.0	0.0	0.1	1.8	0.2	0.0	0.0	0.4	0.1	0.0	1.1	0.6	0.0	2.0	7.5	35%	110%	72	15	15	15																		
0.8	0.0	0.0	0.1	1.8	0.2	0.0	0.0	0.5	0.1	0.0	1.2	0.6	0.0	1.9	7.8	33%	110%	99	16	16	16																		
0.2	0.0	0.0	0.1	2.1	0.2	0.0	0.0	0.5	0.1	0.0	1.5	0.7	0.0	0.3	10.7	44%	131%	59	17	22	22																		
1.8	0.0	0.0	0.1	1.3	0.1	0.0	0.0	0.3	0.2	0.0	0.6	0.4	0.0	5.0	2.4	26%	82%	88	18	2	3																		
1.7	0.0	0.0	0.1	1.8	0.2	0.0	0.0	0.4	0.2	0.0	0.8	0.6	0.0	4.5	3.4	24%	84%	##	19	1	1																		
1.9	0.0	0.0	0.1	1.7	0.2	0.0	0.0	0.3	0.2	0.0	0.7	0.5	0.0	5.2	2.4	25%	79%	65	20	4	6																		
2.1	0.0	0.0	0.1	1.5	0.1	0.0	0.0	0.3	0.2	0.0	0.6	0.5	0.0	5.9	1.5	25%	75%	43	21	10	10																		
2.0	0.0	0.0	0.1	1.8	0.2	0.0	0.0	0.4	0.2	0.0	0.7	0.6	0.0	5.5	1.8	22%	76%	125	22	6	9																		
2.0	0.0	0.0	0.1	1.8	0.2	0.0	0.0	0.4	0.2	0.0	0.7	0.6	0.0	5.5	2.1	22%	76%	##	23	5	8																		
0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.5	0.1	0.0	1.2	0.1	0.0	0.3	15.3	47%	135%	42	24	29	28																		
1.9	0.0	0.0	0.1	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.5	0.0	0.0	5.3	5.6	28%	81%	33	25	13	13																		
0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.6	0.1	0.0	1.5	0.1	0.0	0.4	17.9	43%	119%	42	26	32	30																		
0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.6	0.1	0.0	1.5	0.1	0.0	0.4	17.9	43%	119%	42	27	33	31																		
1.5	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.5	0.1	0.0	1.3	0.1	0.0	4.1	12.5	29%	79%	36	28	23	23																		
1.3	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.6	0.1	0.0	1.5	0.1	0.0	3.3	17.7	29%	78%	38	29	28	29																		
1.1	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.7	0.1	0.0	1.7	0.1	0.0	2.9	20.2	29%	78%	38	30	30	32																		
1.1	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.7	0.1	0.0	1.7	0.1	0.0	2.8	20.5	29%	78%	38	31	31	33																		
0.5	0.0	0.0	0.3	16.0	1.2	0.0	0.1	0.8	0.6	0.1	4.4	5.6	0.0	0.6	5.2	15%	49%	21	32	24	26																		
0.5	0.0	0.0	0.3	16.0	1.2	0.0	0.1	0.8	0.6	0.1	4.4	5.6	0.0	0.6	5.2	15%	49%	21	33	25	27																		
0.4	0.0	0.0	0.1	0.5	0.2	0.0	0.0	1.1	0.1	0.0	2.8	0.1	0.0	0.7	32.4	30%	75%	38	34	34	34																		
0.4	0.0	0.0	0.1	0.5	0.2	0.0	0.0	1.1	0.1	0.0	2.8	0.1	0.0	0.6	32.8	30%	75%	37	35	35	35																		

A4 8 - C1 Germany - 2040-2065 - Batch process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

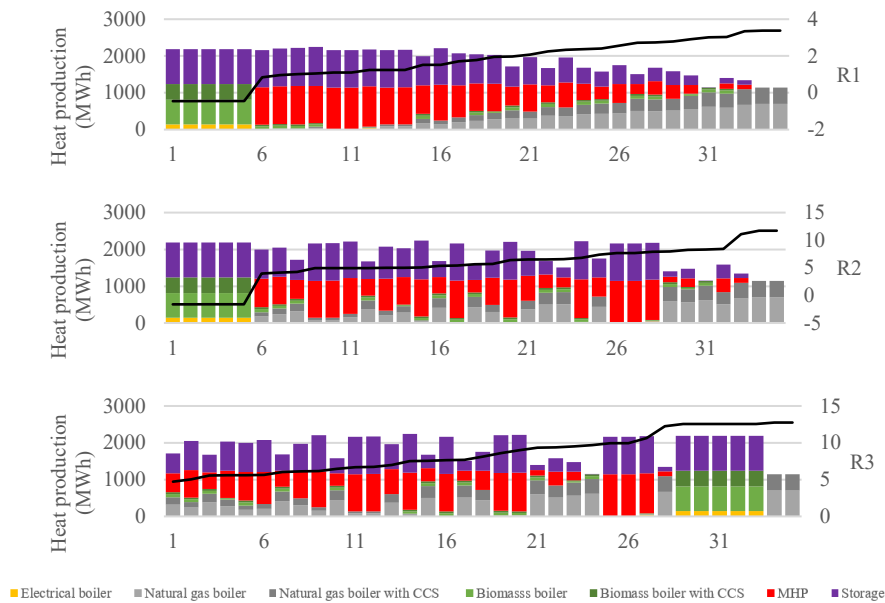
- Dammed hydro
- Onshore wind
- Biomass
- Gas
- Geothermal plants
- Photovoltaic
- Solid
- Nuclear
- Offshore wind
- River hydro
- Petroleum

Optimisation results

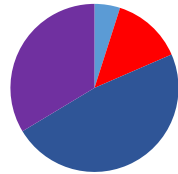
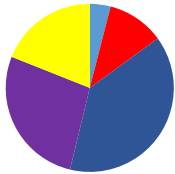
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
0.7	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.8	0.0	0.0	0.8	8.8	52%	92%	60	1	25	25
0.9	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.0	0.0	1.2	8.3	48%	91%	62	2	22	22
0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.4	0.0	0.0	1.0	0.0	0.0	0.3	11.2	51%	86%	57	3	26	26
0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.4	0.0	0.0	1.0	0.0	0.0	0.2	11.7	50%	86%	61	4	33	28
0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.4	0.0	0.0	1.0	0.0	0.0	0.2	11.7	50%	86%	61	5	32	27
0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.4	0.0	0.0	1.0	0.0	0.0	0.2	11.7	50%	86%	61	6	34	29
0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.4	0.1	0.0	1.0	0.0	0.0	0.3	11.8	50%	85%	63	7	35	30
1.3	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.0	0.0	1.8	7.6	43%	88%	66	8	20	19
0.4	0.0	0.0	0.1	2.0	0.2	0.0	0.0	0.5	0.1	0.0	1.3	0.7	0.0	0.4	9.1	43%	83%	69	9	24	24
1.4	0.0	0.0	0.0	1.0	0.1	0.0	0.0	0.3	0.1	0.0	0.8	0.3	0.0	1.9	6.7	39%	86%	67	10	10	16
0.6	0.0	0.0	0.1	2.1	0.2	0.0	0.0	0.5	0.1	0.0	1.3	0.7	0.0	0.7	9.0	41%	83%	75	11	23	23
1.8	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.0	0.0	2.5	7.0	37%	81%	72	12	14	15
2.4	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.5	0.0	0.0	3.4	4.9	36%	85%	60	13	2	3
1.8	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.0	0.0	2.5	7.6	37%	78%	72	14	18	18
1.0	0.0	0.0	0.1	2.3	0.2	0.0	0.0	0.5	0.1	0.0	1.3	0.8	0.0	1.3	7.9	37%	82%	75	15	19	20
2.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.5	0.0	0.0	3.9	4.5	32%	81%	79	16	4	2
1.0	0.0	0.0	0.1	2.7	0.3	0.0	0.0	0.5	0.2	0.0	1.4	0.9	0.0	1.2	8.3	35%	77%	76	17	21	21
1.3	0.0	0.0	0.1	2.7	0.2	0.0	0.0	0.5	0.2	0.0	1.3	0.9	0.0	1.7	7.4	33%	78%	81	18	12	17
3.2	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	4.6	3.2	30%	81%	82	19	7	4
4.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.8	0.7	29%	84%	56	20	16	13
4.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.8	0.7	29%	84%	56	21	17	14
3.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	5.3	2.7	28%	76%	69	22	11	8
4.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.8	1.3	27%	79%	77	23	15	12
3.0	0.0	0.0	0.1	1.3	0.1	0.0	0.0	0.3	0.2	0.0	0.7	0.4	0.0	4.2	3.9	28%	76%	78	24	1	1
3.6	0.0	0.0	0.1	0.8	0.1	0.0	0.0	0.3	0.1	0.0	0.5	0.2	0.0	5.2	2.3	26%	77%	107	25	9	7
2.1	0.0	0.0	0.1	2.7	0.2	0.0	0.0	0.5	0.2	0.0	1.2	0.9	0.0	2.9	6.0	28%	72%	90	26	3	9
3.4	0.0	0.0	0.1	1.3	0.1	0.0	0.0	0.3	0.2	0.0	0.6	0.4	0.0	4.9	2.9	27%	75%	77	27	5	5
2.1	0.0	0.0	0.1	2.7	0.2	0.0	0.0	0.5	0.2	0.0	1.2	0.9	0.0	2.9	6.3	28%	70%	82	28	6	10
4.0	0.0	0.0	0.1	1.2	0.1	0.0	0.0	0.3	0.2	0.0	0.5	0.4	0.0	5.8	1.1	26%	76%	68	29	13	11
3.8	0.0	0.0	0.1	2.7	0.2	0.0	0.0	0.4	0.2	0.0	0.9	0.9	0.0	5.4	2.1	23%	69%	82	30	8	6
0.7	0.0	0.0	0.3	15.8	1.2	0.0	0.1	0.8	0.6	0.1	4.3	5.5	0.0	0.6	5.1	15%	49%	32	31	30	34
0.7	0.0	0.0	0.3	15.8	1.2	0.0	0.1	0.8	0.6	0.1	4.3	5.5	0.0	0.6	5.1	15%	49%	32	32	31	35
0.7	0.0	0.0	0.3	15.8	1.2	0.0	0.1	0.8	0.6	0.1	4.3	5.5	0.0	0.6	5.1	15%	49%	32	33	29	33
0.7	0.0	0.0	0.3	15.8	1.2	0.0	0.1	0.8	0.6	0.1	4.3	5.5	0.0	0.6	5.1	15%	49%	32	34	27	31
0.7	0.0	0.0	0.3	15.8	1.2	0.0	0.1	0.8	0.6	0.1	4.3	5.5	0.0	0.6	5.1	15%	49%	32	35	28	32

A4 9 - C1 Germany - 2065-2090 - Batch process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

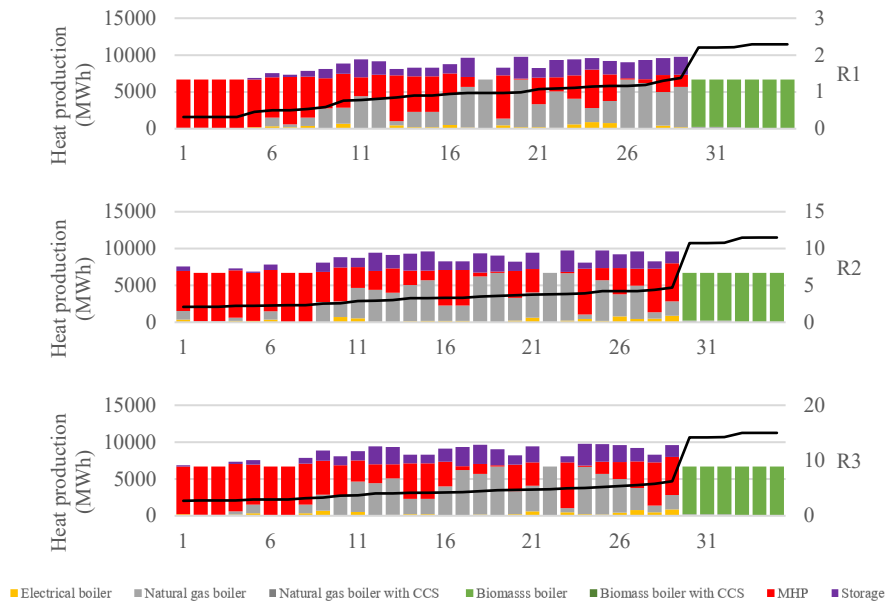
- Dammed hydro
- Onshore wind
- Biomass
- Gas
- Geothermal plants
- Photovoltaic
- Solid
- Nuclear
- Offshore wind
- River hydro
- Petroleum

Optimisation results

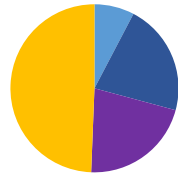
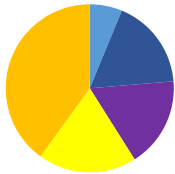
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
-13.5	0.0	0.0	0.3	15.3	1.2	0.1	0.1	1.1	0.7	0.1	4.3	5.2	0.0	0.7	4.8	14%	45%	39	1	1	32
-13.5	0.0	0.0	0.3	15.3	1.2	0.1	0.1	1.1	0.7	0.1	4.3	5.2	0.0	0.7	4.8	14%	45%	39	2	2	33
-13.5	0.0	0.0	0.3	15.3	1.2	0.1	0.1	1.1	0.7	0.1	4.3	5.2	0.0	0.7	4.8	14%	45%	39	3	3	31
-13.5	0.0	0.0	0.3	15.3	1.2	0.1	0.1	1.1	0.7	0.1	4.3	5.2	0.0	0.7	4.8	14%	45%	39	4	4	30
-13.5	0.0	0.0	0.3	15.3	1.2	0.1	0.1	1.1	0.7	0.1	4.3	5.2	0.0	0.7	4.8	14%	45%	39	5	5	29
-0.4	0.0	0.0	0.1	2.0	0.2	0.0	0.0	0.5	0.1	0.0	1.2	0.7	0.0	0.3	8.2	41%	133%	74	6	17	16
-0.2	0.0	0.0	0.1	2.0	0.2	0.0	0.0	0.5	0.1	0.0	1.3	0.7	0.0	0.4	9.1	39%	125%	71	7	20	19
0.2	0.0	0.0	0.0	1.6	0.2	0.0	0.0	0.5	0.1	0.0	1.2	0.5	0.0	0.4	9.4	40%	129%	76	8	24	20
0.9	0.0	0.0	0.0	1.4	0.2	0.0	0.0	0.4	0.1	0.0	1.1	0.5	0.0	0.6	8.0	42%	133%	67	9	15	14
1.2	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.4	0.0	0.0	0.9	0.0	0.0	0.2	10.3	48%	155%	73	10	27	26
1.2	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.4	0.0	0.0	0.9	0.0	0.0	0.2	10.3	48%	155%	73	11	26	25
1.3	0.0	0.0	0.0	0.5	0.1	0.0	0.0	0.4	0.1	0.0	1.0	0.2	0.0	0.4	11.0	46%	141%	71	12	28	27
2.6	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.0	0.0	0.7	0.0	0.0	0.8	7.7	51%	156%	59	13	9	11
2.6	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.0	0.0	0.7	0.0	0.0	0.8	7.7	51%	156%	59	14	10	12
2.6	0.0	0.0	0.1	2.2	0.2	0.0	0.0	0.5	0.2	0.0	1.2	0.7	0.0	1.6	7.1	32%	103%	86	15	6	5
3.8	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.0	0.0	1.3	7.5	44%	135%	64	16	11	9
4.8	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.0	0.0	1.7	6.8	40%	126%	75	17	13	6
4.1	0.0	0.0	0.1	1.8	0.2	0.0	0.0	0.5	0.1	0.0	1.1	0.6	0.0	2.1	6.4	31%	98%	86	18	7	2
5.6	0.0	0.0	0.0	0.8	0.1	0.0	0.0	0.4	0.1	0.0	0.8	0.2	0.0	2.3	6.2	34%	106%	72	19	14	4
5.2	0.0	0.0	0.1	2.0	0.2	0.0	0.0	0.5	0.2	0.0	1.0	0.7	0.0	2.7	5.0	30%	92%	77	20	8	1
6.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.6	0.0	0.0	2.5	5.8	35%	110%	80	21	19	8
6.4	0.0	0.0	0.1	2.0	0.2	0.0	0.0	0.5	0.2	0.0	1.0	0.7	0.0	3.1	4.9	27%	86%	76	22	12	3
7.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.5	0.0	0.0	3.0	5.4	33%	100%	94	23	21	13
7.0	0.0	0.0	0.1	2.0	0.2	0.0	0.0	0.5	0.2	0.0	1.0	0.7	0.0	3.4	4.4	26%	82%	87	24	16	7
7.4	0.0	0.0	0.1	1.9	0.2	0.0	0.0	0.5	0.2	0.0	0.9	0.6	0.0	3.5	3.7	26%	84%	95	25	18	10
9.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.5	0.0	0.0	3.5	4.3	31%	95%	72	26	25	18
8.7	0.0	0.0	0.1	2.1	0.2	0.0	0.0	0.5	0.2	0.0	0.9	0.7	0.0	4.1	3.2	24%	75%	##	27	23	17
8.6	0.0	0.0	0.1	2.0	0.2	0.0	0.0	0.5	0.2	0.0	1.0	0.7	0.0	4.1	3.9	24%	74%	86	28	22	15
10.2	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.0	0.0	4.0	3.4	29%	90%	75	29	32	22
10.4	0.0	0.0	0.1	1.1	0.1	0.0	0.0	0.4	0.2	0.0	0.6	0.3	0.0	4.4	2.6	26%	80%	83	30	30	23
10.5	0.0	0.0	0.1	2.0	0.2	0.0	0.0	0.4	0.2	0.0	0.7	0.6	0.0	4.9	1.4	24%	72%	69	31	31	24
10.3	0.0	0.0	0.1	2.1	0.2	0.0	0.0	0.5	0.2	0.0	0.8	0.7	0.0	4.8	2.4	23%	70%	93	32	29	21
13.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.3	0.0	0.0	5.2	1.6	26%	78%	74	33	33	28
13.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.2	0.0	0.0	5.4	0.7	27%	79%	62	34	34	34
13.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.2	0.0	0.0	5.4	0.7	27%	79%	62	35	35	35

A4 10 - C2 France - 2015-2040 - Continuous process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

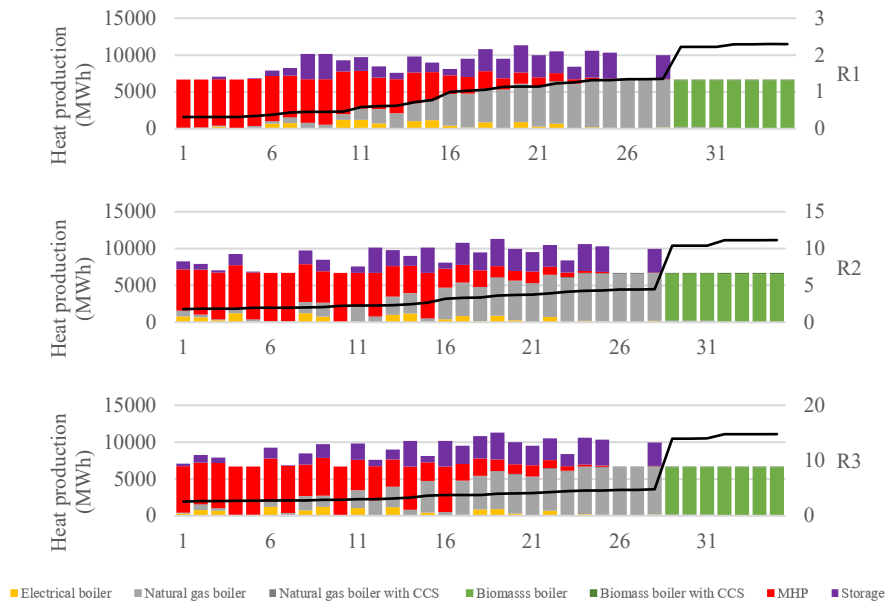
- Dammed hydro
- Geothermal plants
- Offshore wind
- Onshore wind
- Photovoltaic
- River hydro
- Biomass
- Solid
- Petroleum
- Gas
- Nuclear

Optimisation results

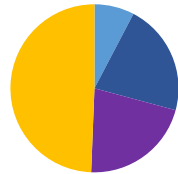
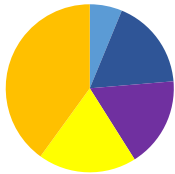
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	2.9	0.5	37%	73%	20	1	3	2
0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	2.9	0.5	37%	73%	20	2	2	3
0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	3.1	0.4	35%	71%	20	3	7	6
0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	3.1	0.4	35%	71%	20	4	8	7
0.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.3	0.0	0.0	3.1	2.1	34%	70%	41	5	5	1
0.4	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	3.3	1.3	33%	72%	34	6	1	5
0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.0	0.0	0.3	0.0	0.0	3.2	2.1	34%	70%	43	7	4	4
0.4	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	3.6	1.5	31%	69%	37	8	6	8
0.9	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.2	0.0	0.0	4.1	0.5	32%	76%	32	9	9	10
0.8	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.4	0.0	0.0	3.8	3.0	29%	69%	60	10	10	9
1.4	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	4.8	0.7	30%	77%	38	11	12	12
1.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.0	1.2	28%	71%	45	12	13	16
0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.5	0.1	0.0	0.6	0.0	0.0	3.3	5.7	31%	67%	97	13	24	23
0.8	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.5	0.0	0.0	4.0	4.7	31%	71%	82	14	16	14
0.8	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.5	0.0	0.0	4.0	4.7	31%	71%	82	15	17	15
1.4	0.0	0.0	0.1	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.3	0.0	0.0	4.7	2.9	28%	72%	63	16	11	11
1.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.5	1.3	28%	77%	49	17	15	18
2.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.1	29%	84%	28	18	22	22
0.5	0.0	0.0	0.0	0.4	0.1	0.0	0.0	0.6	0.1	0.0	0.7	0.0	0.0	3.6	6.6	30%	66%	123	19	28	28
2.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	6.0	0.3	27%	79%	36	20	23	24
1.1	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.5	0.1	0.0	0.5	0.0	0.0	4.4	5.4	30%	73%	103	21	20	20
1.6	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.4	0.0	0.0	5.1	3.5	28%	77%	90	22	14	13
1.2	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.5	0.1	0.0	0.5	0.0	0.0	4.5	5.5	28%	72%	96	23	21	21
0.8	0.0	0.0	0.0	0.4	0.1	0.0	0.0	0.7	0.1	0.0	0.7	0.1	0.0	4.2	7.3	26%	62%	134	24	29	29
1.1	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.6	0.1	0.0	0.6	0.0	0.0	4.3	6.6	28%	70%	122	25	26	27
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.3	0.0	0.0	5.9	2.3	28%	81%	68	26	19	19
2.0	0.0	0.0	0.1	0.2	0.1	0.0	0.0	0.4	0.1	0.0	0.4	0.0	0.0	5.5	3.3	28%	83%	90	27	18	17
1.6	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.6	0.1	0.0	0.6	0.0	0.0	4.9	6.4	27%	73%	123	28	27	26
1.9	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.6	0.1	0.0	0.6	0.0	0.0	5.5	6.0	27%	74%	130	29	25	25
0.5	0.0	0.0	0.3	15.7	1.2	0.0	0.1	0.6	0.6	0.1	4.0	5.5	0.0	0.7	0.6	16%	53%	15	30	30	30
0.5	0.0	0.0	0.3	15.7	1.2	0.0	0.1	0.6	0.6	0.1	4.0	5.5	0.0	0.7	0.6	16%	53%	15	31	31	31
0.5	0.0	0.0	0.3	15.7	1.2	0.0	0.1	0.6	0.6	0.1	4.0	5.5	0.0	0.7	0.6	16%	53%	15	32	32	32
0.4	0.0	0.0	0.3	16.6	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	15	33	33	33
0.4	0.0	0.0	0.3	16.6	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	15	34	34	34
0.4	0.0	0.0	0.3	16.6	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	15	35	35	35

A4 11 - C2 France - 2040-2065 - Continuous process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

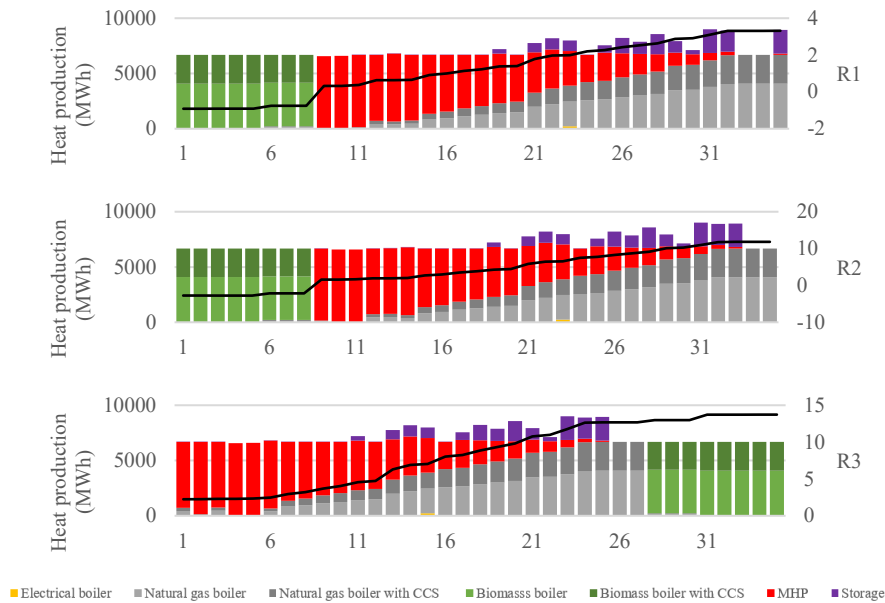
- Dammed hydro
- Geothermal plants
- Offshore wind
- Onshore wind
- Photovoltaic
- River hydro
- Biomass
- Solid
- Petroleum
- Gas
- Nuclear

Optimisation results

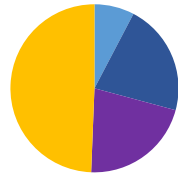
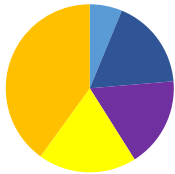
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	2.8	0.4	38%	73%	24	1	7	4
0.2	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	2.8	0.4	38%	73%	24	2	6	5
0.2	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	2.7	0.5	37%	74%	26	3	3	1
0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	3.0	0.4	36%	71%	25	4	10	10
0.2	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	2.9	0.4	37%	73%	26	5	5	7
0.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.2	0.0	0.0	2.9	0.6	33%	70%	32	6	2	3
0.6	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.2	0.0	0.0	3.0	0.6	33%	70%	34	7	1	2
0.5	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	3.5	0.3	34%	71%	28	8	12	14
0.4	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	3.9	0.4	31%	66%	29	9	15	16
0.6	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.2	0.0	0.0	3.1	0.8	30%	65%	40	10	4	6
1.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	3.5	0.7	28%	65%	43	11	8	9
1.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	3.5	0.5	32%	74%	38	12	9	8
1.3	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	3.7	0.3	34%	76%	32	13	11	12
1.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	3.8	0.6	29%	69%	45	14	13	11
1.7	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	4.0	0.6	28%	69%	47	15	14	13
2.6	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	4.7	0.4	29%	74%	46	16	16	15
2.8	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	4.8	0.3	30%	77%	45	17	18	17
2.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	4.9	0.4	27%	70%	52	18	17	18
3.2	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.2	0.1	30%	79%	45	19	21	21
3.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.1	0.4	26%	72%	54	20	19	19
3.2	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.1	0.2	29%	79%	48	21	20	20
3.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.3	26%	74%	55	22	22	22
3.6	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.5	0.1	29%	82%	48	23	23	23
3.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.6	0.1	28%	81%	52	24	24	24
3.9	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.6	0.1	29%	83%	51	25	25	25
3.9	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.0	29%	84%	50	26	26	26
3.9	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.0	29%	84%	50	27	27	27
3.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	6.0	0.1	27%	80%	52	28	28	28
0.7	0.0	0.0	0.3	15.5	1.2	0.0	0.1	0.6	0.6	0.1	4.0	5.4	0.0	0.7	0.5	16%	53%	20	29	29	29
0.7	0.0	0.0	0.3	15.5	1.2	0.0	0.1	0.6	0.6	0.1	4.0	5.4	0.0	0.7	0.5	16%	53%	20	30	30	30
0.7	0.0	0.0	0.3	15.5	1.2	0.0	0.1	0.6	0.6	0.1	4.0	5.4	0.0	0.7	0.5	16%	53%	20	31	31	31
0.6	0.0	0.0	0.3	16.3	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.5	16%	51%	20	32	32	32
0.6	0.0	0.0	0.3	16.3	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.5	16%	51%	20	33	33	33
0.6	0.0	0.0	0.3	16.4	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.5	16%	51%	20	34	34	34
0.6	0.0	0.0	0.3	16.4	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.5	16%	51%	20	35	35	35

A4 12 - C2 France - 2065-2090 - Continuous process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

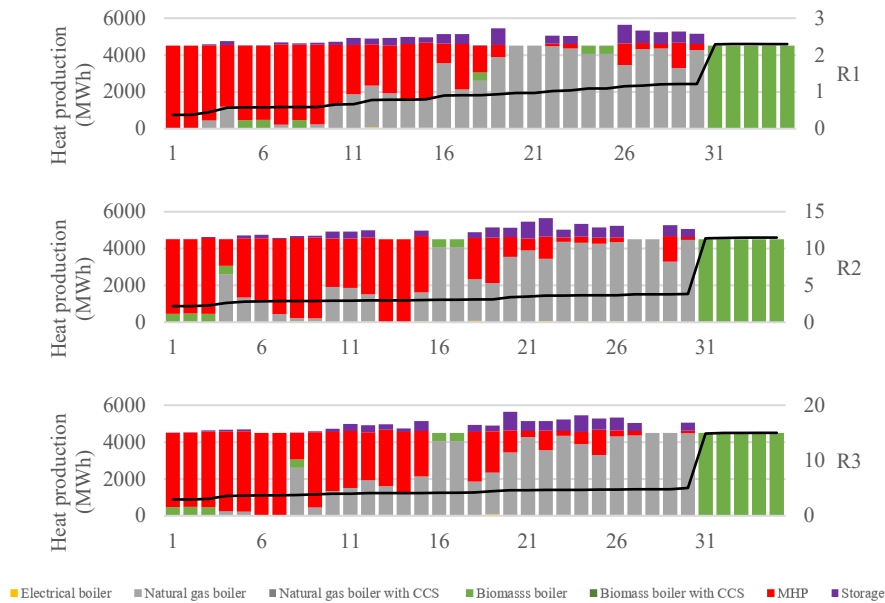
- Dammed hydro
- Geothermal plants
- Offshore wind
- Onshore wind
- Photovoltaic
- River hydro
- Biomass
- Solid
- Petroleum
- Gas
- Nuclear

Optimisation results

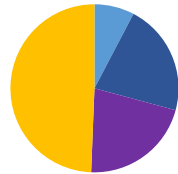
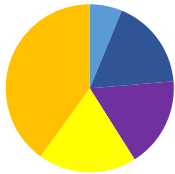
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3	
Sustainable ratio																						
-14.5	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.5	0.0	0.6	0.8	14%	46%	24	1	1	34	
-14.5	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.5	0.0	0.6	0.8	14%	46%	24	2	2	35	
-14.5	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.5	0.0	0.6	0.8	14%	46%	24	3	3	33	
-14.5	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	0.8	14%	46%	24	4	4	31	
-14.5	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	0.8	14%	46%	24	5	5	32	
-13.3	0.0	0.0	0.3	15.1	1.1	0.0	0.1	1.0	0.6	0.1	4.0	5.2	0.0	0.8	0.7	15%	48%	23	6	6	30	
-13.3	0.0	0.0	0.3	15.1	1.1	0.0	0.1	1.0	0.6	0.1	4.0	5.2	0.0	0.8	0.7	15%	48%	23	7	7	28	
-13.3	0.0	0.0	0.3	15.1	1.1	0.0	0.1	1.0	0.6	0.1	4.0	5.2	0.0	0.8	0.7	15%	48%	23	8	8	29	
0.3	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	2.4	0.4	38%	74%	37	9	10	4	
0.3	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	2.5	0.4	38%	73%	38	10	11	5	
0.6	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	2.5	0.4	38%	73%	38	11	9	2	
1.7	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	2.7	0.3	37%	75%	39	12	12	1	
1.6	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	3.0	0.4	34%	70%	42	13	14	6	
1.8	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	2.7	0.3	37%	74%	39	14	13	3	
3.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	2.9	0.3	36%	76%	41	15	15	7	
3.4	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	3.0	0.3	36%	76%	41	16	16	8	
3.9	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	3.1	0.3	35%	77%	42	17	17	9	
4.3	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	3.1	0.3	35%	77%	42	18	18	10	
4.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	3.8	0.3	31%	71%	47	19	19	11	
5.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	3.4	0.3	34%	77%	44	20	20	12	
6.7	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	3.8	0.3	32%	75%	48	21	21	13	
7.4	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	4.3	0.3	29%	70%	51	22	22	14	
7.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	4.1	0.3	30%	73%	53	23	23	15	
8.6	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	4.1	0.2	31%	78%	49	24	24	16	
8.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	4.4	0.2	29%	75%	51	25	25	17	
9.4	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	4.6	0.2	29%	75%	52	26	26	18	
9.9	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	4.7	0.2	29%	76%	52	27	27	19	
10.4	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	4.8	0.2	29%	77%	53	28	28	20	
11.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.1	0.2	27%	75%	55	29	29	21	
11.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.1	0.2	28%	77%	54	30	30	22	
12.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.3	0.2	27%	76%	56	31	31	23	
13.3	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.5	0.1	26%	75%	58	32	32	24	
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.1	27%	79%	56	33	34	26	
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.1	27%	79%	56	34	35	27	
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.5	0.1	27%	77%	58	35	33	25	

A4 13 - C2 France - 2015-2040 - Weekly process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

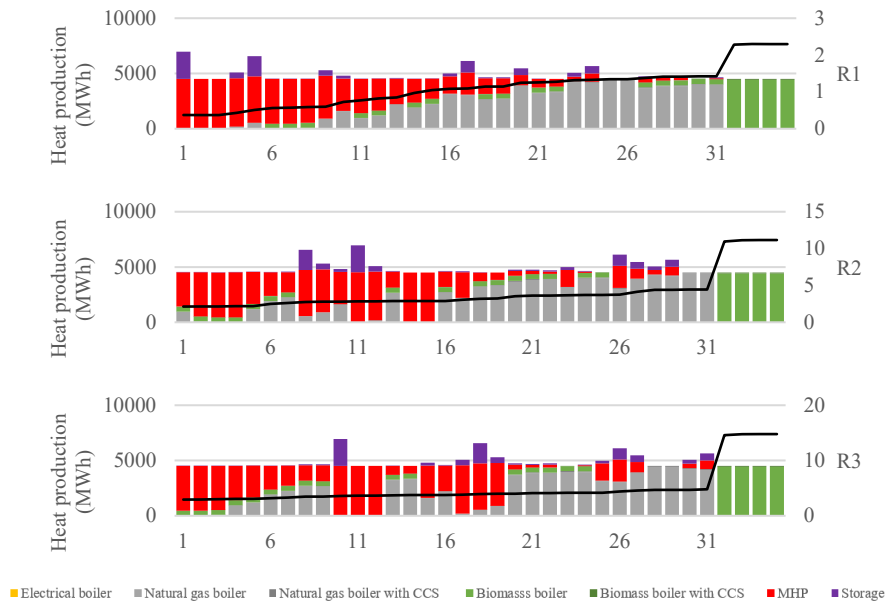
- Dammed hydro
- Geothermal plants
- Offshore wind
- Onshore wind
- Photovoltaic
- River hydro
- Biomass
- Solid
- Petroleum
- Gas
- Nuclear

Optimisation results

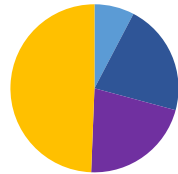
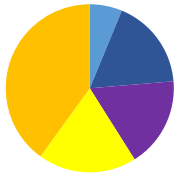
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																32%	67%	24	1	13	6
0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	3.8	0.4	32%	67%	24	1	13	6
0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	3.8	0.4	32%	67%	24	2	14	7
0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	4.0	0.5	31%	68%	28	3	7	9
0.6	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	4.4	0.7	31%	70%	31	4	6	14
0.1	0.0	0.0	0.0	1.8	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.6	0.0	3.5	0.5	29%	65%	25	5	1	1
0.1	0.0	0.0	0.0	1.8	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.6	0.0	3.5	0.5	29%	65%	25	6	2	2
0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.0	0.0	4.1	2.3	31%	65%	50	7	9	5
0.1	0.0	0.0	0.0	1.8	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.6	0.0	3.6	0.5	28%	64%	30	8	3	3
0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.0	0.0	4.1	2.3	31%	65%	50	9	8	4
0.7	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	4.5	1.4	30%	70%	43	10	5	10
0.9	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	4.7	0.8	30%	72%	32	11	11	18
1.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	5.1	1.2	29%	72%	39	12	18	19
0.9	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	4.8	2.0	30%	72%	50	13	10	12
0.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.0	0.0	4.7	2.6	29%	69%	55	14	12	11
0.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.0	0.0	4.8	2.4	29%	68%	54	15	15	13
1.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.5	0.7	28%	77%	35	16	20	22
1.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.0	0.0	4.9	2.9	29%	71%	70	17	19	15
1.3	0.0	0.0	0.1	1.7	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.6	0.0	4.7	0.4	27%	74%	28	18	4	8
1.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.7	0.7	28%	80%	36	19	21	24
2.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.2	29%	84%	21	20	27	28
2.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.2	29%	84%	21	21	28	29
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	6.1	0.5	25%	79%	69	22	30	30
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.9	1.0	28%	81%	39	23	23	27
1.9	0.0	0.0	0.1	1.7	0.1	0.0	0.0	0.2	0.2	0.0	0.5	0.6	0.0	5.3	0.3	27%	80%	22	24	16	16
1.9	0.0	0.0	0.1	1.7	0.1	0.0	0.0	0.2	0.2	0.0	0.5	0.6	0.0	5.3	0.3	27%	80%	22	25	17	17
1.7	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.4	0.0	0.0	5.7	3.6	27%	74%	77	26	22	20
2.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.3	0.0	0.0	6.0	2.5	27%	78%	65	27	24	26
2.1	0.0	0.0	0.1	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.3	0.0	0.0	6.0	2.9	27%	79%	62	28	26	23
1.6	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.5	0.0	0.0	5.6	4.6	27%	73%	84	29	29	25
2.0	0.0	0.0	0.1	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.3	0.0	0.0	5.9	3.2	27%	79%	68	30	25	21
0.5	0.0	0.0	0.3	16.5	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.6	16%	51%	15	31	31	31
0.4	0.0	0.0	0.3	16.6	1.2	0.0	0.1	0.7	0.7	0.1	4.2	5.8	0.0	0.5	0.7	16%	51%	15	32	32	32
0.4	0.0	0.0	0.3	16.6	1.2	0.0	0.1	0.7	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	15	33	33	33
0.4	0.0	0.0	0.3	16.6	1.2	0.0	0.1	0.7	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	15	34	34	34
0.4	0.0	0.0	0.3	16.6	1.2	0.0	0.1	0.7	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	15	35	35	35

A4 14 - C2 France - 2040-2065 - Weekly process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

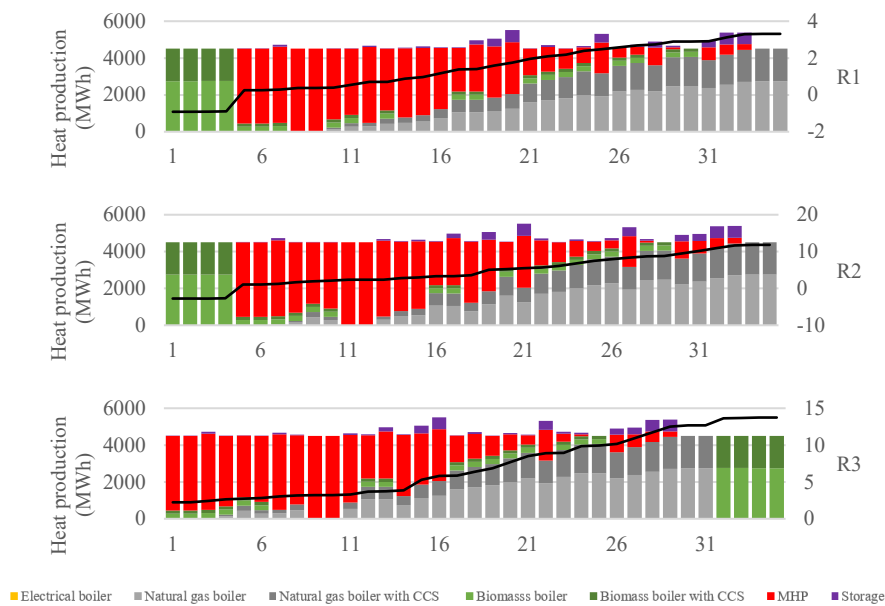
- Dammed hydro
- Geothermal plants
- Offshore wind
- Onshore wind
- Photovoltaic
- River hydro
- Biomass
- Solid
- Petroleum
- Gas
- Nuclear

Optimisation results

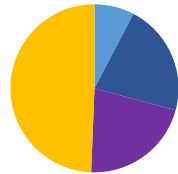
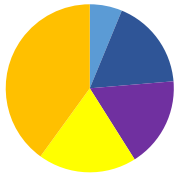
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	3.7	0.4	33%	67%	28	1	11	10
0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	3.7	0.4	33%	67%	28	2	14	11
0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	3.7	0.4	33%	67%	28	3	15	12
0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	4.0	0.4	32%	66%	30	4	12	17
0.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	4.2	0.3	31%	65%	33	5	8	18
0.1	0.0	0.0	0.0	1.8	0.1	0.0	0.0	0.1	0.1	0.0	0.6	0.6	0.0	3.4	0.4	30%	65%	27	6	3	1
0.1	0.0	0.0	0.0	1.8	0.1	0.0	0.0	0.1	0.1	0.0	0.6	0.6	0.0	3.4	0.4	29%	65%	27	7	4	2
0.2	0.0	0.0	0.0	1.8	0.1	0.0	0.0	0.1	0.1	0.0	0.6	0.6	0.0	3.5	0.4	29%	65%	27	8	2	3
0.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	4.4	0.3	30%	65%	35	9	9	19
1.5	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	4.5	0.2	31%	71%	37	10	10	15
1.0	0.0	0.0	0.0	1.7	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.6	0.0	3.8	0.3	29%	68%	32	11	1	4
1.2	0.0	0.0	0.0	1.7	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.6	0.0	4.0	0.3	28%	68%	33	12	5	5
2.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	4.8	0.2	30%	74%	39	13	17	16
1.8	0.0	0.0	0.1	1.7	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.6	0.0	4.3	0.2	28%	71%	36	14	6	6
2.1	0.0	0.0	0.1	1.7	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.6	0.0	4.4	0.2	28%	72%	38	15	7	7
2.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.4	0.1	28%	73%	46	16	23	25
2.7	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.6	0.2	27%	67%	49	17	26	26
2.4	0.0	0.0	0.1	1.7	0.1	0.0	0.0	0.2	0.1	0.0	0.5	0.6	0.0	4.7	0.2	27%	72%	41	18	13	9
2.5	0.0	0.0	0.1	1.7	0.1	0.0	0.0	0.2	0.1	0.0	0.5	0.6	0.0	4.7	0.2	27%	73%	41	19	16	8
3.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.1	27%	74%	50	20	27	27
2.9	0.0	0.0	0.1	1.7	0.1	0.0	0.0	0.2	0.2	0.0	0.5	0.6	0.0	4.9	0.1	27%	76%	43	21	18	13
3.0	0.0	0.0	0.1	1.7	0.1	0.0	0.0	0.2	0.2	0.0	0.5	0.5	0.0	4.9	0.1	27%	77%	43	22	19	14
3.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.9	0.1	28%	78%	51	23	28	30
3.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	6.1	0.1	26%	73%	53	24	29	31
3.9	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.0	29%	84%	50	25	30	28
3.9	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.0	29%	84%	50	26	31	29
3.3	0.0	0.0	0.1	1.8	0.1	0.0	0.0	0.2	0.2	0.0	0.5	0.6	0.0	5.2	0.1	26%	75%	46	27	20	20
3.5	0.0	0.0	0.1	1.7	0.1	0.0	0.0	0.2	0.2	0.0	0.5	0.6	0.0	5.3	0.1	26%	76%	47	28	21	22
3.5	0.0	0.0	0.1	1.7	0.1	0.0	0.0	0.2	0.2	0.0	0.5	0.6	0.0	5.2	0.1	26%	77%	47	29	22	21
3.6	0.0	0.0	0.1	1.7	0.1	0.0	0.0	0.2	0.2	0.0	0.5	0.5	0.0	5.2	0.1	27%	80%	47	30	25	23
3.6	0.0	0.0	0.1	1.7	0.1	0.0	0.0	0.2	0.2	0.0	0.5	0.6	0.0	5.3	0.1	26%	78%	47	31	24	24
0.7	0.0	0.0	0.3	16.2	1.2	0.0	0.1	0.6	0.6	0.1	4.1	5.6	0.0	0.6	0.5	16%	51%	20	32	32	32
0.6	0.0	0.0	0.3	16.3	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.5	16%	51%	20	33	33	33
0.6	0.0	0.0	0.3	16.4	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.5	16%	51%	20	34	34	34
0.6	0.0	0.0	0.3	16.4	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.5	16%	51%	20	35	35	35

A4 15 - C2 France - 2065-2090 - Weekly process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

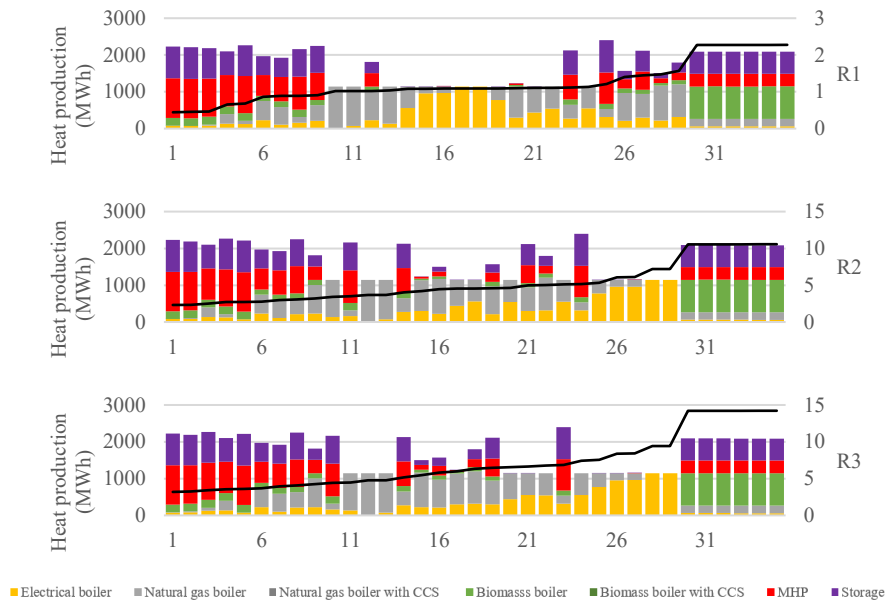
- Dammed hydro
- Geothermal plants
- Offshore wind
- Onshore wind
- Photovoltaic
- River hydro
- Biomass
- Solid
- Petroleum
- Gas
- Nuclear

Optimisation results

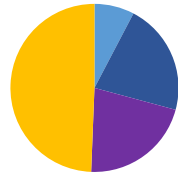
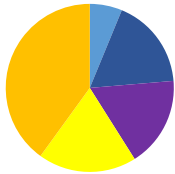
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
-14.5	0.0	0.0	0.3	15.9	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.5	0.0	0.6	0.8	14%	46%	24	1	1	34
-14.5	0.0	0.0	0.3	15.9	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.5	0.0	0.6	0.8	14%	46%	24	2	2	35
-14.5	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.7	0.8	14%	46%	24	3	3	33
-14.3	0.0	0.0	0.3	15.7	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	0.8	14%	46%	24	4	4	32
-1.2	0.0	0.0	0.0	1.7	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.6	0.0	3.0	0.4	29%	64%	42	5	5	1
-1.2	0.0	0.0	0.0	1.7	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.6	0.0	3.0	0.4	29%	64%	42	6	6	2
-1.1	0.0	0.0	0.0	1.7	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.6	0.0	3.2	0.4	28%	62%	44	7	7	3
0.3	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	3.3	0.3	33%	67%	45	8	11	9
0.3	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	3.3	0.3	33%	67%	45	9	12	10
-0.5	0.0	0.0	0.0	1.7	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.6	0.0	3.1	0.4	29%	64%	41	10	8	4
0.1	0.0	0.0	0.0	1.7	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.6	0.0	3.3	0.3	28%	65%	41	11	10	6
1.7	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	3.6	0.3	31%	66%	47	12	13	7
0.9	0.0	0.0	0.0	1.7	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.5	0.0	3.4	0.3	28%	66%	42	13	9	5
2.5	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	3.7	0.3	31%	68%	47	14	14	8
2.9	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	3.8	0.3	31%	68%	48	15	15	11
3.8	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	3.9	0.3	31%	69%	48	16	18	14
3.9	0.0	0.0	0.1	1.7	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.5	0.0	3.9	0.3	27%	67%	45	17	16	12
3.8	0.0	0.0	0.1	1.7	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.5	0.0	4.1	0.3	26%	64%	47	18	17	13
5.7	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	4.3	0.3	29%	69%	52	19	19	15
6.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	4.5	0.3	28%	66%	55	20	21	16
6.5	0.0	0.0	0.1	1.7	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.5	0.0	4.3	0.2	26%	70%	47	21	20	17
7.0	0.0	0.0	0.1	1.7	0.1	0.0	0.0	0.3	0.2	0.0	0.6	0.5	0.0	4.4	0.3	26%	69%	48	22	22	18
7.5	0.0	0.0	0.1	1.7	0.1	0.0	0.0	0.3	0.2	0.0	0.6	0.5	0.0	4.4	0.2	26%	72%	47	23	23	19
8.4	0.0	0.0	0.1	1.7	0.1	0.0	0.0	0.3	0.2	0.0	0.6	0.5	0.0	4.6	0.2	25%	71%	49	24	24	20
9.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.0	0.2	27%	69%	57	25	27	22
9.2	0.0	0.0	0.1	1.7	0.1	0.0	0.0	0.3	0.2	0.0	0.6	0.5	0.0	4.7	0.2	25%	72%	49	26	25	21
9.7	0.0	0.0	0.1	1.7	0.1	0.0	0.0	0.3	0.2	0.0	0.6	0.5	0.0	4.9	0.2	25%	71%	51	27	26	23
10.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.0	0.2	28%	75%	55	28	30	26
10.6	0.0	0.0	0.1	1.7	0.1	0.0	0.0	0.3	0.2	0.0	0.6	0.5	0.0	5.0	0.2	25%	73%	51	29	28	24
10.7	0.0	0.0	0.1	1.6	0.1	0.0	0.0	0.3	0.2	0.0	0.6	0.5	0.0	4.9	0.2	25%	74%	50	30	29	25
11.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.2	0.2	27%	76%	56	31	31	27
12.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.2	26%	73%	59	32	32	28
13.2	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.6	0.1	26%	74%	59	33	33	29
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.1	27%	79%	56	34	34	30
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.1	27%	79%	56	35	35	31

A4 16 - C2 France - 2015-2040 - Batch process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

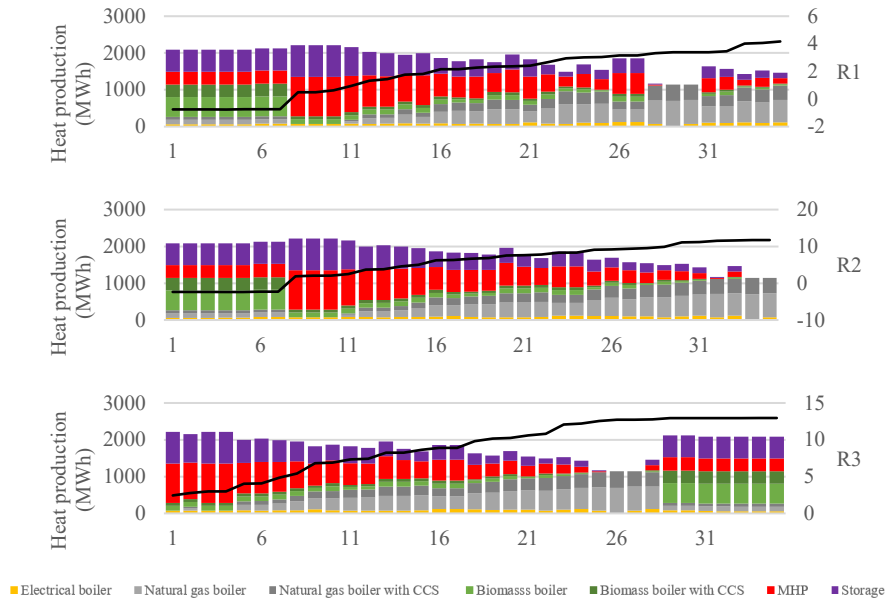
- Dammed hydro
- Onshore wind
- Biomass
- Gas
- Geothermal plants
- Photovoltaic
- Solid
- Nuclear
- Offshore wind
- River hydro
- Petroleum

Optimisation results

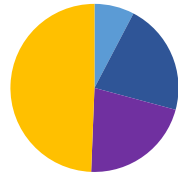
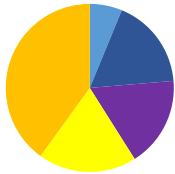
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.3	0.0	0.0	3.5	1.1	32%	70%	59	1	1	1
0.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.3	0.0	0.0	3.9	1.1	29%	66%	59	2	5	5
0.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.3	0.0	0.0	3.5	1.1	31%	71%	60	3	2	2
0.7	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	4.1	1.7	28%	68%	69	4	3	4
0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.4	0.1	0.0	0.4	0.0	0.0	3.8	3.1	29%	67%	87	5	4	3
1.2	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.3	0.0	0.0	4.6	2.4	26%	68%	83	6	6	6
1.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.0	0.0	4.8	2.8	27%	69%	81	7	7	7
0.6	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.5	0.1	0.0	0.6	0.0	0.0	3.9	5.0	27%	68%	127	8	11	10
1.0	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.4	0.0	0.0	4.9	3.0	24%	62%	91	9	8	8
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.9	0.7	29%	84%	33	10	12	12
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.9	0.7	29%	84%	33	11	13	13
1.7	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.3	0.0	0.0	5.4	2.3	24%	67%	86	12	9	9
2.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.6	1.5	29%	84%	39	13	10	11
1.2	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.5	0.0	0.0	7.4	2.1	19%	58%	48	14	18	21
0.5	0.0	0.0	0.0	0.4	0.1	0.0	0.0	0.4	0.1	0.0	0.6	0.0	0.0	8.9	2.2	15%	46%	51	15	26	26
0.5	0.0	0.0	0.0	0.4	0.1	0.0	0.0	0.4	0.1	0.0	0.6	0.0	0.0	9.0	2.2	15%	46%	51	16	27	27
0.1	0.0	0.0	0.0	0.5	0.1	0.0	0.0	0.4	0.1	0.0	0.7	0.0	0.0	9.9	2.1	13%	42%	52	17	28	28
0.1	0.0	0.0	0.0	0.5	0.1	0.0	0.0	0.4	0.1	0.0	0.7	0.0	0.0	9.9	2.1	13%	42%	52	18	29	29
0.8	0.0	0.0	0.0	0.4	0.1	0.0	0.0	0.4	0.1	0.0	0.6	0.0	0.0	8.2	2.3	16%	51%	51	19	25	25
1.6	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.0	0.0	7.0	1.7	21%	64%	52	20	15	17
1.4	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.0	0.0	7.4	1.9	20%	60%	45	21	17	20
1.3	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.0	0.0	7.6	1.9	19%	59%	46	22	20	22
1.0	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.6	0.1	0.0	0.6	0.0	0.0	4.4	6.1	25%	65%	125	23	14	14
1.2	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.5	0.0	0.0	8.2	2.0	18%	55%	48	24	23	24
0.8	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.8	0.1	0.0	0.8	0.1	0.0	4.3	8.0	24%	60%	154	25	24	23
1.7	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.7	0.1	0.0	0.7	0.1	0.0	5.3	7.0	25%	73%	131	26	19	16
1.5	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.8	0.2	0.0	0.8	0.1	0.0	5.3	7.8	21%	61%	175	27	21	19
2.0	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.6	0.2	0.0	0.6	0.1	0.0	5.8	6.3	23%	71%	140	28	16	15
2.0	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.8	0.2	0.0	0.7	0.1	0.0	5.7	7.8	22%	65%	161	29	22	18
0.4	0.0	0.0	0.3	15.8	1.2	0.0	0.1	0.7	0.6	0.1	4.1	5.5	0.0	1.1	1.0	15%	45%	20	30	33	33
0.4	0.0	0.0	0.3	15.8	1.2	0.0	0.1	0.7	0.6	0.1	4.1	5.5	0.0	1.1	1.0	15%	45%	20	31	30	30
0.4	0.0	0.0	0.3	15.8	1.2	0.0	0.1	0.7	0.6	0.1	4.1	5.5	0.0	1.1	1.0	15%	45%	20	32	34	34
0.4	0.0	0.0	0.3	15.8	1.2	0.0	0.1	0.7	0.6	0.1	4.1	5.5	0.0	1.1	1.0	15%	45%	20	33	35	35
0.4	0.0	0.0	0.3	15.8	1.2	0.0	0.1	0.7	0.6	0.1	4.1	5.5	0.0	1.1	1.0	15%	45%	20	34	31	31
0.4	0.0	0.0	0.3	15.8	1.2	0.0	0.1	0.7	0.6	0.1	4.1	5.5	0.0	1.1	1.0	15%	45%	20	35	32	32

A4 18 - C2 France - 2065-2090 - Batch process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

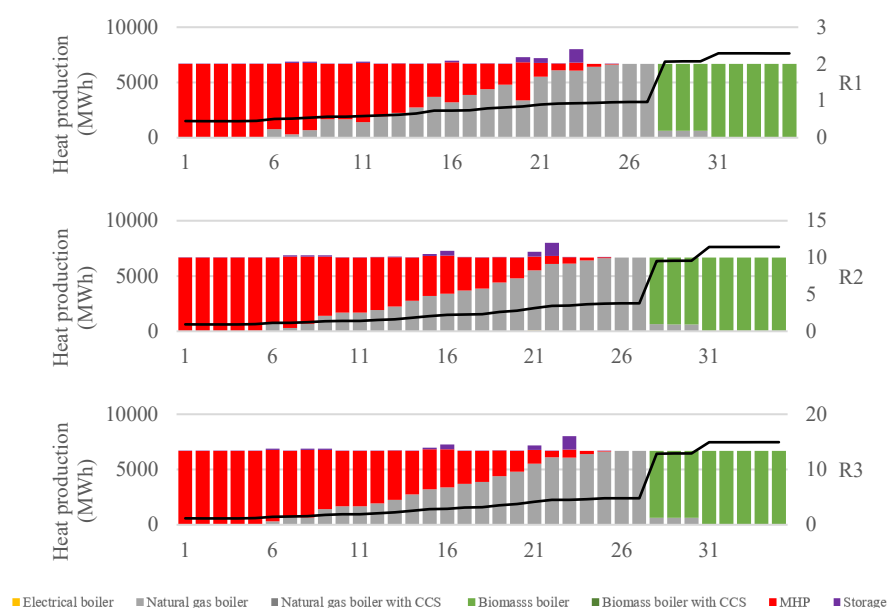
- Dammed hydro
- Onshore wind
- Biomass
- Gas
- Geothermal plants
- Photovoltaic
- Solid
- Nuclear
- Offshore wind
- River hydro
- Petroleum

Optimisation results

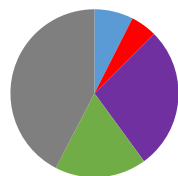
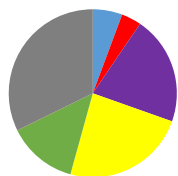
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
-13.7	0.0	0.0	0.3	15.1	1.1	0.0	0.1	1.0	0.6	0.1	4.1	5.2	0.0	1.1	1.2	14%	45%	34	1	1	34
-13.7	0.0	0.0	0.3	15.1	1.1	0.0	0.1	1.0	0.6	0.1	4.1	5.2	0.0	1.1	1.2	14%	45%	34	2	2	35
-13.7	0.0	0.0	0.3	15.1	1.1	0.0	0.1	1.0	0.6	0.1	4.1	5.2	0.0	1.1	1.2	14%	45%	34	3	3	33
-13.7	0.0	0.0	0.3	15.1	1.1	0.0	0.1	1.0	0.6	0.1	4.1	5.2	0.0	1.1	1.2	14%	45%	34	4	4	32
-13.6	0.0	0.0	0.3	15.1	1.1	0.0	0.1	1.0	0.6	0.1	4.1	5.2	0.0	1.2	1.2	14%	45%	34	5	5	31
-13.6	0.0	0.0	0.3	15.1	1.1	0.0	0.1	1.0	0.6	0.1	4.1	5.2	0.0	1.3	1.2	14%	44%	37	6	6	29
-13.6	0.0	0.0	0.3	15.1	1.1	0.0	0.1	1.0	0.6	0.1	4.1	5.2	0.0	1.3	1.2	14%	44%	37	7	7	30
0.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.3	0.0	0.0	3.3	1.0	29%	97%	84	8	9	3
0.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.3	0.0	0.0	3.3	1.0	29%	97%	84	9	10	4
1.4	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.2	0.0	0.0	3.0	0.9	32%	107%	80	10	8	1
2.6	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	3.3	1.4	31%	102%	86	11	11	2
4.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	3.6	0.9	29%	96%	85	12	13	6
4.4	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.3	0.0	0.0	3.6	2.1	29%	97%	100	13	12	5
6.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.3	0.0	0.0	3.9	1.9	28%	92%	100	14	15	8
5.4	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.5	0.0	0.0	3.9	4.1	28%	92%	131	15	14	7
7.6	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.3	0.0	0.0	4.2	2.1	27%	87%	106	16	16	10
8.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	4.6	0.8	26%	85%	90	17	19	12
8.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.3	0.0	0.0	4.6	2.2	26%	84%	106	18	18	11
8.9	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	4.6	0.8	26%	83%	91	19	21	14
8.9	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.3	0.0	0.0	4.8	0.9	25%	79%	95	20	20	13
7.7	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.5	0.1	0.0	0.5	0.0	0.0	4.3	4.9	27%	85%	142	21	17	9
9.5	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.4	0.0	0.0	4.6	3.1	26%	83%	121	22	22	15
11.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.2	0.0	0.0	5.1	0.8	25%	79%	93	23	29	22
11.1	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.4	0.0	0.0	5.2	2.6	24%	75%	117	24	26	20
11.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.4	0.1	0.0	0.3	0.0	0.0	5.2	2.0	25%	77%	103	25	28	21
9.5	0.0	0.0	0.1	0.5	0.1	0.0	0.0	0.9	0.1	0.0	0.8	0.1	0.0	4.6	9.0	25%	80%	214	26	23	16
9.5	0.0	0.0	0.1	0.5	0.1	0.0	0.0	0.9	0.1	0.0	0.8	0.1	0.0	4.6	9.0	25%	80%	214	27	24	17
13.2	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.2	0.0	0.0	5.3	0.7	26%	80%	85	28	32	25
13.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.2	0.0	0.0	5.4	0.7	27%	79%	62	29	34	26
13.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.2	0.0	0.0	5.4	0.7	27%	79%	62	30	35	27
11.0	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.8	0.2	0.0	0.8	0.1	0.0	4.9	7.8	25%	79%	197	31	25	18
11.4	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.8	0.2	0.0	0.7	0.0	0.0	5.0	7.3	25%	78%	182	32	27	19
13.6	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.8	0.2	0.0	0.8	0.1	0.0	5.5	8.0	24%	73%	197	33	31	24
13.5	0.0	0.0	0.1	0.5	0.1	0.0	0.0	0.9	0.2	0.0	0.8	0.1	0.0	5.4	8.9	24%	73%	215	34	30	23
14.2	0.0	0.0	0.1	0.5	0.1	0.0	0.0	0.8	0.2	0.0	0.8	0.1	0.0	5.7	8.0	23%	71%	196	35	33	28

A4 19 - C3 Italy- 2015-2040 - Continuous process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

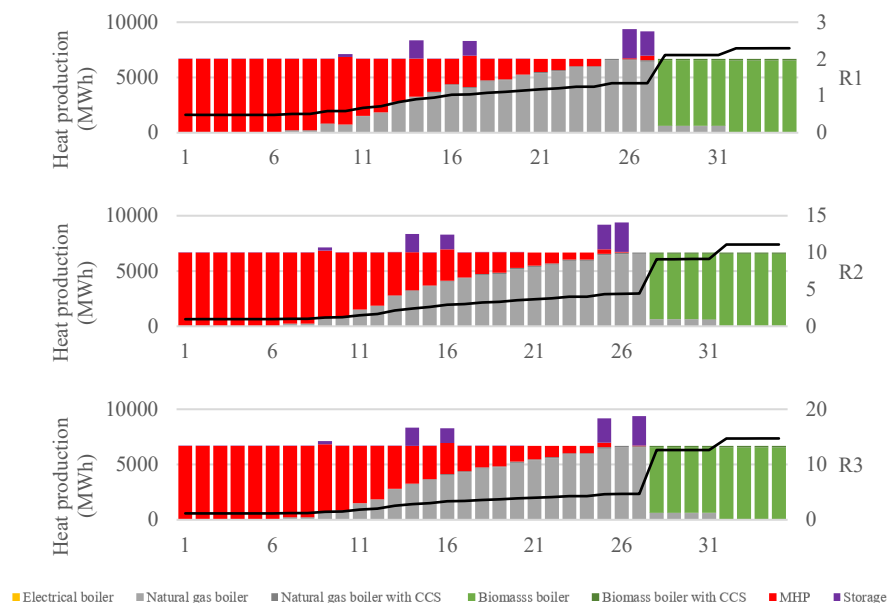
- Dammed hydro
- Geothermal plants
- Offshore wind
- Onshore wind
- Photovoltaic
- River hydro
- Biomass
- Solid
- Petroleum
- Gas
- Nuclear

Optimisation results

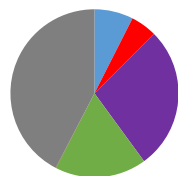
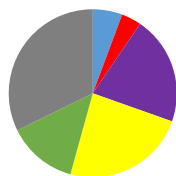
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																44%	78%	31	1	1	1
0.5	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.5	1.3	44%	78%	31	1	1	1
0.5	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.5	1.3	44%	78%	31	2	2	2
0.5	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.5	1.3	44%	78%	31	3	3	3
0.5	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.5	1.3	44%	78%	31	4	4	4
0.5	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.5	1.3	44%	78%	31	5	5	5
0.7	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.7	0.0	2.0	1.2	42%	79%	31	6	6	7
0.6	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.7	0.0	1.8	1.7	42%	77%	38	7	7	6
0.7	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.7	0.0	2.0	1.6	41%	78%	38	8	8	8
0.9	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.5	0.0	2.5	1.1	40%	81%	31	9	10	10
0.9	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.5	0.0	2.5	1.1	40%	81%	31	10	11	11
0.9	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.6	0.0	2.4	1.5	40%	79%	38	11	9	9
1.0	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.5	0.0	2.8	1.0	38%	80%	32	12	12	12
1.0	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.5	0.0	2.9	0.9	37%	80%	33	13	13	13
1.2	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.4	0.0	3.3	0.8	36%	81%	32	14	14	14
1.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.3	0.3	0.0	3.9	0.7	34%	81%	32	15	17	17
1.3	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.4	0.0	3.6	1.2	34%	79%	39	16	15	15
1.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.3	0.3	0.0	4.0	0.6	34%	82%	32	17	18	18
1.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.3	0.3	0.0	4.4	0.6	32%	82%	33	18	19	19
1.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.3	0.2	0.0	4.6	0.5	32%	83%	32	19	20	20
1.4	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.5	0.4	0.0	3.8	2.2	34%	79%	55	20	16	16
1.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.2	0.0	5.1	0.6	30%	82%	35	21	21	21
2.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	5.5	0.2	29%	84%	33	22	23	22
2.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	5.5	0.4	29%	82%	35	23	22	23
2.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.7	0.2	29%	84%	33	24	24	24
2.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.1	29%	84%	33	25	25	25
2.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.1	29%	84%	28	26	26	26
2.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.1	29%	84%	28	27	27	27
0.6	0.0	0.0	0.3	14.3	1.1	0.0	0.1	0.6	0.6	0.1	3.7	5.0	0.0	1.0	0.5	17%	56%	16	28	28	28
0.6	0.0	0.0	0.3	14.3	1.1	0.0	0.1	0.6	0.6	0.1	3.7	5.0	0.0	1.0	0.5	17%	56%	16	29	29	29
0.6	0.0	0.0	0.3	14.4	1.1	0.0	0.1	0.6	0.6	0.1	3.7	5.0	0.0	1.0	0.5	17%	56%	16	30	30	30
0.5	0.0	0.0	0.3	16.5	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	15	31	31	31
0.5	0.0	0.0	0.3	16.5	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	15	32	33	33
0.5	0.0	0.0	0.3	16.5	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	15	33	32	32
0.5	0.0	0.0	0.3	16.5	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	15	34	34	34
0.5	0.0	0.0	0.3	16.5	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	15	35	35	35

A4 20 - C3 Italy- 2040-2065 - Continuous process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

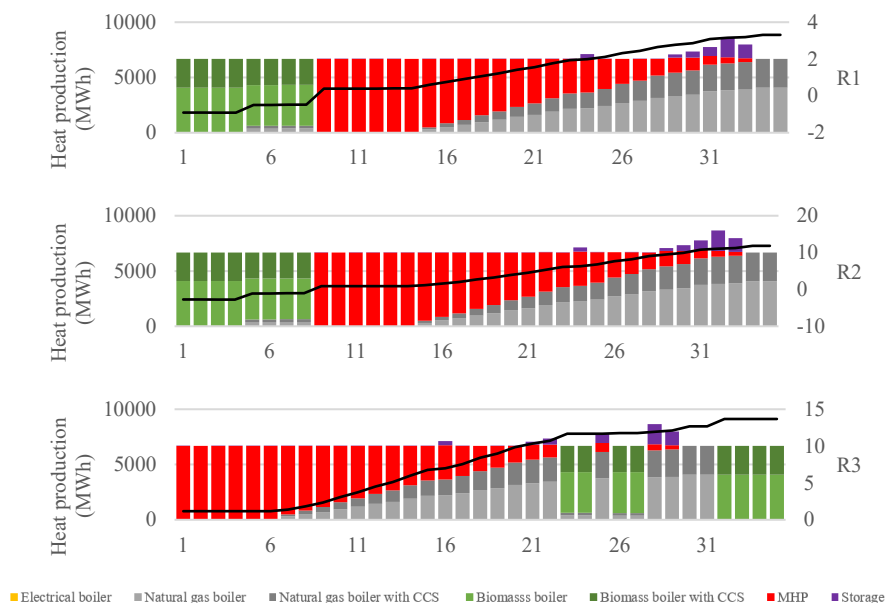
- Dammed hydro
- Geothermal plants
- Offshore wind
- Onshore wind
- Photovoltaic
- River hydro
- Biomass
- Solid
- Petroleum
- Gas
- Nuclear

Optimisation results

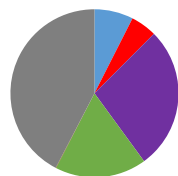
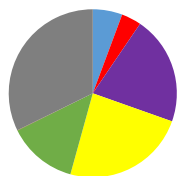
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
0.7	0.0	0.0	0.1	0.4	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.6	1.2	44%	77%	40	1	1	1	
0.7	0.0	0.0	0.1	0.4	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.6	1.2	44%	77%	40	2	2	2	
0.6	0.0	0.0	0.1	0.4	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.6	1.3	43%	77%	41	3	3	3	
0.6	0.0	0.0	0.1	0.4	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.6	1.3	43%	77%	41	4	4	4	
0.6	0.0	0.0	0.1	0.4	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.6	1.3	43%	77%	41	5	5	5	
0.6	0.0	0.0	0.1	0.4	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.6	1.3	43%	77%	41	6	6	6	
0.7	0.0	0.0	0.0	0.4	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.7	1.2	43%	77%	41	7	7	7	
0.7	0.0	0.0	0.0	0.4	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.7	1.2	43%	77%	41	8	8	8	
1.1	0.0	0.0	0.1	0.3	0.0	0.0	0.2	0.1	0.0	0.6	0.7	0.0	2.1	1.1	41%	78%	42	9	10	10	
1.0	0.0	0.0	0.1	0.3	0.0	0.0	0.2	0.1	0.0	0.6	0.7	0.0	2.1	1.1	40%	76%	42	10	9	9	
1.4	0.0	0.0	0.1	0.3	0.0	0.0	0.2	0.1	0.0	0.5	0.6	0.0	2.5	1.0	39%	79%	42	11	11	11	
1.6	0.0	0.0	0.1	0.3	0.0	0.0	0.2	0.1	0.0	0.5	0.6	0.0	2.7	0.9	38%	79%	43	12	12	12	
2.0	0.0	0.0	0.1	0.3	0.0	0.0	0.2	0.1	0.0	0.4	0.4	0.0	3.3	0.7	36%	80%	44	13	13	13	
2.3	0.0	0.0	0.1	0.3	0.0	0.0	0.1	0.1	0.0	0.4	0.4	0.0	3.6	0.7	35%	80%	46	14	14	14	
2.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.3	0.3	3.9	0.6	34%	81%	46	15	15	15	
2.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.3	0.2	4.2	0.5	33%	83%	46	16	17	17	
2.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.3	0.4	4.2	0.5	32%	77%	48	17	16	16	
3.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.3	0.2	4.5	0.4	32%	82%	47	18	18	18	
3.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.3	0.2	4.6	0.4	32%	82%	47	19	19	19	
3.2	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	4.8	0.3	31%	83%	47	20	20	20	
3.3	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	5.0	0.3	31%	83%	48	21	21	21	
3.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	5.1	0.2	31%	83%	48	22	22	22	
3.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.1	5.3	0.2	30%	84%	49	23	23	23	
3.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.1	5.3	0.2	30%	84%	49	24	24	24	
3.9	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	5.8	0.0	29%	84%	50	25	27	26	
3.9	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	5.8	0.0	29%	83%	50	26	26	27	
3.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.1	5.7	0.1	28%	80%	52	27	25	25	
0.9	0.0	0.0	0.3	14.1	1.1	0.0	0.1	0.6	0.6	0.1	3.6	4.9	0.0	1.0	0.4	17%	55%	22	28	29	29
0.9	0.0	0.0	0.3	14.1	1.1	0.0	0.1	0.6	0.6	0.1	3.6	4.9	0.0	1.0	0.4	17%	55%	22	29	28	28
0.9	0.0	0.0	0.3	14.1	1.1	0.0	0.1	0.6	0.6	0.1	3.6	4.9	0.0	1.0	0.4	17%	55%	22	30	31	31
0.9	0.0	0.0	0.3	14.1	1.1	0.0	0.1	0.6	0.6	0.1	3.6	4.9	0.0	1.0	0.4	17%	55%	22	31	30	30
0.6	0.0	0.0	0.3	16.3	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.5	16%	51%	20	32	32	32
0.6	0.0	0.0	0.3	16.3	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.5	16%	51%	20	33	33	33
0.6	0.0	0.0	0.3	16.3	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.5	16%	51%	20	34	34	34
0.6	0.0	0.0	0.3	16.3	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.5	16%	51%	20	35	35	35

A4 21 - C3 Italy- 2065-2090 - Continuous process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

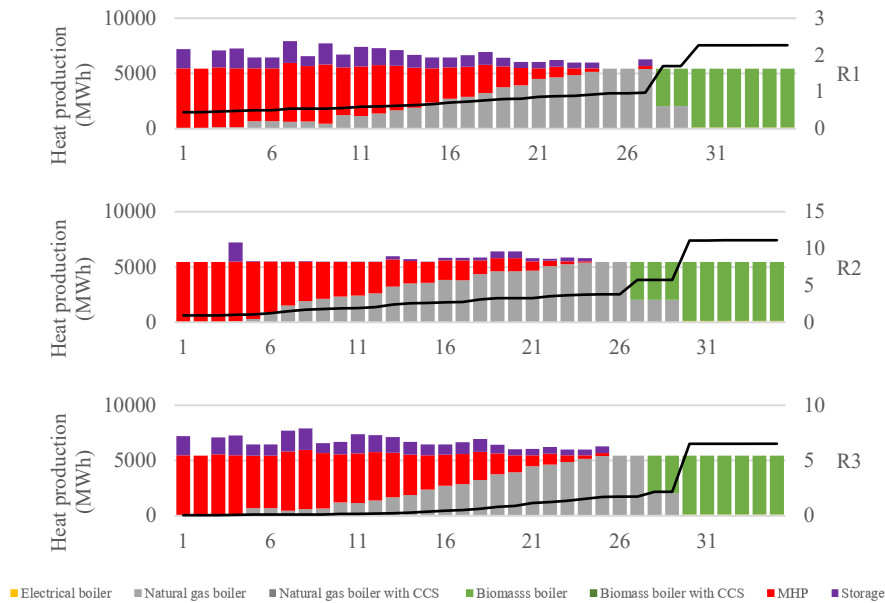
- Dammed hydro
- Geothermal plants
- Offshore wind
- Onshore wind
- Photovoltaic
- River hydro
- Biomass
- Solid
- Petroleum
- Gas
- Nuclear

Optimisation results

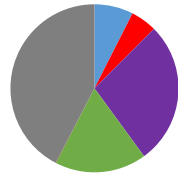
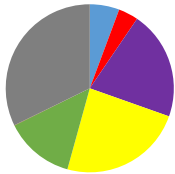
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
-14.4	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	0.8	14%	46%	24	1	1	34
-14.4	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	0.8	14%	46%	24	2	2	35
-14.4	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	0.8	14%	46%	24	3	3	33
-14.4	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	0.8	14%	46%	24	4	4	32
-11.3	0.0	0.0	0.2	13.7	1.0	0.0	0.1	0.9	0.6	0.1	3.7	4.7	0.0	1.0	0.7	16%	50%	23	5	5	26
-11.3	0.0	0.0	0.2	13.7	1.0	0.0	0.1	0.9	0.6	0.1	3.7	4.7	0.0	1.0	0.7	16%	50%	23	6	6	27
-11.2	0.0	0.0	0.2	13.7	1.0	0.0	0.1	0.9	0.6	0.1	3.7	4.7	0.0	1.1	0.7	16%	50%	23	7	7	23
-11.2	0.0	0.0	0.2	13.7	1.0	0.0	0.1	0.9	0.6	0.1	3.7	4.7	0.0	1.1	0.7	16%	50%	23	8	8	24
0.3	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.5	1.1	41%	74%	59	9	11	3
0.3	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.5	1.1	41%	74%	59	10	12	4
0.3	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.5	1.1	41%	74%	59	11	13	5
0.3	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.5	1.1	41%	74%	59	12	14	6
0.4	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.5	1.1	41%	75%	58	13	9	1
0.4	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.5	1.1	41%	75%	58	14	10	2
1.3	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.7	0.0	1.7	1.1	40%	76%	58	15	15	7
2.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.6	0.0	1.9	1.0	39%	76%	58	16	16	8
2.6	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.6	0.0	2.2	1.0	38%	75%	59	17	17	9
3.4	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.5	0.0	2.3	0.9	38%	77%	57	18	18	10
4.1	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.5	0.0	2.5	0.8	37%	77%	57	19	19	11
4.9	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.5	0.0	2.8	0.8	35%	77%	57	20	20	12
5.5	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.4	0.0	3.0	0.7	34%	76%	58	21	21	13
6.4	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.4	0.0	3.3	0.7	33%	77%	57	22	22	14
7.3	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.3	0.0	3.5	0.6	33%	78%	57	23	23	15
7.5	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.3	0.0	3.6	0.6	32%	77%	58	24	24	16
8.1	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.3	0.0	3.8	0.5	32%	78%	57	25	25	17
8.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.2	0.0	4.0	0.5	31%	78%	57	26	26	18
9.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.2	0.0	4.2	0.4	30%	78%	57	27	27	19
10.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.5	0.4	30%	79%	56	28	28	20
10.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.1	0.0	4.6	0.3	29%	77%	57	29	29	21
11.3	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.1	0.0	4.8	0.3	28%	77%	57	30	30	22
12.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.1	0.0	5.1	0.3	27%	76%	59	31	31	25
12.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.1	0.0	5.2	0.2	27%	77%	58	32	32	28
12.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.2	0.2	27%	78%	57	33	33	29
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.1	27%	79%	56	34	34	30
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.1	27%	79%	56	35	35	31

A4 22 - C3 Italy- 2015-2040 - Weekly process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

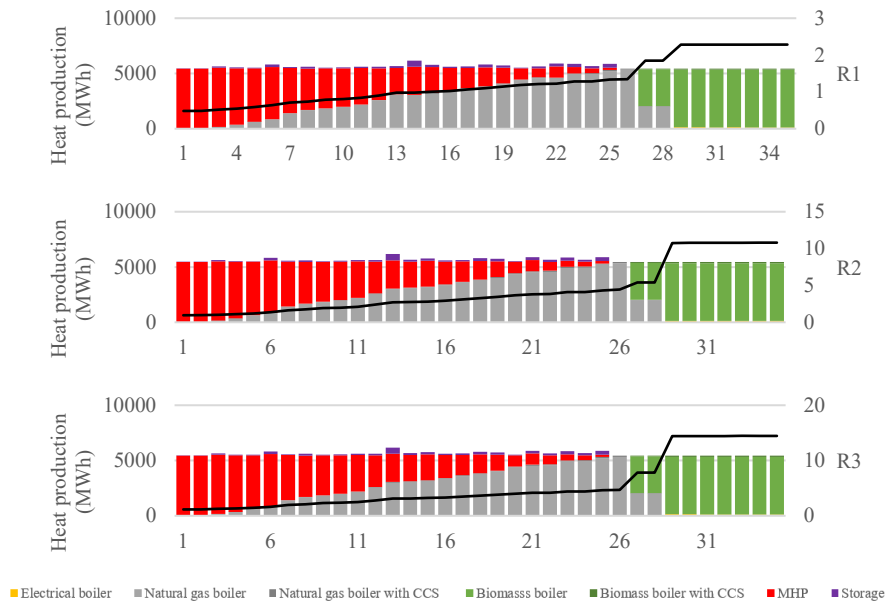
- Dammed hydro
- Onshore wind
- Biomass
- Gas
- Geothermal plants
- Photovoltaic
- Solid
- Nuclear
- Offshore wind
- River hydro
- Petroleum

Optimisation results

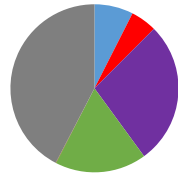
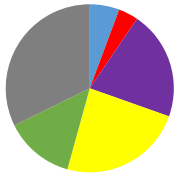
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																44%	78%	30	1	1	1
0.5	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.5	1.3	44%	78%	30	2	2	2
0.5	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.5	1.3	44%	78%	30	3	3	3
0.6	0.0	0.0	0.1	0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.7	1.3	42%	77%	40	4	4	4
0.6	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.7	0.0	1.8	1.3	42%	78%	32	5	5	5
0.8	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.6	0.0	2.2	1.2	41%	80%	32	6	6	6
0.9	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.5	0.0	2.7	1.0	39%	81%	30	7	7	7
1.1	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.5	0.0	3.0	1.0	37%	80%	32	8	8	8
1.1	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.4	0.0	3.2	0.9	37%	81%	30	9	9	9
1.2	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.4	0.0	3.4	0.8	36%	81%	29	10	11	11
1.2	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.4	0.0	3.4	0.8	36%	81%	30	11	10	10
1.3	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.4	0.0	3.6	0.8	35%	81%	29	12	12	12
1.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.3	0.3	0.0	4.3	0.6	32%	82%	29	13	15	15
1.5	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.3	0.0	4.1	0.9	32%	78%	42	14	13	13
1.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.3	0.0	4.3	0.7	32%	80%	34	15	14	14
1.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.3	0.0	4.6	0.6	31%	80%	37	16	17	17
1.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.2	0.0	4.6	0.7	31%	80%	38	17	16	16
1.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.2	0.0	5.1	0.5	30%	80%	37	18	18	18
1.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	5.2	0.4	30%	82%	31	19	21	19
1.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.2	0.0	5.3	0.5	28%	77%	53	20	19	20
1.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.2	0.0	5.3	0.5	28%	77%	53	21	20	21
2.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	5.6	0.3	29%	82%	34	22	22	22
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.7	0.2	29%	83%	29	23	23	23
2.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.1	29%	84%	21	24	25	25
2.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.1	29%	84%	21	25	26	26
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.2	28%	83%	30	26	24	24
1.1	0.0	0.0	0.2	9.8	0.7	0.0	0.1	0.4	0.4	0.1	2.5	3.4	0.0	2.5	0.4	20%	63%	16	27	27	27
1.1	0.0	0.0	0.2	9.8	0.7	0.0	0.1	0.4	0.4	0.1	2.5	3.4	0.0	2.5	0.4	20%	63%	16	28	28	28
1.1	0.0	0.0	0.2	9.8	0.7	0.0	0.1	0.4	0.4	0.1	2.5	3.4	0.0	2.5	0.4	20%	63%	16	29	29	29
0.5	0.0	0.0	0.3	16.2	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.6	0.7	16%	51%	16	30	30	30
0.5	0.0	0.0	0.3	16.2	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.6	0.7	16%	51%	16	31	31	31
0.5	0.0	0.0	0.3	16.2	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.6	0.7	16%	51%	16	32	32	32
0.5	0.0	0.0	0.3	16.3	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.6	0.7	16%	51%	16	33	33	33
0.5	0.0	0.0	0.3	16.3	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.6	0.7	16%	51%	16	34	34	34
0.5	0.0	0.0	0.3	16.3	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.6	0.7	16%	51%	16	35	35	35

A4 23 - C3 Italy- 2040-2065 - Weekly process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

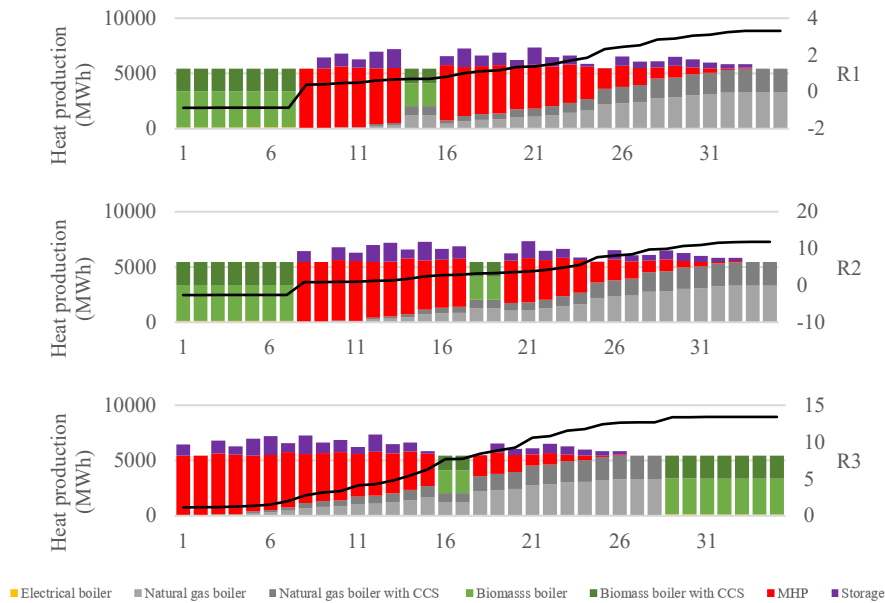
- Dammed hydro
- Onshore wind
- Biomass
- Gas
- Geothermal plants
- Photovoltaic
- Solid
- Nuclear
- Offshore wind
- River hydro
- Petroleum

Optimisation results

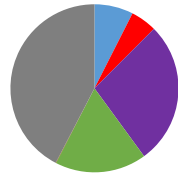
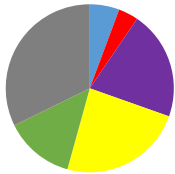
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																44%	77%	41	1	1	1
0.6	0.0	0.0	0.1	0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.6	1.3	44%	77%	41	2	2	2
0.8	0.0	0.0	0.1	0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.7	1.3	42%	75%	42	3	3	3
0.9	0.0	0.0	0.1	0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.7	0.0	1.9	1.2	42%	77%	42	4	4	4
1.0	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.7	0.0	2.1	1.1	41%	77%	42	5	5	5
1.2	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.7	0.0	2.3	1.1	39%	75%	44	6	6	6
1.5	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.6	0.0	2.7	0.9	38%	78%	43	7	7	7
1.6	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.5	0.0	2.8	0.9	38%	80%	43	8	8	8
1.8	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.6	0.0	3.0	0.8	37%	78%	44	9	9	9
1.9	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.5	0.0	3.1	0.8	36%	79%	44	10	10	10
2.0	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.5	0.0	3.3	0.8	36%	78%	45	11	11	11
2.2	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.1	0.1	0.0	0.4	0.4	0.0	3.6	0.7	35%	80%	45	12	12	12
2.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.3	0.3	0.0	4.0	0.6	33%	80%	46	13	14	14
2.5	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.1	0.1	0.0	0.4	0.4	0.0	4.0	0.6	33%	78%	47	14	13	13
2.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.3	0.3	0.0	4.1	0.6	33%	79%	47	15	15	15
2.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.3	0.3	0.0	4.2	0.5	33%	81%	46	16	16	16
2.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.3	0.3	0.0	4.4	0.4	32%	81%	47	17	17	17
3.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.3	0.3	0.0	4.6	0.4	31%	80%	48	18	18	18
3.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.3	0.2	0.0	4.8	0.4	31%	80%	49	19	19	19
3.3	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.2	0.0	5.0	0.3	31%	82%	48	20	20	20
3.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	5.2	0.2	30%	83%	49	21	22	22
3.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	5.1	0.3	30%	80%	50	22	21	21
3.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	5.4	0.2	29%	82%	50	23	23	23
3.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	5.5	0.1	29%	83%	50	24	24	24
3.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	5.7	0.1	28%	82%	51	25	25	25
3.9	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.0	29%	84%	50	26	26	26
1.9	0.0	0.0	0.2	9.7	0.7	0.0	0.1	0.4	0.4	0.1	2.5	3.3	0.0	2.5	0.3	20%	63%	30	27	27	27
1.9	0.0	0.0	0.2	9.7	0.7	0.0	0.1	0.4	0.4	0.1	2.5	3.3	0.0	2.5	0.3	20%	63%	30	28	28	28
0.7	0.0	0.0	0.3	16.0	1.2	0.0	0.1	0.6	0.6	0.1	4.1	5.6	0.0	0.6	0.6	16%	51%	23	29	29	29
0.7	0.0	0.0	0.3	16.0	1.2	0.0	0.1	0.6	0.6	0.1	4.1	5.6	0.0	0.6	0.6	16%	51%	23	30	30	30
0.7	0.0	0.0	0.3	16.0	1.2	0.0	0.1	0.6	0.6	0.1	4.1	5.6	0.0	0.6	0.6	16%	51%	22	31	32	32
0.7	0.0	0.0	0.3	16.0	1.2	0.0	0.1	0.6	0.6	0.1	4.1	5.6	0.0	0.6	0.6	16%	51%	22	32	31	31
0.7	0.0	0.0	0.3	16.0	1.2	0.0	0.1	0.6	0.6	0.1	4.1	5.6	0.0	0.6	0.6	16%	51%	22	33	33	33
0.7	0.0	0.0	0.3	16.0	1.2	0.0	0.1	0.6	0.6	0.1	4.1	5.6	0.0	0.6	0.6	16%	51%	22	34	34	34
0.7	0.0	0.0	0.3	16.0	1.2	0.0	0.1	0.6	0.6	0.1	4.1	5.6	0.0	0.6	0.6	16%	51%	22	35	35	35

A4 24 - C3 Italy- 2065-2090 - Weekly process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

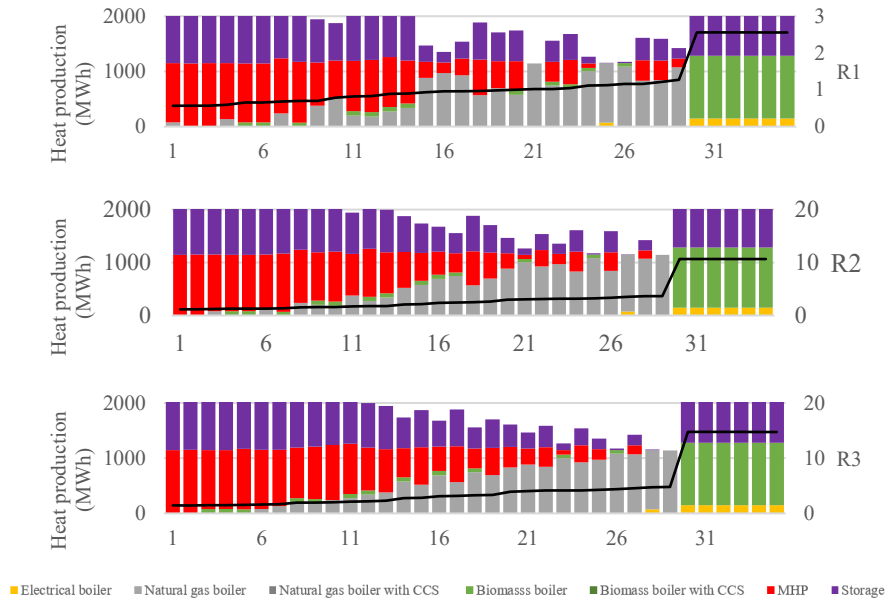
- Dammed hydro
- Onshore wind
- Biomass
- Gas
- Geothermal plants
- Photovoltaic
- Solid
- Nuclear
- Offshore wind
- River hydro
- Petroleum

Optimisation results

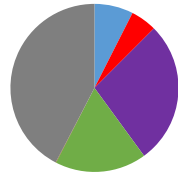
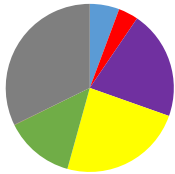
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
-14.2	0.0	0.0	0.3	15.5	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.7	0.8	14%	46%	27	1	1	34
-14.2	0.0	0.0	0.3	15.5	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.7	0.8	14%	46%	27	2	2	35
-14.2	0.0	0.0	0.3	15.5	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.7	0.8	14%	46%	27	3	3	33
-14.2	0.0	0.0	0.3	15.5	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.7	0.9	14%	46%	27	4	4	32
-14.2	0.0	0.0	0.3	15.5	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.7	0.9	14%	46%	28	5	5	31
-14.1	0.0	0.0	0.3	15.5	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.7	0.9	14%	46%	28	6	6	29
-14.1	0.0	0.0	0.3	15.5	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.7	0.9	14%	46%	28	7	7	30
0.3	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.5	1.1	41%	75%	58	8	9	2
0.4	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.7	0.0	1.4	1.2	42%	75%	59	9	8	1
0.7	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.7	0.0	1.5	1.2	40%	73%	61	10	10	3
0.6	0.0	0.0	0.1	0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	1.7	1.1	39%	72%	61	11	11	4
1.3	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.6	0.0	1.7	1.1	41%	76%	58	12	12	5
1.6	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.6	0.0	1.8	1.1	40%	76%	59	13	13	6
-3.5	0.0	0.0	0.2	9.4	0.7	0.0	0.1	0.7	0.4	0.1	2.5	3.2	0.0	2.4	0.5	18%	57%	25	14	18	17
-3.5	0.0	0.0	0.2	9.4	0.7	0.0	0.1	0.7	0.4	0.1	2.5	3.2	0.0	2.4	0.5	18%	57%	25	15	19	16
2.1	0.0	0.0	0.1	0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.8	0.0	2.2	1.1	36%	70%	63	16	14	7
3.1	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.6	0.0	2.2	1.0	37%	75%	59	17	15	8
3.5	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.6	0.0	2.5	0.9	35%	72%	61	18	16	9
3.7	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.6	0.0	2.5	1.0	35%	72%	62	19	17	10
4.5	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.6	0.0	2.8	0.8	34%	73%	60	20	20	11
4.7	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.5	0.0	2.8	0.9	34%	72%	61	21	21	12
5.2	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.5	0.0	3.0	0.8	33%	73%	60	22	22	13
6.0	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.5	0.0	3.4	0.8	31%	70%	63	23	23	14
6.8	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.4	0.0	3.5	0.7	32%	74%	60	24	24	15
9.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.3	0.0	4.1	0.5	31%	78%	57	25	25	18
9.4	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.3	0.0	4.3	0.5	29%	74%	60	26	26	19
9.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.2	0.0	4.3	0.4	30%	77%	58	27	27	20
11.2	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.2	0.0	4.8	0.3	28%	76%	58	28	28	21
11.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.2	0.0	4.9	0.3	28%	75%	59	29	29	22
12.2	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.1	0.0	5.1	0.2	28%	77%	57	30	30	23
12.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.1	0.0	5.1	0.2	28%	79%	56	31	31	24
13.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.3	0.2	27%	79%	56	32	32	25
13.3	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.1	27%	77%	57	33	33	26
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.1	27%	79%	56	34	34	27
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.1	27%	79%	56	35	35	28

A4 25 - C3 Italy - 2015-2040 - Batch process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

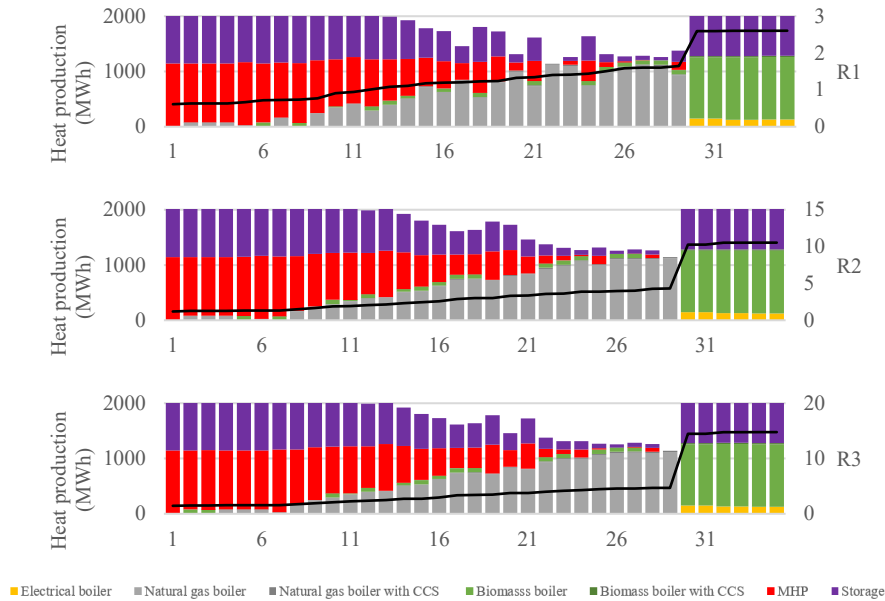
- Dammed hydro
- Onshore wind
- Biomass
- Gas
- Geothermal plants
- Photovoltaic
- Solid
- Nuclear
- Offshore wind
- River hydro
- Petroleum

Optimisation results

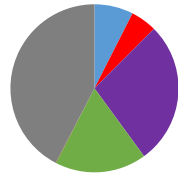
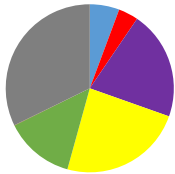
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
0.7	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.7	0.0	1.9	1.9	39%	77%	59	1	3	29
0.7	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.2	0.2	0.0	0.8	1.0	0.0	2.0	1.4	34%	71%	73	2	1	2
0.7	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.2	0.2	0.0	0.8	1.0	0.0	2.0	1.5	34%	70%	73	3	2	33
0.7	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.7	0.0	2.1	1.8	38%	77%	60	4	6	28
0.6	0.0	0.0	0.1	1.4	0.1	0.0	0.0	0.3	0.2	0.0	0.9	1.1	0.0	1.6	2.0	37%	75%	70	5	4	24
0.6	0.0	0.0	0.1	1.4	0.1	0.0	0.0	0.3	0.2	0.0	0.9	1.1	0.0	1.6	2.0	37%	75%	70	6	5	30
0.9	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.7	0.0	2.7	1.8	34%	72%	69	7	8	12
0.6	0.0	0.0	0.1	1.4	0.1	0.0	0.0	0.3	0.2	0.0	1.0	1.2	0.0	1.8	2.0	33%	70%	79	8	7	11
1.1	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.6	0.0	3.0	1.6	34%	78%	60	9	11	35
1.3	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.5	0.0	3.7	1.5	32%	76%	60	10	14	9
0.9	0.0	0.0	0.1	1.5	0.1	0.0	0.0	0.4	0.2	0.0	0.9	1.0	0.0	2.4	2.4	33%	72%	77	11	9	22
0.9	0.0	0.0	0.1	1.5	0.1	0.0	0.0	0.4	0.2	0.0	1.0	1.1	0.0	2.4	2.4	32%	71%	82	12	10	15
1.0	0.0	0.0	0.1	1.5	0.1	0.0	0.0	0.4	0.2	0.0	0.9	1.0	0.0	2.7	2.5	30%	69%	79	13	12	25
1.1	0.0	0.0	0.1	1.4	0.1	0.0	0.0	0.4	0.2	0.0	0.9	1.0	0.0	2.9	2.3	31%	73%	83	14	13	14
1.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.2	0.0	5.0	1.0	29%	79%	53	15	20	26
1.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.2	0.0	5.3	1.0	29%	81%	47	16	23	23
1.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.2	0.0	5.2	1.1	28%	76%	53	17	22	17
1.4	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.4	0.1	0.0	0.6	0.5	0.0	3.9	3.2	31%	74%	88	18	18	7
1.6	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.5	0.4	0.0	4.3	2.7	30%	77%	85	19	19	4
1.4	0.0	0.0	0.1	1.4	0.1	0.0	0.0	0.3	0.2	0.0	0.8	0.8	0.0	3.8	2.1	29%	74%	83	20	15	13
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.9	0.7	29%	84%	33	21	29	27
1.6	0.0	0.0	0.1	1.2	0.1	0.0	0.0	0.3	0.2	0.0	0.6	0.6	0.0	4.4	1.8	29%	77%	67	22	17	8
1.6	0.0	0.0	0.1	1.4	0.1	0.0	0.0	0.3	0.2	0.0	0.7	0.7	0.0	4.3	2.0	28%	74%	77	23	16	21
1.9	0.0	0.0	0.1	1.0	0.1	0.0	0.0	0.3	0.2	0.0	0.5	0.4	0.0	5.3	1.4	27%	80%	63	24	21	20
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.2	0.0	0.3	0.2	0.0	5.9	1.6	27%	79%	42	25	27	32
2.1	0.0	0.0	0.1	1.1	0.1	0.0	0.0	0.3	0.2	0.0	0.4	0.3	0.0	5.6	1.3	27%	80%	48	26	25	6
1.8	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.4	0.2	0.0	0.5	0.3	0.0	4.9	3.8	29%	76%	98	27	24	18
1.8	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.5	0.2	0.0	0.6	0.3	0.0	5.0	4.4	28%	76%	116	28	26	16
2.1	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.4	0.2	0.0	0.5	0.2	0.0	5.9	3.6	26%	76%	98	29	28	3
0.7	0.0	0.0	0.3	16.7	1.3	0.0	0.1	0.7	0.7	0.1	4.6	6.2	0.0	1.4	1.7	14%	45%	31	30	30	5
0.7	0.0	0.0	0.3	16.7	1.3	0.0	0.1	0.7	0.7	0.1	4.6	6.2	0.0	1.4	1.7	14%	45%	31	31	31	31
0.7	0.0	0.0	0.3	16.7	1.3	0.0	0.1	0.7	0.7	0.1	4.6	6.2	0.0	1.4	1.7	14%	45%	31	32	32	10
0.7	0.0	0.0	0.3	16.7	1.3	0.0	0.1	0.7	0.7	0.1	4.6	6.2	0.0	1.4	1.7	14%	45%	31	33	33	1
0.7	0.0	0.0	0.3	16.7	1.3	0.0	0.1	0.7	0.7	0.1	4.6	6.2	0.0	1.4	1.7	14%	45%	31	34	34	34
0.7	0.0	0.0	0.3	16.7	1.3	0.0	0.1	0.7	0.7	0.1	4.6	6.2	0.0	1.4	1.7	14%	45%	31	35	35	19

A4 26 - C3 Italy- 2040-2065 - Batch process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

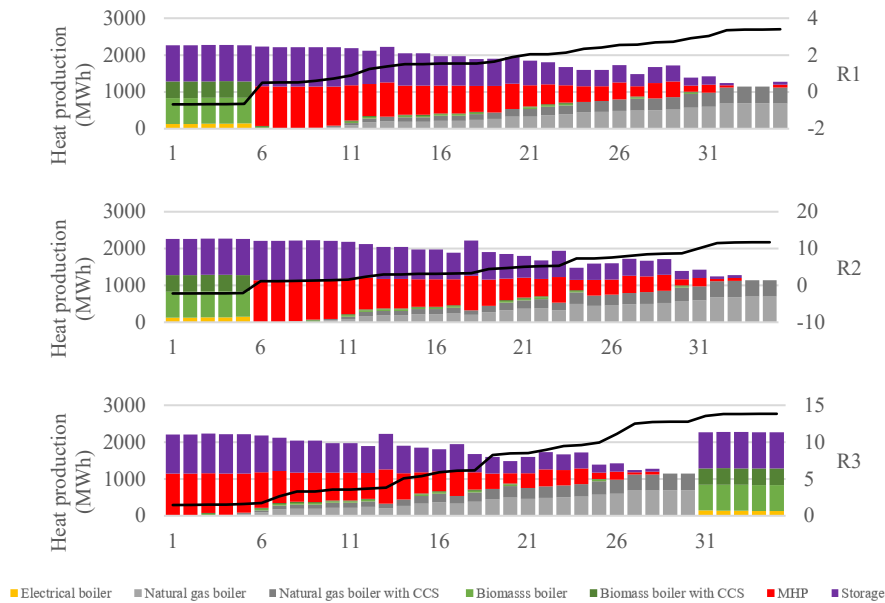
- Dammed hydro
- Onshore wind
- Biomass
- Gas
- Geothermal plants
- Photovoltaic
- Solid
- Nuclear
- Offshore wind
- River hydro
- Petroleum

Optimisation results

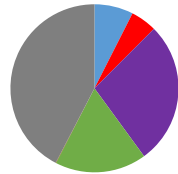
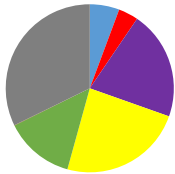
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
0.8	0.0	0.0	0.1	0.5	0.1	0.0	0.0	0.2	0.2	0.0	0.8	1.0	0.0	2.0	1.4	33%	69%	91	1	1	1
0.9	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.8	0.0	1.9	1.9	37%	76%	80	2	2	4
0.9	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.8	0.0	1.9	1.9	37%	76%	80	3	3	5
0.9	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.8	0.0	1.9	1.9	38%	76%	79	4	4	6
0.9	0.0	0.0	0.1	0.5	0.1	0.0	0.0	0.3	0.2	0.0	0.8	1.0	0.0	2.1	1.7	33%	68%	92	5	6	7
0.7	0.0	0.0	0.1	1.5	0.1	0.0	0.0	0.3	0.2	0.0	1.0	1.2	0.0	1.6	1.9	34%	72%	88	6	5	2
1.2	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.7	0.0	2.3	1.8	31%	75%	142	7	8	8
0.8	0.0	0.0	0.1	1.4	0.1	0.0	0.0	0.3	0.2	0.0	1.0	1.2	0.0	1.8	2.0	33%	70%	89	8	7	3
1.5	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.7	0.0	2.6	1.7	34%	73%	82	9	9	9
1.8	0.0	0.0	0.1	0.6	0.1	0.0	0.0	0.3	0.2	0.0	0.7	0.7	0.0	3.1	1.8	29%	72%	120	10	11	11
2.0	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.3	0.2	0.0	0.6	0.6	0.0	3.4	1.6	27%	70%	147	11	13	13
1.6	0.0	0.0	0.1	1.5	0.1	0.0	0.0	0.4	0.2	0.0	0.9	1.0	0.0	2.8	2.3	30%	70%	103	12	10	10
2.0	0.0	0.0	0.1	1.4	0.1	0.0	0.0	0.4	0.2	0.0	0.9	0.9	0.0	3.2	2.2	28%	70%	126	13	12	12
2.3	0.0	0.0	0.1	1.0	0.1	0.0	0.0	0.3	0.2	0.0	0.7	0.7	0.0	3.6	1.9	29%	72%	94	14	14	14
2.9	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.4	0.0	4.5	1.5	29%	73%	82	15	19	19
2.6	0.0	0.0	0.1	1.1	0.1	0.0	0.0	0.3	0.2	0.0	0.7	0.7	0.0	4.0	1.8	29%	75%	89	16	16	16
3.2	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.2	0.0	4.8	1.1	30%	80%	74	17	21	20
2.3	0.0	0.0	0.1	1.4	0.1	0.0	0.0	0.4	0.2	0.0	0.8	0.8	0.0	3.7	2.7	29%	73%	97	18	15	15
3.1	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.4	0.0	4.8	1.2	28%	72%	81	19	20	21
3.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.1	0.0	5.4	0.9	29%	81%	64	20	25	24
3.0	0.0	0.0	0.1	1.3	0.1	0.0	0.0	0.4	0.2	0.0	0.7	0.6	0.0	4.4	1.9	24%	74%	161	21	17	17
4.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.8	0.7	29%	84%	56	22	29	29
4.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.1	0.0	5.8	0.8	28%	80%	65	23	28	28
3.0	0.0	0.0	0.1	1.4	0.1	0.0	0.0	0.4	0.2	0.0	0.8	0.7	0.0	4.5	2.8	26%	73%	124	24	18	18
3.7	0.0	0.0	0.1	1.3	0.1	0.0	0.0	0.4	0.2	0.0	0.5	0.4	0.0	5.3	1.6	24%	78%	140	25	23	23
3.9	0.0	0.0	0.1	1.3	0.1	0.0	0.0	0.4	0.2	0.0	0.5	0.4	0.0	5.6	1.5	23%	77%	141	26	24	25
4.0	0.0	0.0	0.1	1.2	0.1	0.0	0.0	0.3	0.2	0.0	0.5	0.4	0.0	5.8	1.4	26%	76%	78	27	27	27
4.0	0.0	0.0	0.1	1.2	0.1	0.0	0.0	0.3	0.2	0.0	0.5	0.4	0.0	5.8	1.5	26%	76%	73	28	26	26
3.6	0.0	0.0	0.1	1.4	0.1	0.0	0.0	0.5	0.2	0.0	0.7	0.6	0.0	5.2	3.3	26%	75%	116	29	22	22
1.0	0.0	0.0	0.3	16.5	1.2	0.0	0.1	0.8	0.7	0.1	4.5	6.1	0.0	1.4	1.7	14%	44%	45	30	30	30
1.0	0.0	0.0	0.3	16.5	1.2	0.0	0.1	0.8	0.7	0.1	4.5	6.1	0.0	1.4	1.7	14%	44%	45	31	31	31
1.0	0.0	0.0	0.3	16.7	1.3	0.0	0.1	0.8	0.7	0.1	4.6	6.1	0.0	1.3	1.6	14%	44%	46	32	34	34
1.0	0.0	0.0	0.3	16.7	1.3	0.0	0.1	0.8	0.7	0.1	4.6	6.1	0.0	1.3	1.6	14%	44%	46	33	35	35
1.0	0.0	0.0	0.3	16.7	1.3	0.0	0.1	0.8	0.7	0.1	4.6	6.1	0.0	1.3	1.7	14%	44%	46	34	32	32
1.0	0.0	0.0	0.3	16.7	1.3	0.0	0.1	0.8	0.7	0.1	4.6	6.1	0.0	1.3	1.7	14%	44%	46	35	33	33

A4 27 - C3 Italy - 2065-2090 - Batch process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

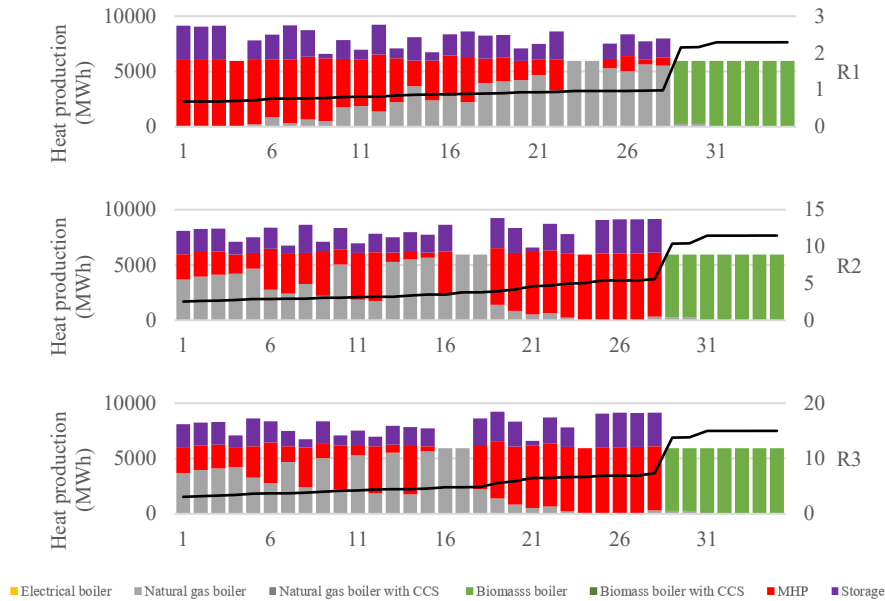
- Dammed hydro
- Onshore wind
- Biomass
- Gas
- Geothermal plants
- Photovoltaic
- Solid
- Nuclear
- Offshore wind
- River hydro
- Petroleum

Optimisation results

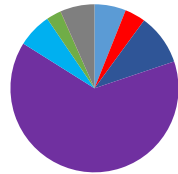
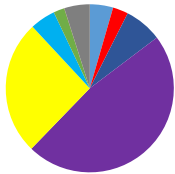
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3			
Sustainable ratio																			13%	40%	55	1	1	34
-14.4	0.0	0.0	0.3	16.2	1.2	0.1	0.1	1.1	0.7	0.1	4.6	5.9	0.0	1.3	1.8	13%	40%	55	2	2	35			
-14.4	0.0	0.0	0.3	16.2	1.2	0.1	0.1	1.1	0.7	0.1	4.6	5.9	0.0	1.4	1.8	13%	40%	57	3	3	33			
-14.4	0.0	0.0	0.3	16.2	1.2	0.1	0.1	1.1	0.7	0.1	4.6	5.9	0.0	1.4	1.8	13%	40%	57	4	4	32			
-14.2	0.0	0.0	0.3	15.9	1.2	0.1	0.1	1.1	0.7	0.1	4.5	5.8	0.0	1.4	1.9	13%	40%	56	5	5	31			
-0.1	0.0	0.0	0.1	1.3	0.1	0.0	0.0	0.3	0.2	0.0	0.9	1.1	0.0	1.6	1.8	33%	69%	102	6	9	3			
0.5	0.0	0.0	0.1	0.5	0.1	0.0	0.0	0.2	0.2	0.0	0.8	1.0	0.0	1.9	1.3	32%	67%	111	7	7	2			
0.5	0.0	0.0	0.1	0.5	0.1	0.0	0.0	0.2	0.2	0.0	0.8	1.0	0.0	1.9	1.3	32%	67%	111	8	6	1			
0.8	0.0	0.0	0.1	0.5	0.1	0.0	0.0	0.3	0.2	0.0	0.8	0.9	0.0	2.0	1.5	31%	67%	111	9	8	4			
1.5	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.7	0.0	1.9	1.7	36%	73%	96	10	10	5			
1.6	0.0	0.0	0.1	1.3	0.1	0.0	0.0	0.4	0.2	0.0	0.9	1.0	0.0	2.1	2.0	31%	70%	104	11	11	6			
3.1	0.0	0.0	0.1	1.3	0.1	0.0	0.0	0.4	0.2	0.0	0.9	0.9	0.0	2.5	2.1	29%	68%	111	12	12	7			
4.3	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.6	0.0	2.8	1.6	30%	68%	104	13	18	13			
3.6	0.0	0.0	0.1	1.4	0.1	0.0	0.0	0.5	0.2	0.0	0.9	0.9	0.0	2.6	3.6	29%	70%	134	14	13	8			
3.6	0.0	0.0	0.1	1.4	0.1	0.0	0.0	0.5	0.2	0.0	0.9	0.9	0.0	2.6	3.6	29%	70%	134	15	14	9			
4.2	0.0	0.0	0.1	1.2	0.1	0.0	0.0	0.4	0.2	0.0	0.8	0.8	0.0	2.8	2.8	30%	71%	112	16	15	10			
4.2	0.0	0.0	0.1	1.2	0.1	0.0	0.0	0.4	0.2	0.0	0.8	0.8	0.0	2.8	2.8	30%	71%	112	17	16	11			
4.3	0.0	0.0	0.1	1.3	0.1	0.0	0.0	0.4	0.2	0.0	0.8	0.9	0.0	3.0	2.0	29%	70%	101	18	17	12			
5.6	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.5	0.5	0.0	3.0	1.4	31%	75%	98	19	19	14			
6.7	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.5	0.5	0.0	3.5	1.3	29%	71%	98	20	23	17			
6.2	0.0	0.0	0.1	1.3	0.1	0.0	0.0	0.5	0.2	0.0	0.8	0.7	0.0	3.4	3.1	28%	71%	123	21	20	15			
6.6	0.0	0.0	0.1	1.3	0.1	0.0	0.0	0.4	0.2	0.0	0.7	0.7	0.0	3.6	1.9	27%	70%	96	22	21	16			
6.9	0.0	0.0	0.1	1.4	0.1	0.0	0.0	0.4	0.2	0.0	0.7	0.7	0.0	3.7	1.9	27%	71%	93	23	22	18			
8.8	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.2	0.0	3.9	1.2	30%	78%	88	24	25	19			
9.1	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.2	0.0	4.0	1.1	29%	77%	88	25	26	21			
9.6	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.3	0.0	4.4	1.1	27%	70%	89	26	27	22			
9.2	0.0	0.0	0.1	1.1	0.1	0.0	0.0	0.4	0.2	0.0	0.6	0.5	0.0	4.3	1.5	27%	74%	87	27	24	20			
10.1	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.3	0.2	0.0	0.4	0.3	0.0	4.6	1.1	23%	70%	170	28	28	23			
10.3	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.3	0.2	0.0	0.4	0.3	0.0	4.7	1.1	26%	68%	90	29	29	24			
10.7	0.0	0.0	0.1	1.1	0.1	0.0	0.0	0.4	0.2	0.0	0.5	0.4	0.0	4.8	1.4	25%	73%	100	30	30	25			
11.8	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.3	0.2	0.0	5.0	1.0	24%	74%	126	31	31	26			
13.2	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.2	0.1	0.0	5.4	0.8	26%	76%	74	32	32	27			
13.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.2	0.0	0.0	5.4	0.7	27%	79%	62	33	34	29			
13.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.2	0.0	0.0	5.4	0.7	27%	79%	62	34	35	30			
13.4	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.3	0.1	0.0	5.5	0.8	23%	74%	133	35	33	28			

A4 28 - C4 Croatia - 2015-2040 - Continuous process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

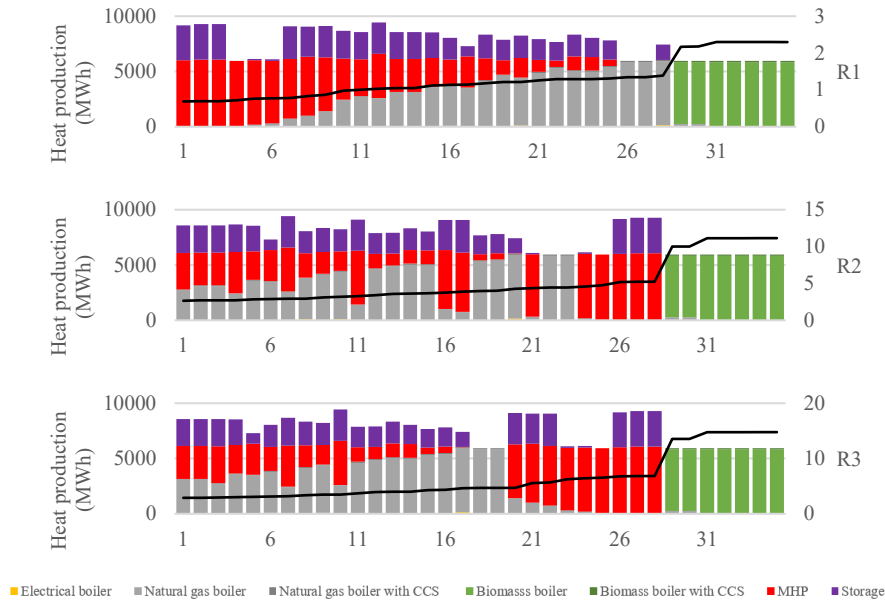
- Dammed hydro
- Geothermal plants
- Offshore wind
- Onshore wind
- Photovoltaic
- River hydro
- Biomass
- Solid
- Petroleum
- Gas
- Nuclear

Optimisation results

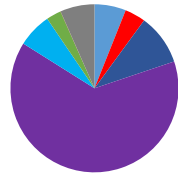
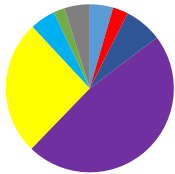
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.2	0.0	0.6	7.0	54%	88%	28	1	26	26
0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.2	0.0	0.6	7.0	54%	88%	28	2	25	25
0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.2	0.0	0.6	7.0	54%	88%	28	3	27	27
0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.2	0.0	0.8	6.8	54%	86%	22	4	24	24
0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.2	0.0	0.9	6.9	51%	86%	29	5	23	23
0.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	1.4	6.3	47%	85%	31	6	20	20
0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.2	0.0	0.9	7.5	51%	87%	37	7	28	28
0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.2	0.0	1.3	6.8	47%	83%	31	8	22	22
0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.2	0.0	1.3	6.8	47%	82%	29	9	21	21
0.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	2.3	5.2	41%	84%	34	10	12	14
0.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	2.3	5.2	41%	84%	33	11	11	12
0.7	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.1	0.0	1.8	6.2	42%	81%	33	12	19	19
0.9	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	2.6	5.0	39%	82%	33	13	9	10
1.4	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	3.8	2.9	35%	86%	36	14	1	1
1.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	2.9	4.7	35%	82%	59	15	7	8
1.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	3.1	4.5	36%	80%	35	16	6	6
0.9	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.5	0.1	0.0	2.6	5.7	39%	83%	46	17	16	18
1.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.1	2.8	33%	84%	37	18	2	2
1.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.2	2.7	33%	83%	37	19	3	3
1.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.4	2.6	30%	83%	62	20	4	4
1.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.1	0.0	4.8	1.9	31%	83%	38	21	5	7
1.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.1	0.0	3.5	4.4	35%	84%	50	22	8	5
2.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.1	29%	84%	28	23	17	16
2.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.1	29%	84%	28	24	18	17
1.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.3	1.4	29%	82%	37	25	13	11
1.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.1	1.8	29%	80%	39	26	10	9
2.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.6	0.7	28%	82%	39	27	15	15
2.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.5	1.1	28%	81%	39	28	14	13
0.5	0.0	0.0	0.3	15.3	1.1	0.0	0.1	0.6	0.6	0.1	3.9	5.3	0.0	0.7	0.6	17%	54%	15	29	29	29
0.5	0.0	0.0	0.3	15.3	1.1	0.0	0.1	0.6	0.6	0.1	3.9	5.3	0.0	0.7	0.6	17%	54%	15	30	30	30
0.4	0.0	0.0	0.3	16.6	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	15	31	34	34
0.4	0.0	0.0	0.3	16.6	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	15	32	35	35
0.4	0.0	0.0	0.3	16.6	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	15	33	31	31
0.4	0.0	0.0	0.3	16.6	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	15	34	32	32
0.4	0.0	0.0	0.3	16.6	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	15	35	33	33

A4 29 - C4 Croatia - 2040-2065 - Continuous process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

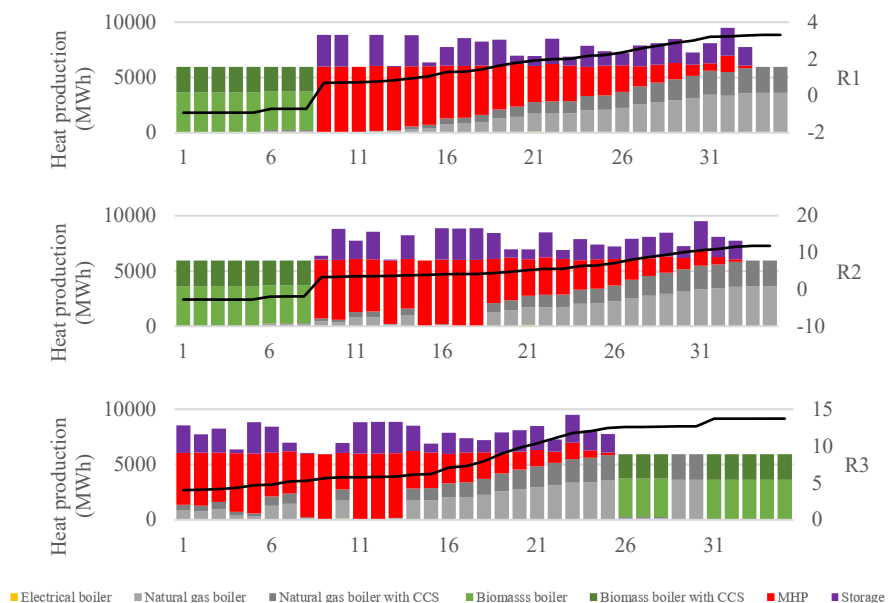
- Dammed hydro
- Geothermal plants
- Offshore wind
- Onshore wind
- Photovoltaic
- River hydro
- Biomass
- Solid
- Petroleum
- Gas
- Nuclear

Optimisation results

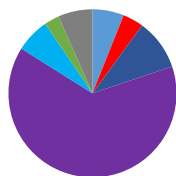
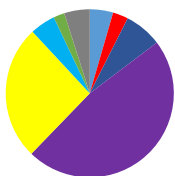
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
0.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	0.6	6.9	57%	89%	28	1	26	26
0.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	0.6	7.0	56%	88%	28	2	27	27
0.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	0.6	7.0	56%	88%	28	3	28	28
0.4	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.2	0.0	0.8	6.7	54%	86%	28	4	25	25
0.5	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	1.0	6.7	52%	84%	30	5	24	24
0.6	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	1.1	6.6	51%	84%	30	6	21	23
0.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	1.2	6.2	50%	87%	31	7	17	22
0.9	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.1	0.0	1.4	6.2	47%	84%	33	8	16	21
1.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	1.8	5.6	45%	84%	34	9	11	20
1.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	2.7	4.3	40%	84%	38	10	4	7
2.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	3.0	3.8	38%	85%	39	11	1	3
1.9	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	2.8	4.7	38%	80%	41	12	7	10
2.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	3.3	3.4	37%	84%	40	13	2	1
2.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	3.3	3.4	37%	84%	40	14	3	2
2.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	3.7	3.1	35%	83%	43	15	5	4
2.6	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	3.9	2.9	34%	84%	43	16	8	6
2.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	3.8	3.2	34%	79%	43	17	6	5
2.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.3	2.3	33%	82%	44	18	9	8
3.2	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	4.7	1.5	32%	84%	46	19	12	11
3.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.4	2.4	32%	82%	47	20	10	9
3.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	5.0	1.3	31%	83%	47	21	13	12
3.6	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.3	0.7	30%	84%	48	22	18	15
3.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.0	1.6	30%	80%	49	23	14	13
3.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	5.1	1.5	30%	80%	49	24	15	14
3.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.4	0.7	29%	82%	49	25	19	16
3.9	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.0	29%	84%	50	26	22	18
3.9	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.0	29%	84%	50	27	23	19
3.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.7	0.6	28%	82%	52	28	20	17
0.8	0.0	0.0	0.3	15.1	1.1	0.0	0.1	0.6	0.6	0.1	3.9	5.2	0.0	0.7	0.5	17%	54%	20	29	29	29
0.8	0.0	0.0	0.3	15.1	1.1	0.0	0.1	0.6	0.6	0.1	3.9	5.3	0.0	0.7	0.5	17%	54%	20	30	30	30
0.6	0.0	0.0	0.3	16.4	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.5	16%	51%	20	31	31	31
0.6	0.0	0.0	0.3	16.4	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.5	16%	51%	20	32	32	32
0.6	0.0	0.0	0.3	16.4	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.5	16%	51%	20	33	34	34
0.6	0.0	0.0	0.3	16.4	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.5	16%	51%	20	34	35	35
0.6	0.0	0.0	0.3	16.4	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.5	16%	51%	20	35	33	33

A4 30 - C4 Croatia - 2065-2090 - Continuous process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

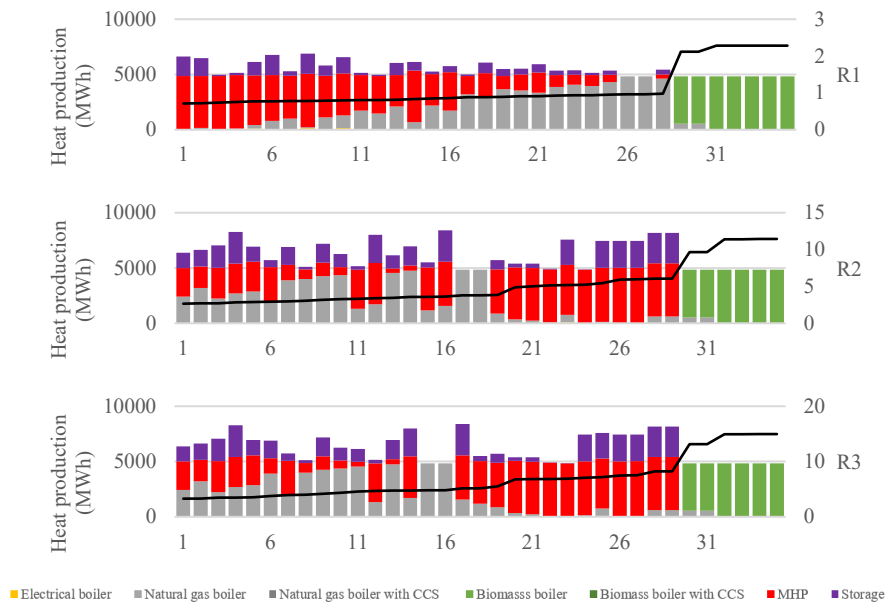
- Dammed hydro
- Geothermal plants
- Offshore wind
- Onshore wind
- Photovoltaic
- River hydro
- Biomass
- Solid
- Petroleum
- Gas
- Nuclear

Optimisation results

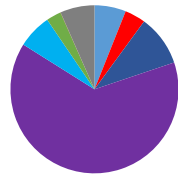
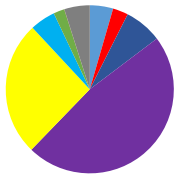
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3			
Sustainable ratio																			14%	46%	24	1	1	34
-14.5	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.5	0.0	0.6	0.8	14%	46%	24	2	2	35			
-14.5	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.5	0.0	0.6	0.8	14%	46%	24	3	3	33			
-14.5	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.5	0.0	0.6	0.8	14%	46%	24	4	4	31			
-14.5	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.5	0.0	0.6	0.8	14%	46%	24	5	5	32			
-12.8	0.0	0.0	0.3	14.7	1.1	0.0	0.1	0.9	0.6	0.1	3.9	5.0	0.0	0.8	0.7	15%	49%	23	6	6	28			
-12.8	0.0	0.0	0.3	14.6	1.1	0.0	0.1	0.9	0.6	0.1	3.9	5.0	0.0	0.8	0.7	15%	49%	23	7	7	26			
-12.8	0.0	0.0	0.3	14.6	1.1	0.0	0.1	0.9	0.6	0.1	3.9	5.0	0.0	0.8	0.7	15%	49%	23	8	8	27			
0.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	0.5	6.1	56%	88%	42	9	18	12			
0.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.5	0.2	0.0	0.5	6.0	56%	88%	42	10	17	11			
0.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.2	0.0	0.7	6.0	53%	85%	42	11	15	9			
1.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	0.6	6.2	54%	87%	44	12	16	13			
1.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.2	0.0	0.9	5.8	51%	84%	43	13	13	8			
2.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	0.9	5.5	52%	88%	43	14	10	5			
2.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	1.3	5.3	47%	83%	45	15	9	4			
3.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	1.7	4.9	44%	83%	47	16	11	2			
3.6	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	1.6	4.8	45%	85%	46	17	12	1			
4.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	1.9	4.6	42%	83%	47	18	14	3			
5.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	2.3	4.1	40%	83%	49	19	19	6			
5.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	2.6	4.0	37%	80%	50	20	20	7			
6.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	2.8	3.8	36%	81%	51	21	21	10			
6.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	2.9	3.5	36%	80%	51	22	22	14			
6.9	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	3.0	3.3	35%	79%	51	23	23	15			
7.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	3.3	2.8	35%	82%	51	24	24	16			
8.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	3.4	2.8	34%	80%	51	25	25	17			
8.7	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	3.6	2.5	33%	79%	52	26	26	18			
9.7	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.0	2.0	31%	80%	53	27	27	19			
10.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	4.3	1.7	30%	79%	55	28	28	20			
11.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.5	1.6	29%	76%	56	29	29	21			
11.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	4.8	1.2	28%	77%	56	30	30	22			
12.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.2	0.8	27%	76%	58	31	32	24			
12.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.3	0.0	0.0	5.1	1.6	26%	70%	63	32	31	23			
13.2	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.3	0.4	27%	77%	57	33	33	25			
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.1	27%	79%	56	34	34	29			
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.1	27%	79%	56	35	35	30			

A4 31 - C4 Croatia - 2015-2040 - Weekly process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

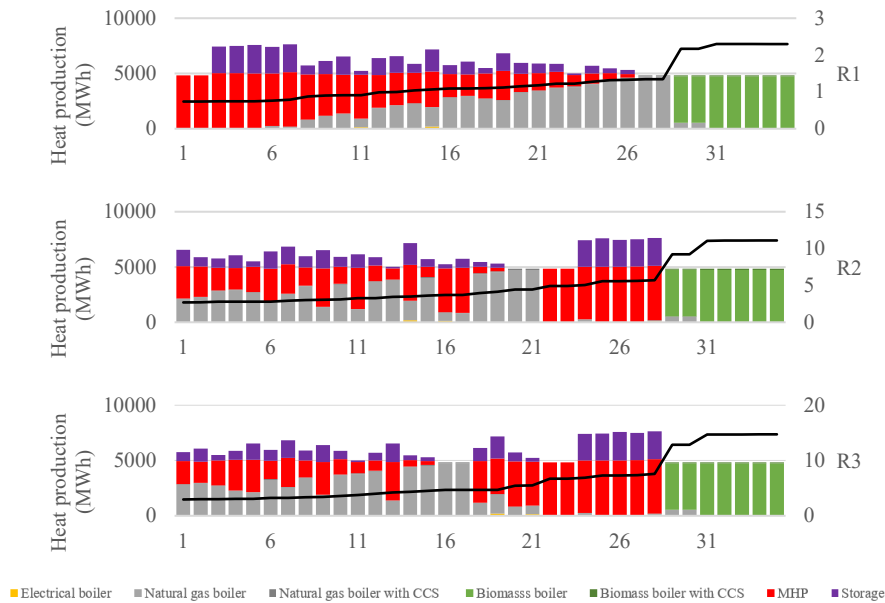
- Dammed hydro
- Onshore wind
- Biomass
- Gas
- Geothermal plants
- Photovoltaic
- Solid
- Nuclear
- Offshore wind
- River hydro
- Petroleum

Optimisation results

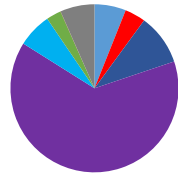
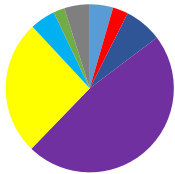
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.2	0.0	0.7	7.2	52%	87%	36	1	25	24
0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.2	0.0	0.8	7.1	53%	85%	23	2	24	23
0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.2	0.0	0.6	7.6	51%	85%	35	3	26	26
0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.2	0.0	0.6	7.6	51%	85%	37	4	27	27
0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.2	0.0	0.9	7.1	51%	85%	26	5	22	22
0.6	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.5	0.2	0.0	1.6	6.0	45%	86%	41	6	19	19
0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.2	0.0	1.1	7.1	48%	83%	40	7	21	21
0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.2	0.0	1.2	7.1	47%	81%	43	8	20	20
0.7	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.5	0.2	0.0	2.0	5.8	42%	83%	45	9	15	18
0.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	2.2	5.4	42%	84%	30	10	11	12
1.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.1	0.0	2.7	4.8	38%	83%	47	11	6	7
0.5	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.2	0.0	1.4	7.5	43%	80%	48	12	23	25
1.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	3.0	4.2	37%	84%	42	13	3	3
1.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	3.3	3.9	36%	83%	52	14	1	1
0.9	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.5	0.1	0.0	2.5	5.6	38%	78%	57	15	12	14
0.9	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.5	0.1	0.0	2.4	5.9	38%	77%	61	16	16	17
0.5	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.7	0.2	0.0	1.3	8.5	44%	80%	68	17	28	28
0.5	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.7	0.2	0.0	1.3	8.5	44%	80%	68	18	29	29
1.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.1	3.0	32%	81%	45	19	2	2
1.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.1	0.0	3.6	4.1	33%	78%	60	20	4	4
1.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.1	0.0	5.0	1.7	30%	83%	31	21	8	8
2.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.1	29%	84%	21	22	17	15
2.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.1	29%	84%	21	23	18	16
1.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.1	0.0	3.8	4.1	32%	76%	77	24	5	5
1.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	4.8	2.3	30%	79%	58	25	7	6
2.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.6	0.9	29%	82%	46	26	13	11
2.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.1	0.0	5.4	1.3	28%	80%	57	27	10	10
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.8	0.9	27%	78%	55	28	14	13
1.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.3	0.1	0.0	5.3	2.0	28%	75%	67	29	9	9
0.6	0.0	0.0	0.3	14.6	1.1	0.0	0.1	0.6	0.6	0.1	3.8	5.1	0.0	1.1	0.6	17%	54%	15	30	30	30
0.6	0.0	0.0	0.3	14.6	1.1	0.0	0.1	0.6	0.6	0.1	3.8	5.1	0.0	1.1	0.6	17%	54%	15	31	31	31
0.4	0.0	0.0	0.3	16.5	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.7	16%	51%	14	32	34	34
0.4	0.0	0.0	0.3	16.5	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.7	16%	51%	14	33	35	35
0.4	0.0	0.0	0.3	16.5	1.2	0.0	0.1	0.7	0.7	0.1	4.2	5.8	0.0	0.5	0.7	16%	51%	14	34	32	32
0.4	0.0	0.0	0.3	16.5	1.2	0.0	0.1	0.7	0.7	0.1	4.2	5.8	0.0	0.5	0.7	16%	51%	14	35	33	33

A4 32 - C4 Croatia - 2040-2065 - Weekly process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

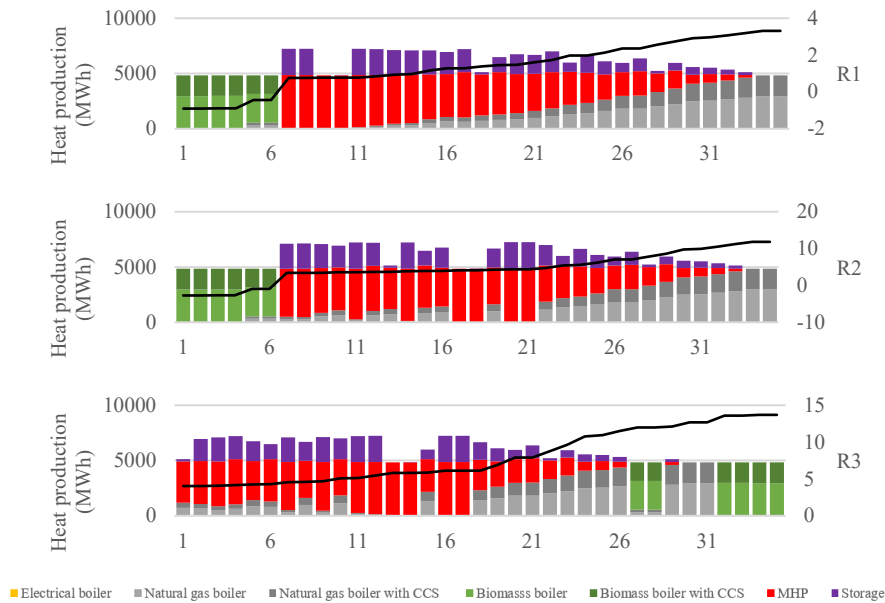
- Dammed hydro
- Onshore wind
- Biomass
- Gas
- Geothermal plants
- Photovoltaic
- Solid
- Nuclear
- Offshore wind
- River hydro
- Petroleum

Optimisation results

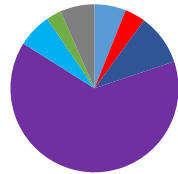
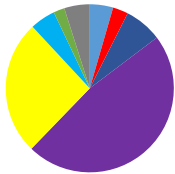
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	0.8	6.9	53%	85%	29	1	22	22
0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	0.8	6.9	53%	85%	29	2	23	23
0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.2	0.0	0.6	7.4	53%	85%	30	3	26	25
0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.2	0.0	0.6	7.5	53%	85%	30	4	27	27
0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.2	0.0	0.7	7.4	53%	84%	30	5	25	26
0.5	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	0.8	7.1	52%	86%	31	6	24	24
0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.2	0.0	0.7	7.7	51%	83%	32	7	28	28
1.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.2	0.0	1.6	6.2	45%	83%	34	8	17	20
1.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	1.9	5.7	43%	84%	35	9	11	18
1.4	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	2.1	5.3	43%	86%	36	10	9	13
1.0	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	1.8	6.3	44%	82%	35	11	16	21
1.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	2.7	4.6	40%	85%	38	12	6	9
1.9	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	2.9	4.1	39%	84%	39	13	1	5
2.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	3.1	4.0	37%	82%	40	14	2	4
1.7	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.1	0.0	2.5	6.0	38%	80%	42	15	14	19
2.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	3.7	3.0	36%	84%	42	16	3	1
2.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	3.8	2.7	35%	85%	42	17	4	2
2.4	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	3.6	3.4	35%	82%	42	18	5	3
2.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	3.4	4.2	35%	79%	43	19	7	7
2.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.1	2.4	34%	84%	44	20	8	6
2.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.3	2.3	33%	83%	45	21	10	8
3.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	4.6	2.0	32%	81%	47	22	12	10
3.2	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	4.8	1.5	32%	84%	46	23	13	11
3.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	5.0	1.3	30%	81%	48	24	15	12
3.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.4	0.9	29%	81%	49	25	18	14
3.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.6	0.5	29%	82%	50	26	19	15
3.9	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.0	29%	84%	50	27	20	16
3.9	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.0	29%	84%	50	28	21	17
1.0	0.0	0.0	0.3	14.4	1.1	0.0	0.1	0.6	0.6	0.1	3.7	5.0	0.0	1.1	0.4	17%	54%	23	29	29	29
1.0	0.0	0.0	0.3	14.4	1.1	0.0	0.1	0.6	0.6	0.1	3.7	5.0	0.0	1.1	0.4	17%	54%	23	30	30	30
0.6	0.0	0.0	0.3	16.3	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.6	16%	51%	20	31	34	34
0.6	0.0	0.0	0.3	16.3	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.6	16%	51%	20	32	35	35
0.6	0.0	0.0	0.3	16.3	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.6	16%	51%	20	33	31	31
0.6	0.0	0.0	0.3	16.3	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.6	16%	51%	20	34	33	33
0.6	0.0	0.0	0.3	16.3	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.6	16%	51%	20	35	32	32

A4 33 - C4 Croatia - 2065-2090 - Weekly process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

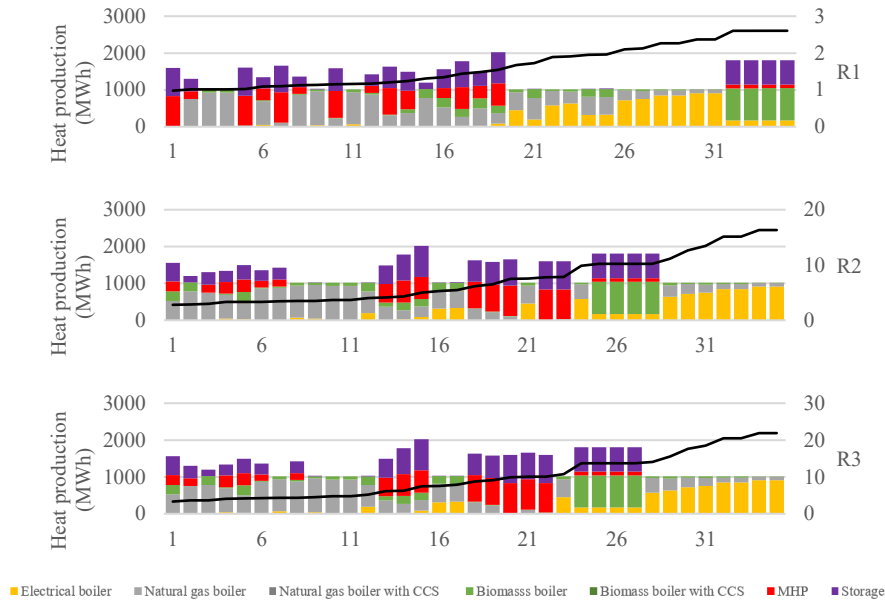
- Dammed hydro
- Onshore wind
- Biomass
- Gas
- Geothermal plants
- Photovoltaic
- Solid
- Nuclear
- Offshore wind
- River hydro
- Petroleum

Optimisation results

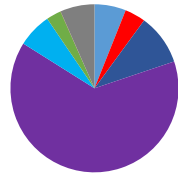
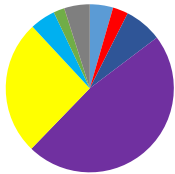
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3			
Sustainable ratio																			14%	46%	24	1	1	34
-14.5	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	0.8	14%	46%	24	2	2	35			
-14.4	0.0	0.0	0.3	15.7	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	1.0	14%	46%	25	3	3	32			
-14.4	0.0	0.0	0.3	15.7	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	1.0	14%	46%	25	4	4	33			
-11.3	0.0	0.0	0.3	14.0	1.0	0.0	0.1	0.9	0.6	0.1	3.7	4.8	0.0	1.1	0.7	15%	49%	24	5	5	28			
-11.3	0.0	0.0	0.3	14.0	1.0	0.0	0.1	0.9	0.6	0.1	3.7	4.8	0.0	1.2	0.7	15%	49%	24	6	6	27			
0.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	0.6	6.4	54%	86%	45	7	7	16			
0.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	0.6	6.4	54%	86%	45	8	8	17			
0.9	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.2	0.0	0.8	6.1	52%	84%	43	9	9	13			
0.9	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.6	0.2	0.0	0.8	6.2	52%	84%	43	10	10	14			
1.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	0.7	5.9	55%	88%	42	11	11	12			
1.4	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	0.7	5.7	54%	89%	43	12	12	11			
1.9	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	0.9	5.5	53%	89%	43	13	8	9			
2.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	1.0	5.4	52%	89%	43	14	7	7			
3.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	1.3	5.1	48%	87%	45	15	9	3			
3.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	1.5	4.9	46%	86%	46	16	10	2			
3.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	1.5	5.1	45%	84%	47	17	12	4			
3.9	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	1.9	4.6	42%	82%	46	18	13	1			
4.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	1.9	4.8	42%	81%	49	19	15	6			
4.4	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	1.9	4.4	43%	86%	47	20	16	5			
5.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	2.2	4.3	41%	83%	49	21	19	8			
5.6	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	2.4	4.1	39%	81%	50	22	22	10			
6.6	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	2.9	3.9	35%	76%	53	23	23	15			
6.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	2.9	3.5	36%	81%	51	24	24	18			
7.6	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	3.2	2.9	35%	82%	50	25	25	19			
8.6	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	3.6	2.7	33%	78%	54	26	26	20			
8.6	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	3.5	2.9	33%	78%	54	27	27	21			
9.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.0	2.3	31%	77%	55	28	28	22			
10.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.3	2.1	29%	75%	57	29	29	23			
11.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	4.6	1.1	29%	79%	55	30	30	24			
11.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	4.7	1.1	29%	78%	55	31	31	25			
12.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	4.9	0.8	28%	79%	55	32	32	26			
12.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.2	0.4	28%	79%	56	33	33	29			
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.1	27%	79%	56	34	34	30			
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.1	27%	79%	56	35	35	31			

A4 34 - C4 Croatia - 2015-2040 - Batch process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

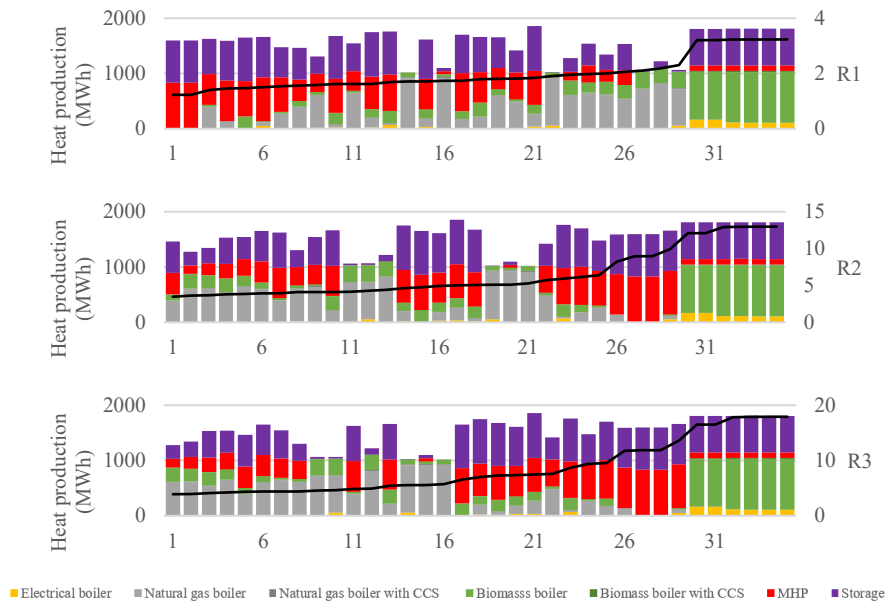
- Dammed hydro
- Onshore wind
- Biomass
- Gas
- Geothermal plants
- Photovoltaic
- Solid
- Nuclear
- Offshore wind
- River hydro
- Petroleum

Optimisation results

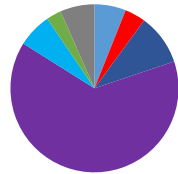
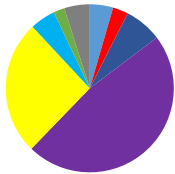
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.8	0.3	0.0	0.9	10.1	40%	83%	67	1	22	20
1.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	4.7	3.0	30%	84%	63	2	3	2
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.9	0.7	29%	84%	33	3	10	10
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.9	0.7	29%	84%	33	4	11	11
0.4	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.8	0.2	0.0	1.0	10.3	39%	83%	71	5	23	22
1.5	0.0	0.0	0.1	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.5	0.1	0.0	4.3	4.7	30%	81%	74	6	4	4
0.5	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.8	0.2	0.0	1.5	10.4	35%	77%	74	7	20	21
2.0	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.1	0.0	5.4	2.7	23%	76%	144	8	6	6
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	5.7	2.4	28%	82%	40	9	9	9
0.8	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.8	0.2	0.0	2.1	9.7	32%	75%	77	10	19	19
2.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.0	0.0	5.5	3.1	28%	83%	39	11	8	7
2.0	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.1	0.0	5.6	2.9	22%	73%	150	12	7	8
0.9	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.8	0.2	0.0	2.5	9.5	29%	72%	108	13	18	18
1.1	0.0	0.0	0.1	1.4	0.2	0.0	0.0	0.4	0.2	0.0	0.9	0.6	0.0	2.9	7.4	29%	74%	69	14	13	13
1.8	0.0	0.0	0.1	3.0	0.2	0.0	0.0	0.3	0.2	0.0	0.9	1.0	0.0	5.0	1.5	25%	76%	49	15	2	3
1.4	0.0	0.0	0.1	3.1	0.3	0.0	0.0	0.4	0.2	0.0	1.1	1.1	0.0	3.8	4.1	25%	72%	91	16	1	1
0.9	0.0	0.0	0.1	3.5	0.3	0.0	0.0	0.6	0.2	0.0	1.5	1.3	0.0	2.3	7.7	25%	68%	124	17	14	14
1.4	0.0	0.0	0.1	3.4	0.3	0.0	0.0	0.5	0.2	0.0	1.3	1.2	0.0	3.7	5.5	24%	68%	97	18	5	5
1.0	0.0	0.0	0.1	3.2	0.3	0.0	0.0	0.6	0.2	0.0	1.5	1.2	0.0	2.6	8.9	25%	64%	97	19	15	15
1.5	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.5	0.2	0.0	1.0	0.3	0.0	4.1	12.1	26%	75%	51	20	21	23
1.7	0.0	0.0	0.1	3.5	0.3	0.0	0.0	0.5	0.3	0.0	1.6	1.4	0.0	4.5	6.9	23%	67%	61	21	12	12
1.4	0.0	0.0	0.1	0.5	0.1	0.0	0.0	0.6	0.2	0.0	1.3	0.4	0.0	3.8	15.2	25%	70%	55	22	24	28
1.2	0.0	0.0	0.1	0.5	0.1	0.0	0.0	0.6	0.2	0.0	1.3	0.4	0.0	3.4	16.4	25%	72%	55	23	29	29
1.6	0.0	0.0	0.1	3.6	0.3	0.0	0.0	0.6	0.3	0.1	1.9	1.5	0.0	4.4	9.7	21%	62%	66	24	16	16
1.6	0.0	0.0	0.1	3.6	0.3	0.0	0.0	0.6	0.3	0.1	1.9	1.5	0.0	4.2	10.0	22%	63%	66	25	17	17
1.2	0.0	0.0	0.1	0.5	0.1	0.0	0.0	0.7	0.2	0.0	1.6	0.6	0.0	3.4	18.5	24%	67%	60	26	30	30
1.1	0.0	0.0	0.1	0.6	0.1	0.0	0.0	0.7	0.2	0.0	1.6	0.5	0.0	3.2	19.3	24%	67%	60	27	31	31
1.1	0.0	0.0	0.1	0.6	0.2	0.0	0.0	0.7	0.2	0.0	1.9	0.7	0.0	3.1	21.2	23%	64%	60	28	32	32
1.1	0.0	0.0	0.1	0.6	0.2	0.0	0.0	0.7	0.2	0.0	1.9	0.7	0.0	3.1	21.2	23%	64%	60	29	33	33
1.0	0.0	0.0	0.1	0.7	0.2	0.0	0.0	0.8	0.2	0.0	2.1	0.8	0.0	3.0	22.6	22%	61%	60	30	34	34
1.0	0.0	0.0	0.1	0.7	0.2	0.0	0.0	0.8	0.2	0.0	2.1	0.8	0.0	3.0	22.6	22%	61%	60	31	35	35
0.5	0.0	0.0	0.3	16.0	1.2	0.0	0.1	0.8	0.7	0.1	4.4	5.6	0.0	0.7	5.2	15%	46%	28	32	25	24
0.5	0.0	0.0	0.3	16.0	1.2	0.0	0.1	0.8	0.7	0.1	4.4	5.6	0.0	0.7	5.2	15%	46%	28	33	26	25
0.5	0.0	0.0	0.3	16.0	1.2	0.0	0.1	0.8	0.7	0.1	4.4	5.6	0.0	0.7	5.2	15%	46%	28	34	27	26
0.5	0.0	0.0	0.3	16.0	1.2	0.0	0.1	0.8	0.7	0.1	4.4	5.6	0.0	0.7	5.2	15%	46%	28	35	28	27

A4 35 - C4 Croatia - 2040-2065 - Batch process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

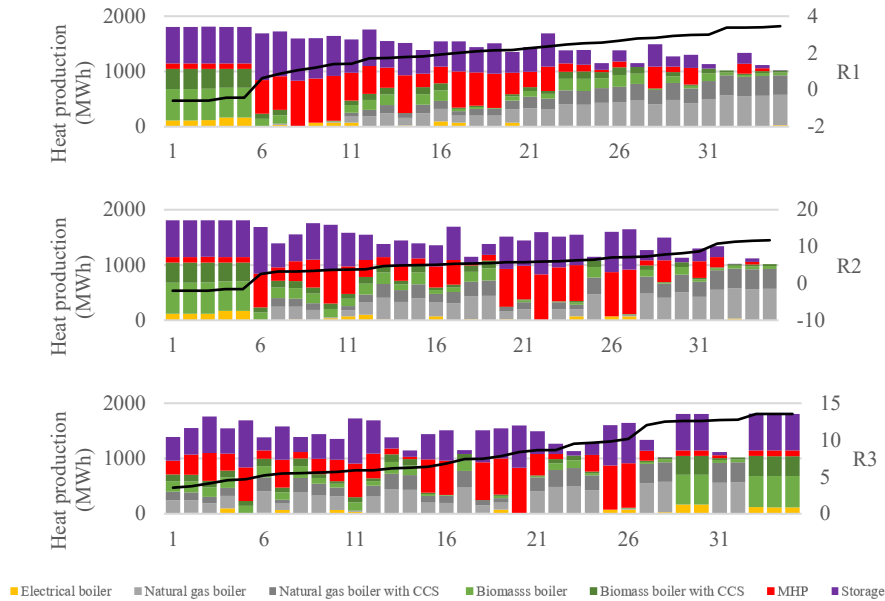
- Dammed hydro
- Geothermal plants
- Offshore wind
- Onshore wind
- Photovoltaic
- River hydro
- Biomass
- Solid
- Petroleum
- Gas
- Nuclear

Optimisation results

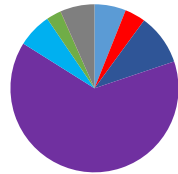
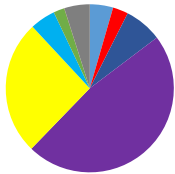
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3			
Sustainable ratio																			32%	68%	100	1	27	27
0.6	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.4	0.1	0.0	1.0	0.3	0.0	1.1	12.1	32%	68%	100	2	28	28			
2.5	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.2	0.0	3.8	6.5	27%	66%	102	3	7	11			
1.2	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.5	0.1	0.0	1.0	0.3	0.0	1.9	12.5	26%	65%	163	4	26	26			
0.7	0.0	0.0	0.1	4.6	0.4	0.0	0.0	0.6	0.3	0.0	1.9	1.8	0.0	1.1	7.9	26%	64%	108	5	15	17			
1.0	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.5	0.1	0.0	1.1	0.3	0.0	1.6	14.1	29%	64%	116	6	29	29			
1.9	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.9	0.2	0.0	2.9	10.7	26%	63%	112	7	25	24			
2.4	0.0	0.0	0.1	2.0	0.2	0.0	0.0	0.5	0.2	0.0	1.1	0.8	0.0	3.5	6.1	23%	68%	165	8	1	5			
3.3	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.5	0.1	0.0	4.9	5.5	25%	67%	92	9	8	8			
1.0	0.0	0.0	0.1	4.3	0.4	0.0	0.0	0.6	0.3	0.0	1.9	1.7	0.0	1.6	8.9	25%	62%	111	10	18	19			
3.5	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.5	0.1	0.0	5.2	5.0	22%	64%	166	11	9	7			
1.6	0.0	0.0	0.1	3.0	0.3	0.0	0.0	0.6	0.2	0.0	1.5	1.2	0.0	2.4	8.7	23%	62%	168	12	14	18			
0.9	0.0	0.0	0.1	4.4	0.4	0.0	0.0	0.7	0.3	0.0	1.9	1.7	0.0	1.4	10.2	24%	59%	113	13	23	23			
4.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.2	0.0	0.2	0.0	0.0	7.1	0.8	23%	68%	68	14	21	16			
1.5	0.0	0.0	0.1	3.6	0.3	0.0	0.0	0.7	0.2	0.0	1.8	1.5	0.0	2.3	9.2	22%	61%	165	15	16	20			
4.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.2	0.0	0.3	0.0	0.0	7.0	1.4	23%	66%	88	16	20	15			
1.5	0.0	0.0	0.1	2.8	0.3	0.0	0.0	0.6	0.2	0.0	1.5	1.1	0.0	2.2	11.0	23%	57%	114	17	24	25			
1.8	0.0	0.0	0.1	4.6	0.4	0.0	0.0	0.6	0.3	0.1	1.8	1.7	0.0	2.7	7.4	22%	57%	124	18	10	13			
3.4	0.0	0.0	0.1	1.6	0.2	0.0	0.0	0.4	0.2	0.0	0.9	0.6	0.0	5.1	5.4	21%	58%	135	19	6	6			
3.0	0.0	0.0	0.1	0.4	0.1	0.0	0.0	0.5	0.2	0.0	0.8	0.2	0.0	4.4	9.8	21%	58%	176	20	22	22			
2.0	0.0	0.0	0.1	3.1	0.3	0.0	0.0	0.6	0.2	0.0	1.7	1.3	0.0	3.1	9.5	22%	55%	127	21	17	21			
4.8	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.3	0.2	0.0	0.4	0.1	0.0	7.1	3.2	22%	64%	79	22	19	14			
3.5	0.0	0.0	0.1	4.3	0.4	0.0	0.0	0.5	0.3	0.1	1.4	1.5	0.0	4.9	3.3	20%	60%	110	23	2	1			
3.7	0.0	0.0	0.1	3.0	0.3	0.0	0.0	0.5	0.3	0.0	1.2	1.1	0.0	5.4	4.5	20%	56%	125	24	5	4			
3.4	0.0	0.0	0.1	4.5	0.4	0.0	0.0	0.5	0.3	0.1	1.5	1.6	0.0	4.8	3.9	20%	57%	111	25	3	2			
3.3	0.0	0.0	0.1	4.4	0.4	0.0	0.0	0.6	0.3	0.1	1.6	1.6	0.0	4.7	5.1	19%	55%	134	26	4	3			
4.1	0.0	0.0	0.1	4.5	0.4	0.0	0.0	0.5	0.3	0.1	1.4	1.6	0.0	5.9	1.9	19%	59%	84	27	11	9			
4.5	0.0	0.0	0.1	4.3	0.3	0.0	0.0	0.5	0.3	0.1	1.3	1.5	0.0	6.4	1.9	19%	56%	88	28	13	12			
4.1	0.0	0.0	0.2	4.6	0.4	0.0	0.1	0.6	0.3	0.1	1.6	1.7	0.0	5.9	4.3	19%	56%	94	29	12	10			
0.9	0.0	0.0	0.3	19.3	1.5	0.1	0.1	1.0	0.8	0.1	5.3	6.8	0.0	0.8	6.2	12%	38%	49	30	30	30			
0.9	0.0	0.0	0.3	19.3	1.5	0.1	0.1	1.0	0.8	0.1	5.3	6.8	0.0	0.8	6.2	12%	38%	49	31	31	31			
0.9	0.0	0.0	0.4	20.4	1.6	0.1	0.1	1.0	0.8	0.1	5.5	7.1	0.0	0.8	4.7	12%	37%	49	32	32	32			
0.9	0.0	0.0	0.4	20.5	1.6	0.1	0.1	1.0	0.8	0.1	5.5	7.2	0.0	0.8	4.7	12%	37%	49	33	34	34			
0.9	0.0	0.0	0.4	20.5	1.6	0.1	0.1	1.0	0.8	0.1	5.5	7.2	0.0	0.8	4.5	12%	37%	49	34	35	35			
0.9	0.0	0.0	0.4	20.5	1.6	0.1	0.1	1.0	0.8	0.1	5.5	7.2	0.0	0.8	4.6	12%	37%	49	35	33	33			

A4 36 - C4 Croatia - 2065-2090 - Batch process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

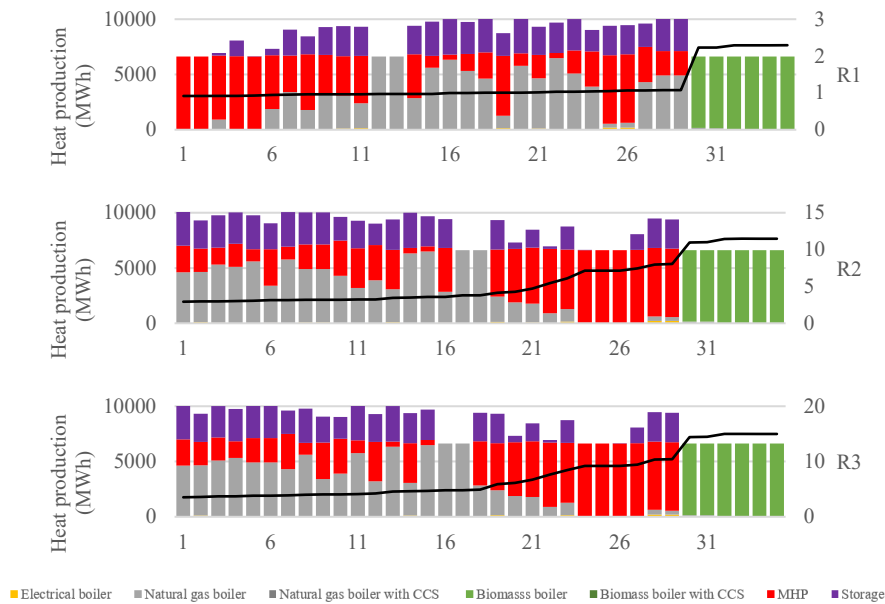
- Dammed hydro
- Onshore wind
- Biomass
- Gas
- Geothermal plants
- Photovoltaic
- Solid
- Nuclear
- Offshore wind
- River hydro
- Petroleum

Optimisation results

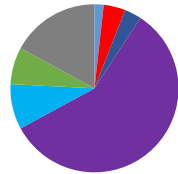
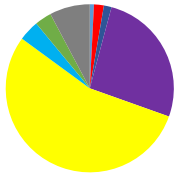
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
-14.3	0.0	0.0	0.3	16.1	1.2	0.1	0.1	1.1	0.7	0.1	4.5	5.6	0.0	0.8	3.8	13%	42%	48	1	1	34
-14.3	0.0	0.0	0.3	16.1	1.2	0.1	0.1	1.1	0.7	0.1	4.5	5.6	0.0	0.8	3.8	13%	42%	48	2	2	35
-14.3	0.0	0.0	0.3	16.1	1.2	0.1	0.1	1.1	0.7	0.1	4.5	5.6	0.0	0.8	3.8	13%	41%	49	3	3	33
-13.5	0.0	0.0	0.3	15.3	1.2	0.1	0.1	1.1	0.7	0.1	4.3	5.3	0.0	0.8	4.8	13%	42%	52	4	4	29
-13.5	0.0	0.0	0.3	15.3	1.2	0.1	0.1	1.1	0.7	0.1	4.3	5.3	0.0	0.8	4.8	13%	42%	52	5	5	30
-2.0	0.0	0.0	0.1	3.9	0.3	0.0	0.0	0.6	0.2	0.0	1.6	1.5	0.0	0.8	6.0	26%	74%	154	6	6	5
-1.4	0.0	0.0	0.1	3.9	0.3	0.0	0.0	0.7	0.2	0.0	1.6	1.5	0.0	1.0	7.2	25%	71%	165	7	10	11
1.2	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.3	0.0	0.8	8.8	39%	82%	103	8	22	20
1.4	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.8	0.2	0.0	0.8	10.2	37%	80%	113	9	26	25
1.9	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.8	0.2	0.0	1.0	10.8	35%	77%	120	10	27	26
1.5	0.0	0.0	0.1	3.1	0.3	0.0	0.0	0.6	0.2	0.0	1.4	1.1	0.0	1.9	6.9	26%	71%	115	11	11	7
2.6	0.0	0.0	0.1	3.9	0.3	0.0	0.0	0.7	0.3	0.0	1.5	1.4	0.0	2.6	5.5	21%	62%	167	12	9	3
2.6	0.0	0.0	0.1	4.4	0.4	0.0	0.0	0.6	0.3	0.1	1.6	1.6	0.0	2.8	4.6	22%	63%	96	13	8	2
4.1	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.7	0.2	0.0	1.8	9.1	32%	76%	118	14	20	18
3.3	0.0	0.0	0.1	4.3	0.4	0.0	0.0	0.6	0.3	0.1	1.5	1.5	0.0	3.0	3.9	21%	66%	146	15	7	1
2.9	0.0	0.0	0.1	4.4	0.4	0.0	0.0	0.7	0.3	0.1	1.7	1.6	0.0	3.0	6.1	21%	61%	123	16	12	4
4.9	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.7	0.2	0.0	2.0	9.6	30%	73%	124	17	24	19
5.9	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.6	0.1	0.0	2.5	7.5	30%	74%	115	18	21	15
5.8	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.8	0.2	0.0	2.5	8.3	26%	71%	176	19	23	16
5.7	0.0	0.0	0.1	1.5	0.2	0.0	0.0	0.5	0.2	0.0	0.9	0.6	0.0	2.9	6.6	26%	73%	116	20	16	10
6.6	0.0	0.0	0.1	2.3	0.2	0.0	0.0	0.5	0.2	0.0	1.0	0.8	0.0	3.5	3.7	23%	71%	162	21	14	9
6.7	0.0	0.0	0.1	1.8	0.2	0.0	0.0	0.5	0.2	0.0	1.0	0.7	0.0	3.4	5.2	23%	67%	170	22	17	12
6.2	0.0	0.0	0.1	4.4	0.4	0.0	0.0	0.6	0.3	0.1	1.5	1.5	0.0	4.2	3.0	20%	60%	93	23	13	6
6.5	0.0	0.0	0.1	4.5	0.4	0.0	0.0	0.7	0.3	0.1	1.5	1.5	0.0	4.3	2.8	19%	60%	133	24	15	8
7.3	0.0	0.0	0.1	3.6	0.3	0.0	0.0	0.6	0.3	0.0	1.2	1.2	0.0	4.3	2.3	22%	67%	91	25	18	14
7.3	0.0	0.0	0.1	4.4	0.4	0.0	0.0	0.6	0.3	0.1	1.4	1.5	0.0	4.6	2.3	19%	58%	85	26	19	13
8.5	0.0	0.0	0.1	3.6	0.3	0.0	0.0	0.5	0.3	0.1	1.2	1.2	0.0	4.8	1.6	21%	64%	69	27	25	17
9.6	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.5	0.1	0.0	3.9	5.4	27%	71%	98	28	29	21
9.6	0.0	0.0	0.1	2.3	0.2	0.0	0.0	0.5	0.2	0.0	0.9	0.8	0.0	4.7	2.5	23%	67%	91	29	28	22
10.6	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.1	0.0	4.3	4.4	26%	71%	98	30	31	24
10.4	0.0	0.0	0.1	2.3	0.2	0.0	0.0	0.4	0.2	0.0	0.8	0.7	0.0	5.0	1.2	23%	70%	66	31	30	23
13.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.2	0.0	0.0	5.4	0.7	27%	79%	62	32	35	32
12.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.1	0.0	5.2	2.5	25%	71%	93	33	32	27
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.2	0.0	0.0	5.4	1.0	26%	76%	80	34	34	31
13.3	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.3	0.1	0.0	5.5	1.8	26%	76%	70	35	33	28

A4 37 - C5 Italy - 2015-2040 - Continuous process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

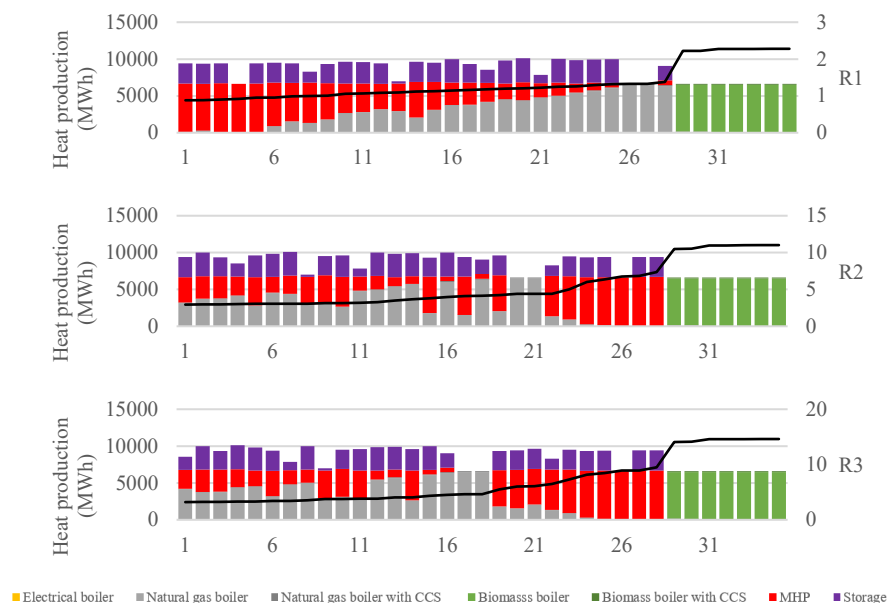
- Dammed hydro
- Onshore wind
- Biomass
- Gas
- Geothermal plants
- Photovoltaic
- Solid
- Nuclear
- Offshore wind
- River hydro
- Petroleum

Optimisation results

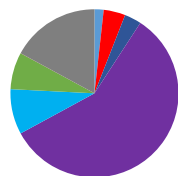
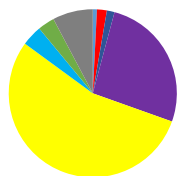
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.4	0.0	0.8	9.3	52%	86%	27	1	25	24
0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.4	0.0	0.8	9.3	52%	86%	27	2	26	25
0.5	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.3	0.0	1.5	8.0	47%	86%	30	3	22	22
0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.4	0.0	0.7	9.6	51%	86%	33	4	27	27
0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.4	0.0	0.8	9.4	52%	86%	28	5	24	26
0.8	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	2.2	6.9	41%	85%	36	6	20	20
1.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	3.3	5.0	36%	85%	38	7	6	9
0.8	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	2.1	7.4	42%	84%	36	8	21	21
1.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	3.2	5.2	37%	84%	38	9	11	12
1.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	3.0	5.6	38%	86%	38	10	13	14
0.9	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	2.5	6.7	40%	86%	38	11	19	19
2.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.1	29%	84%	28	12	17	16
2.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.1	29%	84%	28	13	18	17
1.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	2.9	5.9	38%	84%	38	14	16	18
1.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.1	0.0	5.1	1.7	30%	84%	39	15	5	8
2.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.7	0.9	29%	82%	34	16	14	13
1.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.8	2.6	31%	83%	40	17	3	4
1.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.3	3.5	32%	81%	39	18	1	1
0.6	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.3	0.0	1.6	8.9	44%	85%	39	19	23	23
1.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.1	0.0	5.2	1.8	30%	81%	36	20	7	11
1.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	4.3	3.7	32%	83%	40	21	2	2
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.8	1.0	28%	80%	37	22	15	15
1.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.7	3.2	30%	79%	40	23	4	3
1.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	3.8	4.9	33%	79%	34	24	12	10
0.4	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.8	0.3	0.0	1.0	10.6	46%	83%	39	25	29	29
0.4	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.8	0.3	0.0	1.1	10.6	45%	83%	39	26	28	28
1.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	4.2	4.5	31%	75%	35	27	10	7
1.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	4.5	4.0	31%	79%	48	28	8	5
1.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	4.5	4.0	31%	79%	48	29	9	6
0.5	0.0	0.0	0.3	16.0	1.2	0.0	0.1	0.6	0.6	0.1	4.1	5.6	0.0	0.6	0.6	16%	52%	15	30	30	30
0.5	0.0	0.0	0.3	16.0	1.2	0.0	0.1	0.6	0.6	0.1	4.1	5.6	0.0	0.6	0.6	16%	52%	15	31	31	31
0.4	0.0	0.0	0.3	16.6	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	15	32	34	34
0.4	0.0	0.0	0.3	16.6	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	15	33	35	35
0.4	0.0	0.0	0.3	16.6	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	15	34	33	33
0.4	0.0	0.0	0.3	16.6	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.7	16%	51%	15	35	32	32

A4 38 - C5 Italy - 2040-2065 - Continuous process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

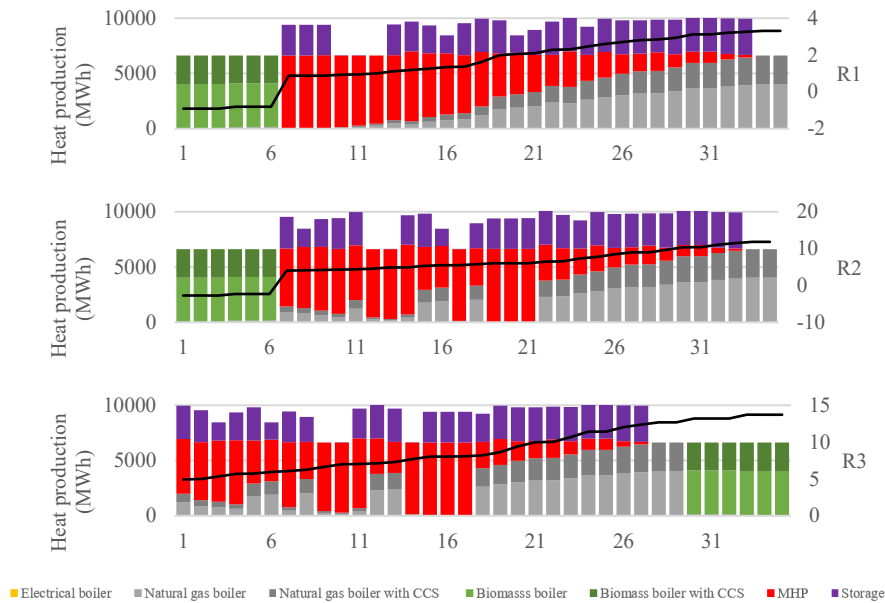
- Dammed hydro
- Geothermal plants
- Offshore wind
- Onshore wind
- Photovoltaic
- River hydro
- Biomass
- Solid
- Petroleum
- Gas
- Nuclear

Optimisation results

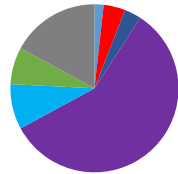
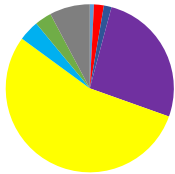
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.3	0.0	0.8	8.6	54%	88%	34	1	25	25
0.5	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	0.9	8.4	54%	89%	35	2	24	24
0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.3	0.0	0.7	9.1	54%	87%	35	3	27	27
0.4	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.4	0.0	0.8	9.1	53%	86%	36	4	26	26
0.4	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.4	0.0	0.7	9.7	52%	85%	37	5	28	28
0.8	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	1.4	7.8	48%	86%	37	6	23	23
1.2	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	1.9	6.9	45%	86%	38	7	17	20
1.1	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	1.8	7.3	45%	85%	38	8	22	22
1.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.3	0.0	2.1	6.5	44%	86%	39	9	15	19
1.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	2.7	5.3	40%	86%	40	10	10	14
1.9	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	2.8	5.1	40%	87%	41	11	5	11
2.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	3.1	4.6	39%	87%	41	12	1	6
1.9	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	3.0	5.0	39%	85%	41	13	8	9
1.5	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.2	0.0	2.3	7.2	40%	82%	43	14	19	21
2.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	3.1	5.1	38%	83%	43	15	9	10
2.4	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	3.6	4.0	36%	85%	43	16	2	2
2.4	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	3.6	4.0	36%	84%	44	17	3	3
2.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.2	0.0	3.9	3.4	35%	84%	45	18	4	1
2.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.2	2.8	34%	85%	45	19	6	5
2.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.1	3.3	34%	83%	45	20	7	4
3.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.3	0.1	0.0	4.4	2.5	33%	84%	46	21	11	7
3.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.3	0.1	0.0	4.5	2.4	32%	83%	47	22	12	8
3.3	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	4.8	1.6	32%	85%	47	23	13	12
3.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	5.1	1.4	30%	83%	48	24	14	13
3.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.4	0.9	30%	83%	49	25	16	15
3.9	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.7	0.0	29%	85%	49	26	20	17
3.9	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.7	0.0	29%	85%	49	27	21	18
3.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.6	0.9	28%	80%	51	28	18	16
0.7	0.0	0.0	0.3	15.6	1.2	0.0	0.1	0.6	0.6	0.1	4.0	5.4	0.0	0.6	0.5	16%	53%	20	29	29	29
0.7	0.0	0.0	0.3	16.2	1.2	0.0	0.1	0.6	0.6	0.1	4.0	5.4	0.0	0.6	0.5	16%	53%	20	30	30	30
0.6	0.0	0.0	0.3	16.2	1.2	0.0	0.1	0.6	0.6	0.1	4.1	5.6	0.0	0.5	0.5	16%	52%	20	31	34	34
0.6	0.0	0.0	0.3	16.2	1.2	0.0	0.1	0.6	0.6	0.1	4.1	5.6	0.0	0.5	0.5	16%	52%	20	32	35	35
0.6	0.0	0.0	0.3	16.2	1.2	0.0	0.1	0.6	0.6	0.1	4.1	5.6	0.0	0.5	0.5	16%	52%	20	33	33	33
0.6	0.0	0.0	0.3	16.2	1.2	0.0	0.1	0.6	0.6	0.1	4.1	5.6	0.0	0.5	0.6	16%	52%	20	34	31	31
0.6	0.0	0.0	0.3	16.2	1.2	0.0	0.1	0.6	0.6	0.1	4.1	5.6	0.0	0.5	0.6	16%	52%	20	35	32	32

A4 39 - C5 Italy - 2065-2090 - Continuous process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

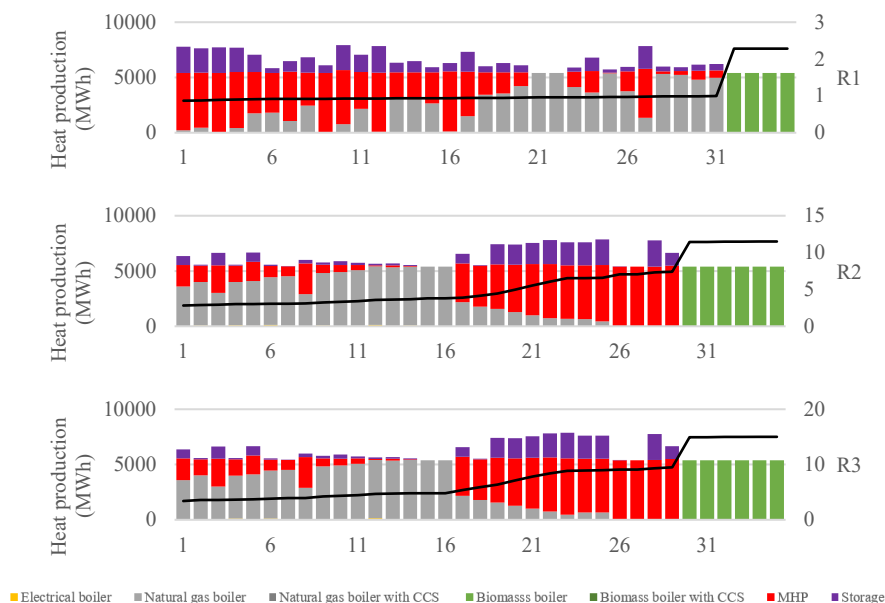
- Dammed hydro
- Geothermal plants
- Offshore wind
- Onshore wind
- Photovoltaic
- River hydro
- Biomass
- Solid
- Petroleum
- Gas
- Nuclear

Optimisation results

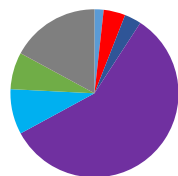
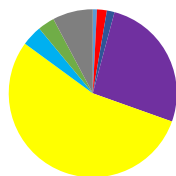
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3			
Sustainable ratio																			14%	46%	24	1	1	34
-14.5	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	0.8	14%	46%	24	2	2	35			
-14.5	0.0	0.0	0.3	15.8	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	0.8	14%	46%	24	3	3	33			
-13.7	0.0	0.0	0.3	15.3	1.1	0.0	0.1	1.0	0.6	0.1	4.1	5.3	0.0	0.7	0.8	15%	47%	23	4	4	32			
-13.7	0.0	0.0	0.3	15.3	1.1	0.0	0.1	1.0	0.6	0.1	4.1	5.3	0.0	0.7	0.8	15%	47%	23	5	5	30			
-13.7	0.0	0.0	0.3	15.3	1.1	0.0	0.1	1.0	0.6	0.1	4.1	5.3	0.0	0.7	0.8	15%	47%	23	6	6	31			
0.6	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	0.7	8.2	52%	86%	55	7	19	15				
0.6	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	0.7	8.2	52%	86%	55	8	20	16				
0.6	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	0.7	8.2	52%	85%	55	9	21	17				
0.8	0.0	0.0	0.3	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.4	0.0	0.9	8.0	50%	84%	55	10	17	14				
1.1	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.4	0.0	1.0	7.4	50%	85%	52	11	10				
1.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.4	0.0	1.1	7.2	49%	85%	52	12	9				
2.1	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	1.2	6.9	48%	86%	53	13	7				
2.0	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	1.2	7.9	46%	81%	58	14	11				
2.6	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	1.4	6.8	45%	83%	55	15	4				
3.1	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	1.6	6.6	44%	82%	55	16	3				
3.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	1.7	6.2	45%	85%	53	17	2				
4.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	2.1	5.9	40%	81%	56	18	1				
6.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	2.8	5.0	36%	80%	58	19	5				
6.6	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	3.0	4.5	35%	79%	57	20	6				
7.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	3.1	4.1	36%	82%	55	21	8				
8.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	3.4	3.4	34%	82%	55	22	13				
7.9	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	3.4	3.9	33%	78%	57	23	12				
8.9	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	3.8	2.9	32%	81%	55	24	18				
9.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.0	3.0	31%	78%	58	25	19				
10.2	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.2	2.3	30%	79%	57	26	20				
10.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.4	2.0	30%	79%	57	27	21				
10.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.4	2.1	29%	77%	58	28	22				
11.3	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.7	1.5	29%	78%	57	29	23				
12.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	5.0	1.3	28%	76%	59	30	24				
12.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	5.0	1.3	28%	76%	59	31	25				
12.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.2	0.7	27%	78%	57	32	26				
13.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.3	0.4	27%	78%	57	33	27				
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.1	27%	79%	56	34	28				
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.1	27%	79%	56	35	29				

A4 40 - C5 Italy - 2015-2040 - Weekly process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

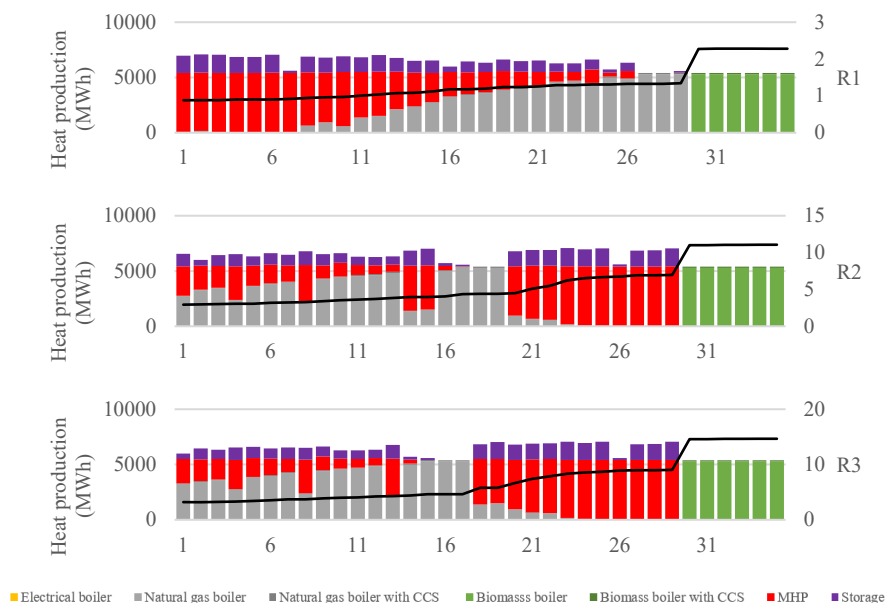
- Dammed hydro
- Geothermal plants
- Offshore wind
- Onshore wind
- Photovoltaic
- River hydro
- Biomass
- Solid
- Petroleum
- Gas
- Nuclear

Optimisation results

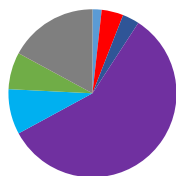
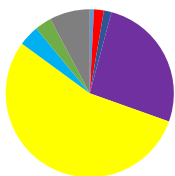
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.4	0.0	0.8	9.2	53%	86%	27	1	27	27
0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.4	0.0	0.8	9.2	53%	86%	27	2	26	26
0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.4	0.0	0.8	9.5	51%	87%	38	3	28	28
0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.8	0.4	0.0	0.8	9.7	50%	84%	37	4	29	29
1.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	3.6	4.3	35%	84%	40	5	3	3
0.4	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.3	0.0	1.2	9.1	47%	84%	40	6	25	23
0.8	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.3	0.0	2.2	7.1	41%	84%	45	7	19	19
1.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.1	3.4	33%	83%	40	8	1	1
2.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.1	29%	84%	21	9	15	15
2.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.8	0.1	29%	84%	21	10	16	16
0.9	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	2.5	6.8	40%	84%	31	11	18	18
0.5	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.3	0.0	1.5	8.7	44%	83%	42	12	22	22
0.7	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.3	0.0	2.0	7.7	41%	83%	43	13	20	20
0.6	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.3	0.0	1.7	8.3	43%	82%	41	14	21	21
1.3	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	3.5	4.8	35%	82%	40	15	8	8
1.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	1.2	29%	83%	38	16	10	10
1.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.5	3.0	32%	83%	31	17	2	2
1.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	5.0	2.1	30%	83%	29	18	7	7
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.8	0.7	28%	82%	35	19	13	13
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.9	0.6	28%	83%	27	20	14	14
1.0	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	2.9	6.4	37%	80%	37	21	17	17
0.5	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.3	0.0	1.4	9.3	45%	84%	51	22	24	25
0.5	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.3	0.0	1.4	9.3	45%	84%	51	23	23	24
1.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.1	0.0	5.3	1.8	29%	82%	32	24	9	9
1.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.9	2.5	30%	83%	31	25	6	6
1.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	4.5	3.6	31%	82%	31	26	4	4
1.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.7	3.3	30%	79%	45	27	5	5
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	5.8	1.1	28%	82%	28	28	12	12
2.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.1	0.0	5.6	1.8	28%	80%	37	29	11	11
0.4	0.0	0.0	0.3	16.6	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	14	30	32	32
0.4	0.0	0.0	0.3	16.6	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	14	31	34	34
0.4	0.0	0.0	0.3	16.6	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	14	32	35	35
0.4	0.0	0.0	0.3	16.6	1.2	0.0	0.1	0.6	0.7	0.1	4.2	5.8	0.0	0.5	0.6	16%	51%	14	33	33	33
0.4	0.0	0.0	0.3	16.5	1.2	0.0	0.1	0.7	0.7	0.1	4.2	5.8	0.0	0.5	0.7	16%	51%	14	34	30	30
0.4	0.0	0.0	0.3	16.5	1.2	0.0	0.1	0.7	0.7	0.1	4.2	5.8	0.0	0.5	0.7	16%	51%	14	35	31	31

A4 41 - C5 Italy - 2040-2065 - Weekly process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

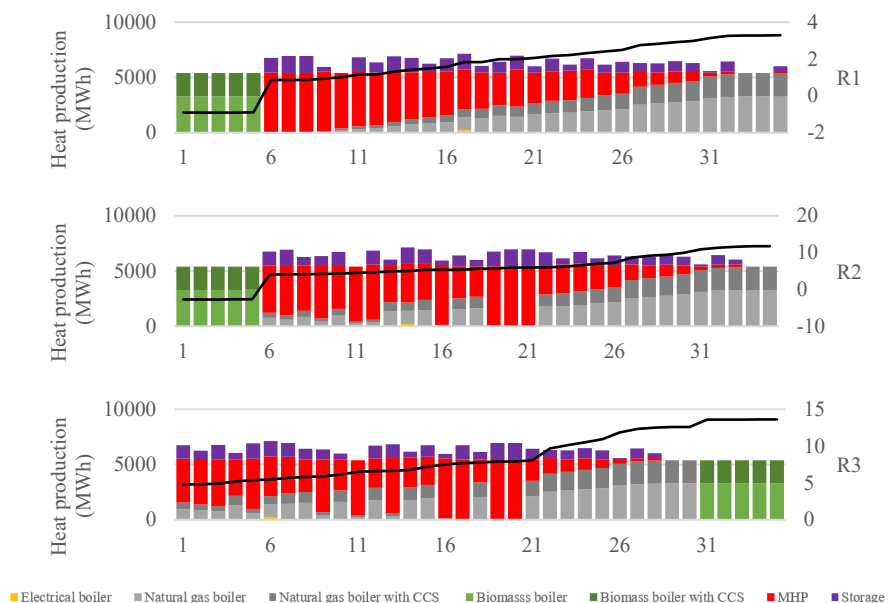
- Dammed hydro
- Onshore wind
- Biomass
- Gas
- Geothermal plants
- Photovoltaic
- Solid
- Nuclear
- Offshore wind
- River hydro
- Petroleum

Optimisation results

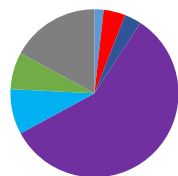
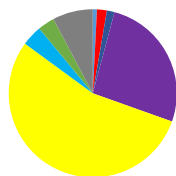
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.3	0.0	0.8	8.8	55%	88%	34	1	24	24
0.5	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.3	0.0	0.8	8.6	54%	88%	35	2	23	23
0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.3	0.0	0.7	8.9	55%	88%	35	3	25	25
0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.3	0.0	0.7	9.1	54%	87%	35	4	28	28
0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.3	0.0	0.7	9.1	54%	87%	35	5	27	27
0.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.3	0.0	0.7	9.2	54%	87%	35	6	29	29
0.4	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.4	0.0	0.8	9.1	53%	86%	36	7	26	26
0.8	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	1.3	7.9	49%	87%	37	8	21	21
1.0	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	1.6	7.3	48%	87%	37	9	20	20
0.8	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.3	0.0	1.3	8.3	48%	85%	38	10	22	22
1.3	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.5	0.3	0.0	2.0	6.7	45%	86%	39	11	14	18
1.4	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	2.1	6.8	43%	85%	40	12	15	19
1.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	2.7	5.6	40%	85%	41	13	8	13
1.9	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	2.9	5.0	39%	86%	41	14	4	8
2.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	3.3	4.4	38%	86%	42	15	1	4
2.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	3.9	3.6	35%	84%	45	16	2	1
2.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	3.9	3.3	35%	85%	45	17	3	2
2.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.1	3.0	34%	84%	45	18	5	3
2.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.3	2.9	33%	83%	47	19	6	5
3.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.3	0.1	0.0	4.5	2.4	32%	84%	47	20	7	6
3.2	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	4.7	2.0	32%	84%	47	21	9	7
3.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	5.0	1.5	31%	83%	48	22	11	10
3.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	5.1	1.3	30%	83%	48	23	12	11
3.3	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	4.9	2.1	30%	81%	49	24	10	9
3.7	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.4	0.6	30%	84%	49	25	16	14
3.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	5.3	1.2	30%	82%	49	26	13	12
3.9	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.7	0.0	29%	85%	49	27	18	16
3.9	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.7	0.0	29%	85%	49	28	19	17
3.9	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	5.7	0.2	29%	84%	50	29	17	15
0.6	0.0	0.0	0.3	16.2	1.2	0.0	0.1	0.6	0.6	0.1	4.1	5.6	0.0	0.5	0.5	16%	52%	20	30	32	32
0.6	0.0	0.0	0.3	16.2	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.5	16%	51%	20	31	34	34
0.6	0.0	0.0	0.3	16.2	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.5	16%	51%	20	32	35	35
0.6	0.0	0.0	0.3	16.2	1.2	0.0	0.1	0.6	0.6	0.1	4.2	5.7	0.0	0.5	0.5	16%	51%	20	33	33	33
0.6	0.0	0.0	0.3	16.2	1.2	0.0	0.1	0.6	0.6	0.1	4.1	5.6	0.0	0.5	0.6	16%	51%	20	34	30	30
0.6	0.0	0.0	0.3	16.2	1.2	0.0	0.1	0.6	0.6	0.1	4.1	5.6	0.0	0.5	0.6	16%	51%	20	35	31	31

A4 42 - C5 Italy - 2065-2090 - Weekly process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

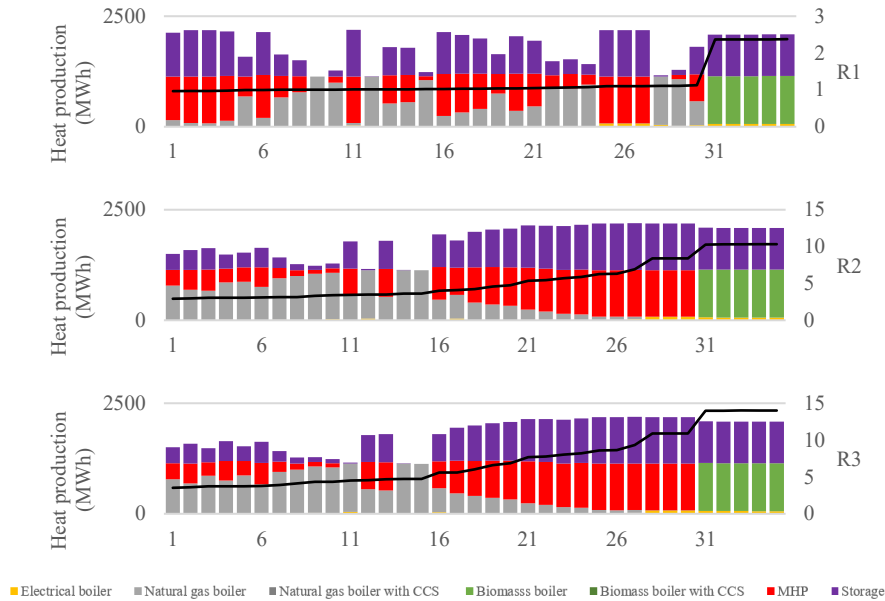
- Dammed hydro
- Geothermal plants
- Offshore wind
- Onshore wind
- Photovoltaic
- River hydro
- Biomass
- Solid
- Petroleum
- Gas
- Nuclear

Optimisation results

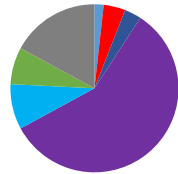
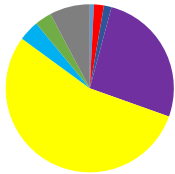
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3	
Sustainable ratio																						
-14.4	0.0	0.0	0.3	15.7	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	0.8	14%	47%	23	1	1	34	
-14.4	0.0	0.0	0.3	15.7	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	0.8	14%	47%	23	2	2	35	
-14.4	0.0	0.0	0.3	15.7	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	0.8	14%	47%	23	3	3	33	
-14.4	0.0	0.0	0.3	15.7	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	0.8	14%	47%	24	4	4	32	
-14.3	0.0	0.0	0.3	15.7	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.4	0.0	0.6	0.8	14%	47%	23	5	5	31	
0.6	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	0.7	7.9	53%	86%	53	6	19	17	
0.6	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	0.7	8.1	53%	86%	54	7	20	19	
0.6	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	0.7	8.1	53%	86%	54	8	21	20	
0.9	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.2	0.1	0.0	0.7	0.4	0.0	0.9	7.8	49%	83%	55	9	16	16	
1.5	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	1.1	7.1	49%	86%	52	10	11	11	
2.0	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	1.2	7.5	46%	82%	56	11	12	13	
2.2	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	1.3	6.9	48%	86%	53	12	9	9	
2.9	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.6	0.3	0.0	1.6	6.6	45%	83%	54	13	7	5	
3.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.3	0.0	1.8	6.1	43%	84%	54	14	6	3	
3.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.3	0.0	1.9	6.0	42%	83%	55	15	8	2	
4.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.3	0.0	2.1	5.8	41%	83%	55	16	10	1	
5.2	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.5	0.2	0.0	2.4	6.3	37%	80%	61	17	14	6	
5.7	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	2.6	4.8	38%	83%	54	18	13	4	
6.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	2.9	4.3	37%	83%	54	19	17	8	
6.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	2.8	5.2	36%	79%	59	20	15	7	
6.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	3.0	4.1	36%	82%	55	21	18	10	
7.4	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	3.2	3.9	35%	81%	56	22	22	12	
7.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	3.3	3.9	34%	80%	56	23	23	14	
8.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	3.4	3.8	33%	79%	57	24	24	15	
8.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	3.6	3.3	33%	81%	56	25	25	18	
8.9	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	3.8	3.4	32%	80%	58	26	26	21	
10.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.4	2.1	30%	78%	57	27	27	22	
10.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.5	1.7	30%	80%	56	28	28	23	
11.2	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.6	1.7	29%	78%	58	29	29	24	
11.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.1	0.0	4.8	1.3	29%	79%	56	30	30	25	
12.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.1	0.6	28%	80%	56	31	31	26	
13.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.3	0.5	27%	77%	58	32	32	27	
13.3	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.1	27%	80%	56	33	34	29	
13.3	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.1	27%	80%	56	34	35	30	
13.2	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.4	0.5	27%	77%	58	35	33	28	

A4 43 - C5 Italy - 2015-2040 - Batch process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

- Dammed hydro
- Onshore wind
- Biomass
- Gas
- Geothermal plants
- Photovoltaic
- Solid
- Nuclear
- Offshore wind
- River hydro
- Petroleum

Optimisation results

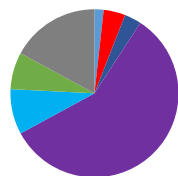
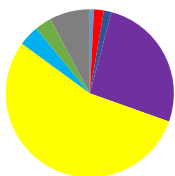
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
0.6	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.4	0.0	1.5	8.4	44%	86%	58	1	23	23
0.5	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.8	0.4	0.0	1.3	8.9	45%	86%	58	2	25	25
0.5	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.8	0.4	0.0	1.3	8.9	45%	86%	58	3	26	26
0.6	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.4	0.0	1.5	8.6	44%	85%	59	4	24	24
1.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	3.9	4.2	33%	85%	61	5	2	2
0.7	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.4	0.0	1.8	8.3	41%	83%	60	6	22	22
1.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	3.8	4.5	34%	84%	51	7	3	6
1.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	4.3	3.6	32%	85%	49	8	1	1
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.0	5.8	0.7	29%	85%	33	9	15	15
1.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.1	0.0	5.2	1.8	30%	85%	46	10	8	8
0.4	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.8	0.4	0.0	1.2	9.6	45%	85%	59	11	27	27
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.8	0.8	29%	85%	33	12	14	14
1.2	0.0	0.0	0.1	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.5	0.2	0.0	3.2	5.7	34%	83%	74	13	13	13
1.2	0.0	0.0	0.1	0.2	0.1	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	3.3	5.6	34%	83%	60	14	11	12
2.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.1	0.0	5.5	1.5	28%	84%	58	15	9	10
0.7	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.4	0.0	2.0	8.3	39%	82%	71	16	21	21
0.9	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.3	0.0	2.4	7.6	37%	81%	64	17	20	20
1.0	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.3	0.0	2.7	7.0	36%	81%	61	18	18	18
1.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	4.2	4.2	32%	81%	57	19	6	4
0.9	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.3	0.0	2.5	7.4	36%	81%	71	20	19	19
1.1	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.3	0.0	2.9	6.6	34%	81%	72	21	16	17
1.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	4.6	3.5	31%	82%	51	22	4	3
1.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	4.7	3.4	29%	80%	77	23	5	5
1.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	5.1	2.9	29%	81%	51	24	7	7
0.4	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.9	0.5	0.0	1.0	11.1	44%	84%	60	25	28	28
0.4	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.9	0.5	0.0	1.0	11.1	44%	84%	60	26	29	29
0.4	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.9	0.5	0.0	1.0	11.1	44%	84%	59	27	30	30
2.1	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	5.7	2.0	28%	83%	37	28	12	11
2.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	5.6	2.4	28%	81%	44	29	10	9
1.2	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.3	0.0	3.4	6.7	34%	80%	57	30	17	16
0.5	0.0	0.0	0.3	15.8	1.2	0.0	0.1	0.7	0.6	0.1	4.2	5.6	0.0	0.7	2.5	16%	51%	20	31	34	34
0.5	0.0	0.0	0.3	15.8	1.2	0.0	0.1	0.7	0.6	0.1	4.2	5.6	0.0	0.7	2.5	16%	51%	20	32	35	35
0.5	0.0	0.0	0.3	15.8	1.2	0.0	0.1	0.7	0.6	0.1	4.2	5.6	0.0	0.7	2.5	16%	51%	20	33	33	33
0.5	0.0	0.0	0.3	15.8	1.2	0.0	0.1	0.7	0.6	0.1	4.2	5.6	0.0	0.7	2.5	16%	51%	21	34	32	32
0.5	0.0	0.0	0.3	15.8	1.2	0.0	0.1	0.7	0.6	0.1	4.2	5.6	0.0	0.7	2.6	16%	51%	21	35	31	31

A4 45 - C5 Italy - 2065-2090 - Batch process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

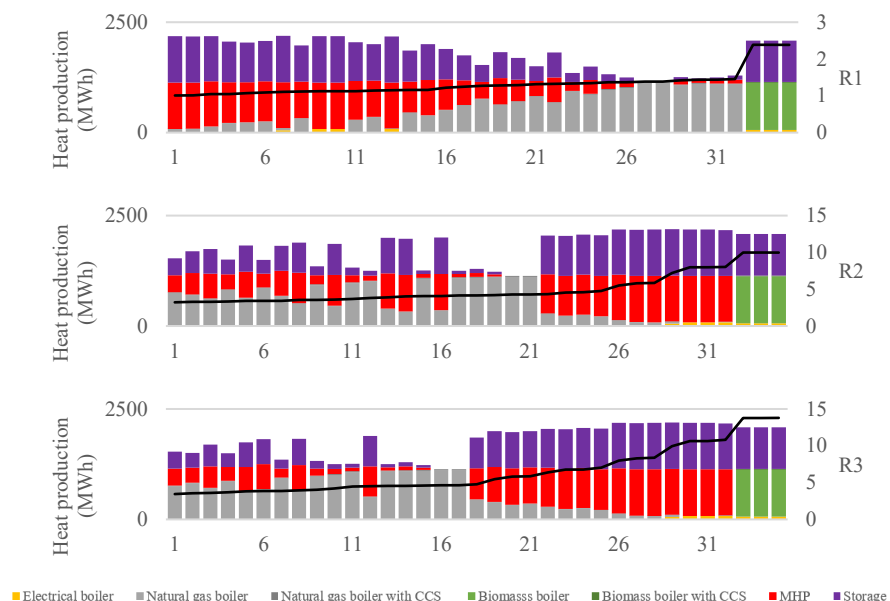
- Dammed hydro
- Onshore wind
- Biomass
- Gas
- Geothermal plants
- Photovoltaic
- Solid
- Nuclear
- Offshore wind
- River hydro
- Petroleum

Optimisation results

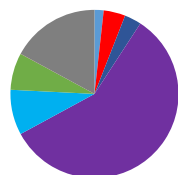
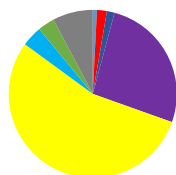
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
Sustainable ratio																					
-13.7	0.0	0.0	0.3	15.2	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.3	0.0	0.8	2.5	14%	46%	36	1	1	33
-13.7	0.0	0.0	0.3	15.3	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.3	0.0	0.8	2.5	14%	46%	36	2	2	34
-13.7	0.0	0.0	0.3	15.3	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.3	0.0	0.8	2.5	14%	46%	36	3	3	35
-13.7	0.0	0.0	0.3	15.2	1.2	0.1	0.1	1.0	0.7	0.1	4.2	5.3	0.0	0.8	2.5	14%	46%	37	4	4	32
-13.7	0.0	0.0	0.3	15.2	1.1	0.1	0.1	1.0	0.7	0.1	4.2	5.3	0.0	0.8	2.5	14%	46%	37	5	5	31
-13.7	0.0	0.0	0.3	15.2	1.1	0.1	0.1	1.0	0.7	0.1	4.2	5.3	0.0	0.8	2.6	14%	46%	37	6	6	30
-13.7	0.0	0.0	0.3	15.2	1.1	0.1	0.1	1.0	0.7	0.1	4.2	5.3	0.0	0.8	2.6	14%	46%	37	7	7	29
0.8	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.8	0.5	0.0	1.0	9.8	42%	81%	97	8	8	19
0.8	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.8	0.5	0.0	1.0	9.8	42%	81%	97	9	9	18
1.6	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.4	0.0	1.2	7.9	43%	82%	89	10	13	12
1.7	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.4	0.0	1.2	7.9	43%	83%	90	11	12	11
1.7	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.4	0.0	1.2	7.8	43%	83%	88	12	11	10
1.2	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.9	0.5	0.0	1.1	10.6	40%	80%	104	13	26	21
2.9	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.3	0.0	1.6	7.1	40%	83%	92	14	8	5
3.0	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.3	0.0	1.6	8.7	37%	81%	112	15	16	13
3.7	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.3	0.0	1.8	8.3	36%	80%	113	16	14	8
4.5	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.3	0.0	2.2	6.5	36%	79%	90	17	9	1
5.0	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.3	0.0	2.3	6.3	35%	80%	101	18	10	2
5.9	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.3	0.0	2.8	6.3	33%	75%	95	19	15	3
6.4	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.5	0.2	0.0	2.9	5.4	33%	78%	91	20	17	4
6.8	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.5	0.2	0.0	3.0	5.1	33%	78%	91	21	18	6
6.9	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.5	0.2	0.0	3.0	5.5	32%	76%	91	22	19	7
7.6	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.5	0.2	0.0	3.4	4.7	31%	77%	91	23	20	9
8.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.2	0.0	3.6	4.1	31%	79%	89	24	25	16
8.4	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.5	0.2	0.0	3.5	5.8	29%	75%	116	25	23	14
8.4	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.5	0.2	0.0	3.6	5.8	28%	75%	116	26	24	15
9.5	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.2	0.0	4.1	3.6	29%	77%	86	27	27	17
10.5	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.4	0.1	0.0	4.3	3.7	27%	72%	96	28	28	20
12.3	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.3	0.1	0.0	5.0	2.1	26%	75%	84	29	29	22
12.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.3	0.0	0.0	5.1	2.4	25%	74%	112	30	30	23
13.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.3	0.1	0.0	5.3	1.6	25%	73%	95	31	31	24
13.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.2	0.0	0.0	5.4	0.7	27%	79%	62	32	34	27
13.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.2	0.0	0.0	5.4	0.7	27%	79%	62	33	35	28
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.2	0.0	0.0	5.4	1.0	27%	78%	64	34	33	25
13.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.2	0.0	0.0	5.4	1.1	26%	76%	76	35	32	26

A4 44 - C5 Italy - 2040-2065 - Batch process

Technology's presence by ranking



Electricity mix



New installed electricity production - total

New installed electricity production - high tension

- Dammed hydro
- Geothermal plants
- Offshore wind
- Onshore wind
- Photovoltaic
- River hydro
- Biomass
- Solid
- Petroleum
- Gas
- Nuclear

Optimisation results

Sustainable ratio																					
Climate change	Ozone depletion	Ionising radiation	Photochemical ozone formation	Particulate matter	Human toxicity, non-cancer	Human toxicity, cancer	Acidification	Eutrophication, freshwater	Eutrophication, marine	Eutrophication, terrestrial	Ecotoxicity, freshwater	Land use	Water use	Resource use, fossils	Resource use, minerals and metals	Exergy efficiency	Energy efficiency	Energy Cost (k€/MWh)	Rank R1	Rank R2	Rank R3
0.7	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.8	0.4	0.0	1.3	8.8	45%	85%	72	1	28	28
0.7	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.4	0.0	1.3	8.7	45%	85%	72	2	27	27
0.9	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.4	0.0	1.5	8.6	43%	83%	72	3	26	26
1.1	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.3	0.0	1.8	7.8	42%	86%	72	4	25	25
1.2	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.4	0.0	1.9	7.6	41%	85%	73	5	23	23
1.2	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.3	0.0	2.0	7.7	40%	83%	74	6	24	24
0.6	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.9	0.5	0.0	1.2	10.3	43%	83%	75	7	29	29
1.5	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.3	0.0	2.4	7.0	39%	83%	71	8	14	20
0.5	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.9	0.5	0.0	1.0	10.9	43%	83%	75	9	31	31
0.5	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.9	0.5	0.0	1.0	10.9	43%	83%	75	10	30	30
1.4	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.7	0.4	0.0	2.2	7.5	37%	82%	85	11	22	22
1.6	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.3	0.0	2.4	7.1	38%	82%	75	12	16	21
0.6	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.4	0.1	0.0	0.9	0.5	0.0	1.1	11.1	43%	83%	78	13	32	32
1.8	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.5	0.3	0.0	2.8	6.2	37%	84%	71	14	10	18
1.7	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.6	0.3	0.0	2.6	6.8	37%	81%	76	15	13	19
2.1	0.0	0.0	0.1	0.3	0.1	0.0	0.0	0.3	0.1	0.0	0.5	0.3	0.0	3.1	6.0	34%	80%	75	16	8	12
2.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.5	0.2	0.0	3.6	5.0	33%	81%	76	17	3	5
2.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	4.2	3.7	32%	84%	71	18	1	1
2.4	0.0	0.0	0.1	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.5	0.2	0.0	3.7	5.3	32%	79%	81	19	5	8
2.7	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.2	0.0	4.0	4.5	32%	80%	79	20	2	3
3.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.4	0.1	0.0	4.5	3.3	30%	82%	77	21	4	2
2.6	0.0	0.0	0.1	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.5	0.2	0.0	3.9	5.0	31%	77%	82	22	7	6
3.4	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.9	2.3	30%	84%	67	23	9	7
3.2	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	4.7	3.1	30%	81%	69	24	6	4
3.5	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.3	0.1	0.0	5.1	2.2	29%	83%	71	25	11	9
3.6	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.1	0.0	5.3	1.7	29%	84%	65	26	12	10
3.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.7	0.7	29%	85%	55	27	20	16
3.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.7	0.7	29%	85%	55	28	21	17
3.8	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.1	0.0	5.6	1.4	28%	81%	64	29	15	11
3.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	5.7	1.2	27%	81%	82	30	19	15
3.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.1	0.0	5.7	1.3	26%	81%	96	31	17	13
3.9	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.1	0.0	5.7	1.4	27%	79%	86	32	18	14
0.7	0.0	0.0	0.3	15.6	1.2	0.0	0.1	0.7	0.6	0.1	4.1	5.5	0.0	0.7	2.5	16%	51%	30	33	34	34
0.7	0.0	0.0	0.3	15.6	1.2	0.0	0.1	0.7	0.6	0.1	4.1	5.5	0.0	0.7	2.5	16%	51%	30	34	35	35
0.7	0.0	0.0	0.3	15.6	1.2	0.0	0.1	0.7	0.6	0.1	4.1	5.5	0.0	0.7	2.5	16%	51%	30	35	33	33

FOLIO ADMINISTRATIF

THESE DE L'INSA LYON, MEMBRE DE L'UNIVERSITE DE LYON

NOM : JOVET

DATE de SOUTENANCE : 13/10/2023

Prénoms : Yoann

TITRE : Sustainability of industrial heat decarbonisation strategies through 4E (energy, exergy, economic and environmental) optimisation

NATURE : Doctorat

Numéro d'ordre : AAAAINSALXXXX

Ecole doctorale : MEGA

Spécialité : Energétique, thermique, combustion

RESUME : Cette recherche a pour but d'évaluer la performance annuelle globale de différentes solutions de production de chaleur industrielle, par une méthode multicritère 4E (énergie, exergie, économie et environnement). Au-delà de cette évaluation, le travail proposé porte également sur le développement d'une méthode originale permettant de prendre en compte les limites planétaires dans la prise de décision visant à remplacer un moyen de production (généralement chaudières à gaz) par une solution moins carbonée.

L'atteinte de cet objectif a conduit au développement d'un modèle d'optimisation génétique multi-objectif original combinant critères technico-économiques et environnementaux, basés sur une approche par Analyse de Cycle de Vie (ACV). Afin d'être en mesure d'évaluer les transformations à l'échelle d'un secteur industriel, différents pays européens sont considérés sur trois périodes comprises entre 2015 et 2090 pour intégrer les évolutions de contraintes sur les émissions de GES et la disponibilité de technologies de capture et stockage de carbone (CCS). Une approche par regroupement (clustering) est proposée pour réduire l'étude à 100 pas de temps représentatifs de l'année afin de limiter le temps de calcul.

Une étude de sensibilité a été menée pour classer l'ensemble des solutions non-dominées trouvées par l'algorithme, aucune de ces solutions n'étant soutenable sur l'ensemble des critères environnementaux. Pour ce faire, trois approches d'évaluation sont proposées : R1 (Référence ACV de pondérations), R2 (pénalisation linéaire du dépassement des limites planétaires), et R3 (pénalisation exponentielle de ces limites et pénalisation du CCS).

Pour le classement R1, la technologie la plus performante est la pompe à chaleur, complétée par la chaudière biomasse quand le CCS devient suffisamment développé. Pour les méthodes R2 et R3, on observe des combinaisons de technologies qui dépendent du mix électrique : combinaison pompe à chaleur et chaudière gaz pour les mix majoritairement renouvelables ou chaudière biomasse pour les mix basés sur le nucléaire.

MOTS-CLÉS : Optimisation multi-objectif ; Chaleur industrielle ; Limites planétaires ; Soutenabilité ; Analyse environnementale

Laboratoire (s) de recherche : CETHIL

Directeur de thèse: Marc CLAUSSE

Président de jury :

Composition du jury :

Natacha GONDRAN, Professeur, Ecole Nationale Supérieure des Mines de Saint-Etienne

Vincent LEMORT, Professeur, Université de Liège

Anne PRIEUR-VERNAT, Dr. Eng., ENGIE

Martin PATEL, Professeur, Université de Genève

Alexis LAURENT, Associate professor, DTU

Frederic LEFEVRE, Professeur, INSA Lyon

Marc CLAUSSE, Professeur, INSA Lyon