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Assessing the relevance of energy indicators as sustainability screening metrics for the decarbonisation of industrial heat through electrification

Yoann JOVET^a, Frédéric LEFEVRE^a, Alexis LAURENT^b and Marc CLAUSSE^{a,*}

^a INSA Lyon, CNRS, CETHIL, UMR5008, 69621 Villeurbanne, France.

^b Section for Quantitative Sustainability Assessment, Department of Environmental and Resource Engineering, Technical University of Denmark (DTU), 2800 Kgs. Lyngby, Denmark.

*marc.clausse@insa-lyon.fr

Key words

Decarbonisation; Environmental assessment; Sustainability; Exergy indicator; Power generation; Industrial heat

Abstract

Power generation faces the challenge of reducing its greenhouse gas emissions without shifting the burden to other environmental impacts. Energy and exergy-based environmental indicators have proven to some extent to be effective environmental proxies for the current energy mix but the robustness of this approach has barely been discussed in the frame of energy transition scenarios. Hence, the aim of this study is to analyse their relevance in the context of decarbonisation of industrial heat through electrification. To this end, we investigate the potential relationships between two different energy indicators and environmental indicators using life cycle assessment (Ecoinvent database, 16 environmental indicators, 2 energy indicators) for 28 pairs of energy sources shifting for the production of 1 kWh of electricity. For the reference French case, no similar trends across all sources of energy, for given environmental and energy indicators are found neither between all environmental and energy indicators. The extension to other cases is discussed, leading to the same conclusion. These results highlight the need for a multi-criteria assessment to evaluate the impacts of industrial heat in a context of intensive process electrification, which will be country dependent because of the various strategies in achieving net-zero electricity mix.

Nomenclature

Abbreviations

CC	Climate change	LCA	Life cycle analyse
CED	Cumulative energy demand	LCI	Life cycle inventory
CExD	Cumulative exergy demand	MHP	Mechanical heat pump
EF	Environmental footprint	LCIA	Life Cycle Impact Assessment
GHG	Greenhouse gases	EF	Environmental Footprint
IQR	Interquartile range		

Variables & Parameters

Rc	Relative change	I_i or I_j	Impact category
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1. 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, this sector is often overlooked in comparison with the mobility and building sectors, as highlighted by Sorknæs et al. [3]. Furthermore, according to the same authors, most of the reported studies do not provide sufficient indications on this transformation, with for instance evaluated scenarios that are not easily reproducible. In consequence, the overall environmental impact due to the change in the electricity generation resulting from increased electricity demand is often not considered, the focus being on the technology (e.g. refrigerant choice for industrial heat pumps in [4]), the change in demand [5], [6], or on techno-economic criterions (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, a full environmental assessment is required to have a fair picture of the impacts and hence make informed decision.

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 [10], Power-to-Methane [11], waste recovery in CHP plant [12].

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. [11]. 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 [13]–[15]. Hence, methods for simplifying LCA analyses have been widely proposed over the past 20 years [14], [16], [17]. From a systematic review of the LCA simplification state of the art, Beemsterboe et al. [14] identified five simplifying strategies: exclusion, inventory data substitution, qualitative expert judgment, standardisation and automation. For each of these strategies, the authors outline the main concerns linked to these simplifications. Simplification methods based on the exclusion of certain impact categories are among the most common approaches [16], [17]. Many studies have examined the effectiveness of a limited number of indicators to best reflect the environmental impact of a product or a process [13], [15], [18]–[21]. The most radical of these approaches consists in adopting only one environmental indicator such as the carbon footprint [15], [22] or an energy indicator like Cumulative Energy Demand (CED) or Cumulative Exergy Demand (CExD) [18], [19], [23], [24]. Energy and exergy indicators are often used as sustainability indicators because of their ability to identify, quantify, and comprehend thermodynamic inefficiencies within a particular system or process as formulated by Soltanian et al. [25] for municipal solid waste treatment systems and also highlighted in the review paper of Shahbeig et al. [26] for biomass gasification processes.

Using cumulative energy demand as a single proxy for environmental performance was the title of one of the first papers related to LCA simplification [18], 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. [18], 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 mechanical heat pumps (MHP) to raise the temperature level to the process temperature [27]. For the same amount of heat generated, these two technologies have very different impacts in terms of electricity consumption, but also in terms of environmental footprint of the system itself, such as the use of refrigerants in MHP. Hence, analysis of the energy and 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. [28].

Therefore, the present paper questions the use of cumulative energy/exergy demand as a single proxy for environmental performance in the frame of the electrification of the industrial heat production. Compared with similar works [18], [19], [23], [24] described above, which were clearly part of the current energy mix, the originality of this work (Table 1) is that it focuses on the transition from fossil to decarbonized energies. The large-scale deployment of new power generation facilities will radically shift the environmental footprint of an electricity mix, depending on the roadmap chosen by the country's political decision-makers. This contrasts with the reference contributions discussed in the introduction, as they were mainly focused on an energy mix whose environmental footprint was predominantly influenced by fossil fuels.

Table 1 – Scope of this study in relation to reference studies on environmental assessment based on exergy and energy indicators

Indicator compared to environmental impacts	Energy mix	Date	Source
Cumulative Fossil Energy Demand	Current mix	2006	Huijbregts et al.[18]
Cumulative Exergy Demand	Current mix	2007	Bösch et al. [24]
Cumulative Energy Demand	Current mix	2010	Huijbregts et al. [19]
Cumulative Energy Demand Non-renewable cumulative energy demand Fossil energy use	Current mix	2016	Aridsson et Svanström [23]
Cumulative Energy Demand Cumulative Exergy Demand	Transition to decarbonized electricity sources	2023	Present work

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 examined to determine whether the difference in value between their energy indicators can be correlated to the resulting difference in their LCA's environmental indicators. The existence of two possible correlations is questioned:

- Do similar trends exist across all sources of energy, for given environmental and energy indicators?
- Do 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 and a sensitivity analysis is carried out to assess the impact of the choice of this particular country on the conclusions.

2. Methodology

The approach generally used to assess correlations between several indicators, as in the studies by Huijbregts et al. [18], is to plot the impacts of two indicators for a large number of products and observe graphically the level of correlation between them. In this paper, another evaluation framework is proposed for assessing correlation between different impact categories when shifting from one energy to another.

2.1. Evaluation framework developed to assess correlation between indicators

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 both the environmental impact I_i and the energy indicator impact I_j . The impact I for energy A and environmental indicator 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 ΔI_i as defined in equation (1) for each indicator i , which is dimensional, or the relative change Rc_i presented in equation (2), which is non dimensional.

$$\Delta I_i(A; B) = I_i(A) - I_i(B) \quad (1)$$

$$Rc_i(A; B) = \frac{\Delta I_i(A; B)}{\text{ref}(I_i)} \quad (2)$$

Where $\text{ref}(I_i)$ is the reference value usually taken at $I_i(A)$. In the frame of this assessment, as the aim is to compare indicators with different dimensions, 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 when switching from energy source A to energy source B to produce 1 kWh of electricity is expressed as:

$$Rc_i(A; B) = \frac{\Delta I_i(A; B)}{I_{i \max} - I_{i \min}} = \frac{I_i(A) - I_i(B)}{I_{i \max} - I_{i \min}} \quad (3)$$

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 influence on indicator i . On the contrary, a value close to 1 indicates a significant influence for this indicator.

The 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 :

$$Rc_{i/j}(A; B) = \frac{Rc_i(A; B)}{Rc_j(A; B)} \quad (4)$$

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 and 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. On the other hand, if $Rc_{i/j}(A; B)$ is negative, changing the source of energy production leads to an improvement in one of the criteria while the other deteriorates. 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 :

$$Rc_{i/j}(A; B) = Rc_{i/j}(B; A) = \frac{1}{Rc_{j/i}(A; B)} \quad (5)$$

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 $0 < Rc_{i/j} < 1$, the relative improvement (degradation) of indicator i is lower than the relative improvement (degradation) of indicator j and the opposite is true if $Rc_{i/j} > 1$.

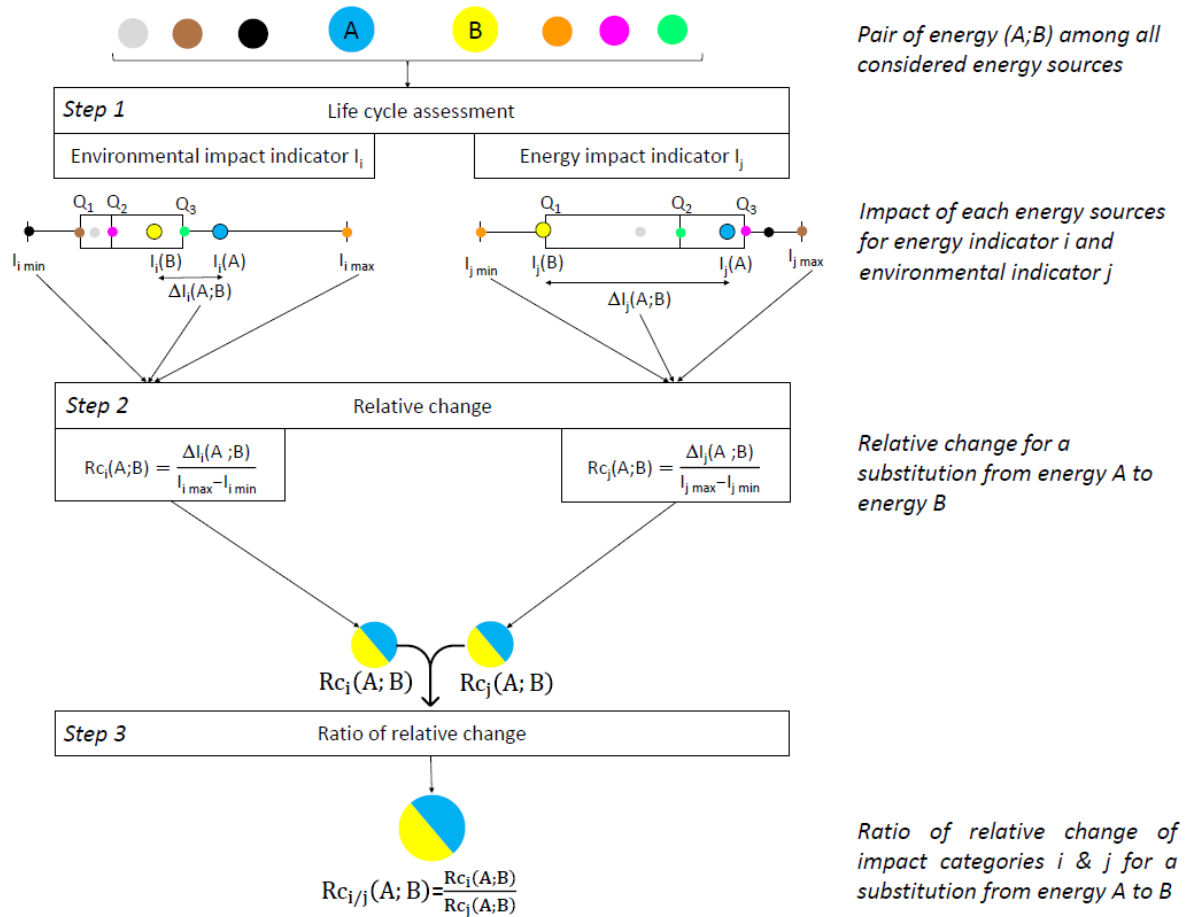


Fig. 1 - Evaluation framework developed to assess the correlation between the environmental impact and the energy indicator for two energy sources.

2.2. Life cycle assessment model description

The life cycle assessment follows the ISO 14040:2006 [29] and ISO 14044:2006 standards (ISO, 2006) [30]. This methodology is proven for studying the sustainability of different solutions, as it enables to assess the contribution of each of them for a large number of impacts for which it is also possible to define a sustainable level. One of the best-known examples is climate change, with reduction targets based on GHG emissions as assessed by the IPCC [31].

2.2.1. Goal and scope definition

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 is defined as the average generation of 1 kWh of electricity. The data are based on the average performance of the country, for all countries and/or regions available in the Ecoinvent database [32]; these country and regions are presented in supplementary information SI2. The following energy sources are considered: coal, deep geothermal, gas combined cycle, hydro river, nuclear, solar, wind 1-3 MW and wood. For the sake of simplicity, it was chosen to exclude 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 the International Energy Agency [33]) and concentrated solar power being seen as still marginal in the future in the European based mix [34].

The analysed system considers a full life cycle assessment, encompassing the extraction of the necessary resources, the construction of the power station, the construction of the plant and the commissioning of the equipment (electricity generation) and its final decommissioning and disposal as described in Fig. 2.

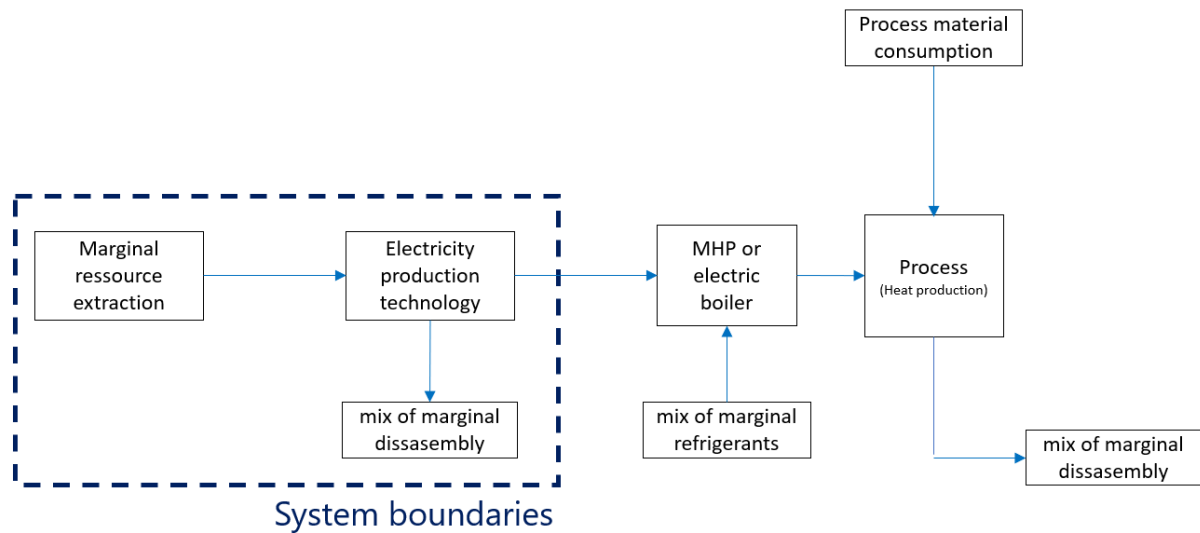


Fig. 2 – Life cycle assessment system boundaries of electricity production for industrial heat production, the elements inside the dotted box are considered in the study.

2.2.2. Life cycle inventory modelling and impact assessment

The study adopts a consequential modelling, with a view to investigating 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 [23] (version v.3.7.1) are used, with as much specificity as possible for the energy supply systems of a country, where available. The data used for the conversion of primary energy to electricity are taken from the same database. 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 16 impact categories, presented in Table A in SI1. These 16 environmental indicators are compared with two energy indicators: cumulative energy demand (CED) and cumulative exergy demand (CExD). This study focuses on electricity generation from different primary energy sources (fossil fuel, renewable energies, nuclear).

3. Results and discussion

The results are presented for France as a case study, to enable analysis and present trends. The study is then generalized by a global assessment based on all the data available in the Ecoinvent database, to check whether it is also possible to extend the conclusions to all countries.

3.1. Impact of electricity sources on energy and environment indicators

This section presents the relative change (R_c) calculated for each pair of energy and all 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 presented in equations (6) and (7). By switching from gas to wind power, relative change for cumulative exergy demand falls by 38%, while climate change impacts fall by 49%.

$$R_{C_{CExD}} \left(\frac{\text{gas}}{\text{wind}} \right) = \frac{9.2 - 4.3}{14.3 - 1.3} = 38\% \quad (6)$$

$$R_{c_{CC}} \left(\frac{\text{gas}}{\text{wind}} \right) = \frac{0.55 - 0.024}{1.079 - 0.009} = 49\% \quad (7)$$

The results for each source of energy are reported in Table 2. 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 2 – Relative change for the different combinations of energy; (a) Cumulative exergy demand (CexD), and (b) Climate change (CC) indicators. A negative value implies an increase in the considered impact indicators compared to the reference energy (A).

(a)

CExD	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)

CC	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 (Rc) calculated for each environmental and energy indicator and for the 28 energy pairs studied in this paper. An energy pair, for example coal/hydro, is used to compare the impacts associated with the production of 1 kWh of electricity with these two energy sources based on their average impact in France. For each of the 28 pairs, the relative changes for the 16 environmental impact categories and the CED and CExD indicators are presented using a boxplot; furthermore, the relative changes (Rc) of the CED and CExD indicators are highlighted in blue and red respectively. When the size of the boxplot is small, it is possible to conclude that there is a strong correlation between all the indicators for these 2 energies, as for example for the wind/hydro pair.

This figure provides two major insights: i) it indicates whether or not the distance between the relative changes is significant in all environmental and energy categories and ii) it shows whether this change leads to environmental trade-offs, i.e. positive values indicate benefits, while negative values represent negative impacts. For the first insight i), a smaller boxplot height indicates a more closely related set of 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 larger the boxplot, the more important the counterparties. 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.

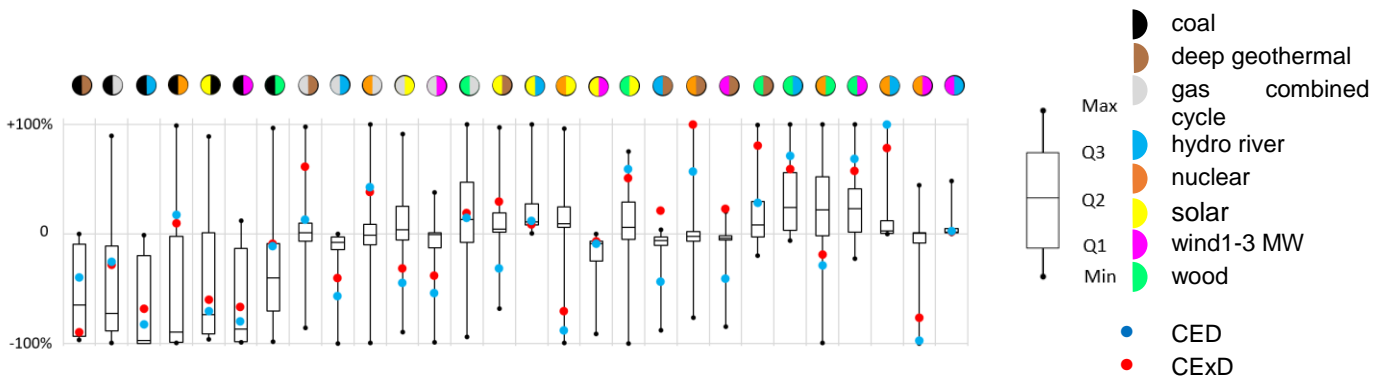


Fig. 3 – Relative change (Rc_i) of the 28 energy pairs. The color on the left of the bicolor circle is the reference energy A and the color on the right the alternative energy B. Negative values imply a reduction of impact after the energy change for the impact category. The evolution of the energy indicators 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. For the remainder of this study, only the results for the CExD indicator are presented, as the trends are similar for the CED indicator.

3.2. Correlation between exergy and environmental impact indicators

To assess the existence of a correlation between the exergy indicator and the 16 environmental indicators, the ratio of relative change (Eq. 2) is used. Using the example of the wind/gas pair, the result for the climate change indicator and for the cumulative exergy demand is presented in equation (8).

$$Rc_{CC/CExD} \left(\frac{\text{gas}}{\text{wind}} \right) = \frac{49\%}{38\%} = 1.31 \quad (8)$$

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 3 show both negative and positive values. Negative values indicate that an improvement in one indicator leads to a deterioration in the other. Out of 28 possible pairs of energy, 11 are negative and 17 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 3 - Ratio of the relative change between the climate change indicator and cumulative exergy demand for studied energy sources. Positive values are identified in red and negative values are identified in blue.

$Rc_{CC/CExD}(A; B)$	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	

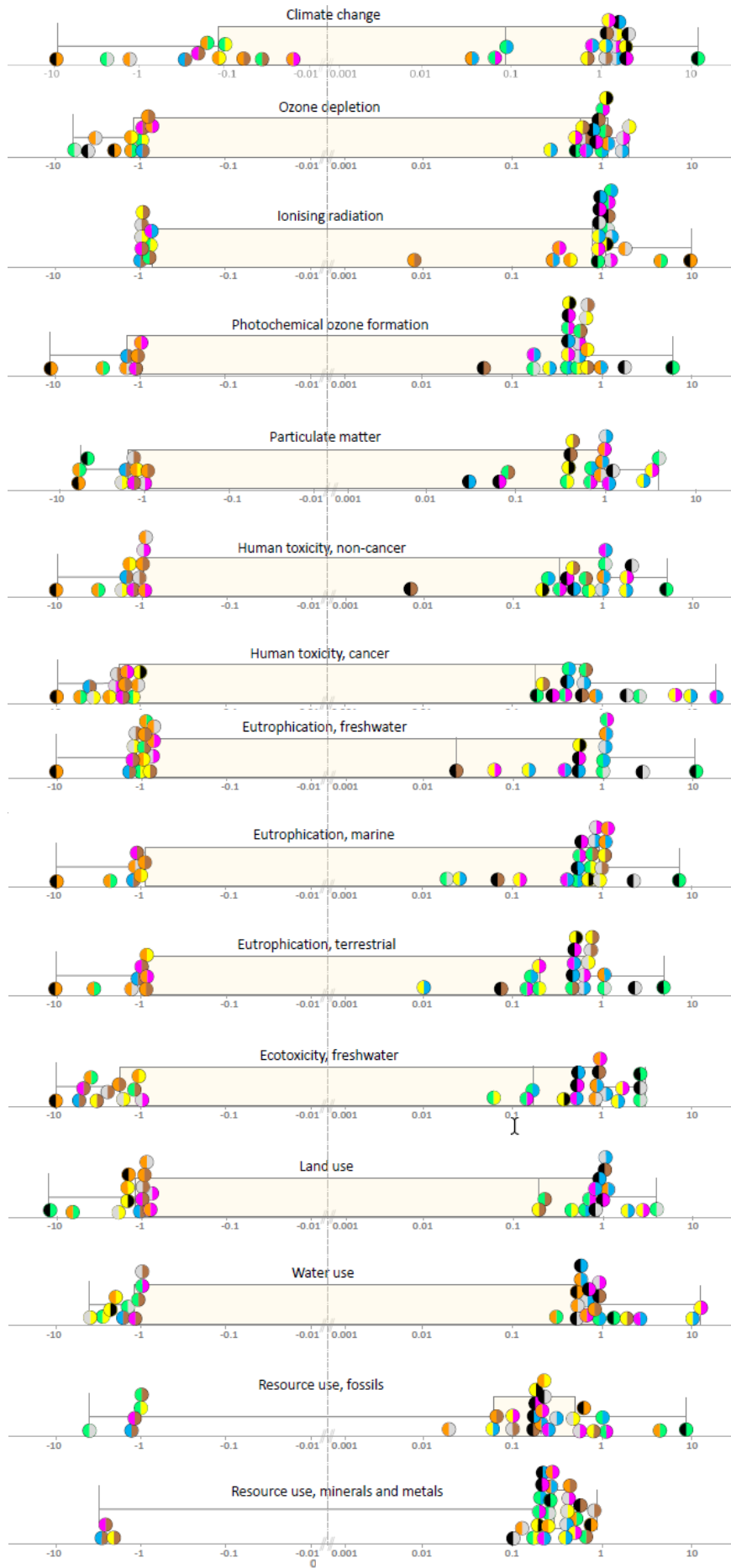
The ratios vary from -10 for pair coal/nuclear to +11 for pair coal/wood. Even if some of the values are relatively close such as coal/geothermal or gas/geothermal, no general correlation can be found due to the disparity of values across the different energy sources. This shows that the CExD indicator 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.

3.2.1. Classification of each ratio of relative change by environmental impact category

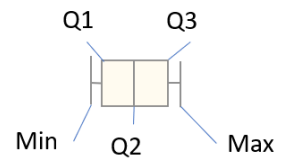
The ratios of relative change for CExD and the 16 environmental impacts are reported in Fig.4. The more pairs with a positive value, the more the CExD can be used as an indication of the direction of change of the environmental impact.

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. [18], [19]. The scale width – from 0.1 (resource consumption metals and minerals) to 2.5 (freshwater 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., [35]), 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.



- coal
- deep geothermal
- gas combined cycle
- hydro river
- nuclear
- solar
- wind1-3 MW
- wood



- Q1: 1st quartile
- Q2: median
- Q3: 3rd quartile

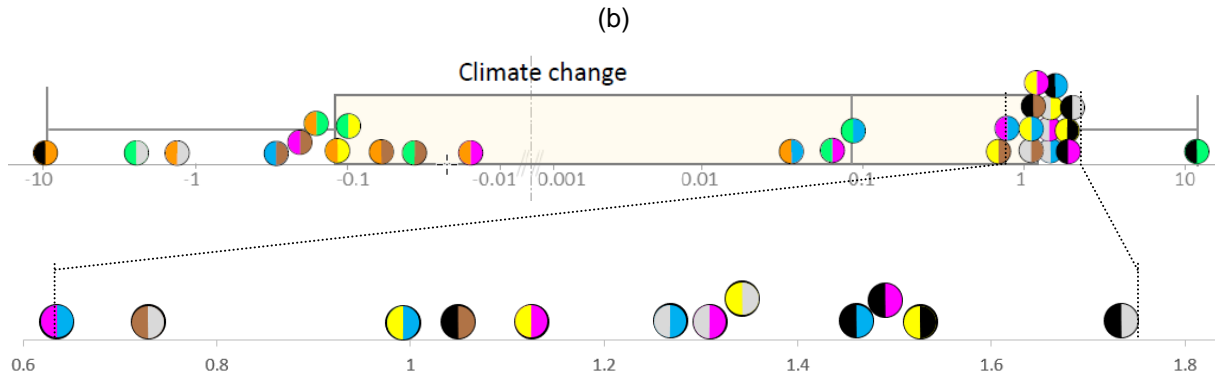


Fig. 4 – (a) Ratios of relative change for CExD and the 16 environmental impacts (log scale); for each pair (bicolor circle), the left colour represents the energy with the maximal CExD, (b) focus on the cluster around 1 for climate change indicator. For positive values, the energy on the left has the highest environmental impact, while for negative values the energy with the highest 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 (b) 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 certain groups of energy pairs for each impact category, these groups differ from one impact category to another, so there is no general trend.

3.2.2. 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.

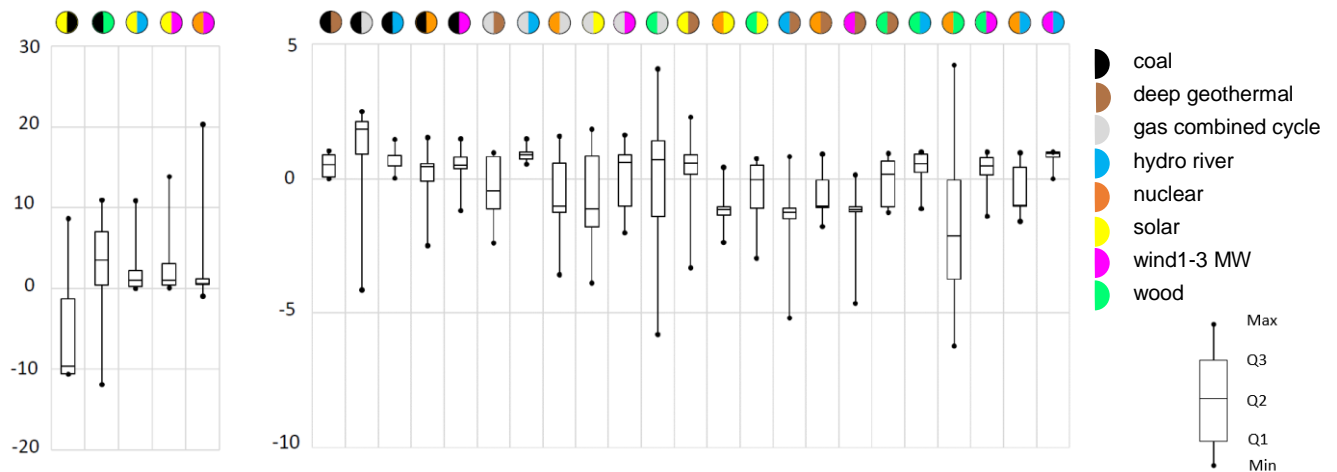


Fig. 5 – Ratios of relative change with Cumulative exergy demand reference and the 16 environmental indicators. The color on the left of the bicolor circle is the energy with the highest Cumulative exergy demand.

From the previous results, no general trends are observed between the CED or CExD indicators and the 16 environmental impact categories when shifting from one source of energy to another for electricity production in France.

For all studied shifting pairs, the larger the observed differences in the ratio of relative changes, the less the CExD indicator is representative of the environmental impacts. Energy pairs such as coal/deep geothermal (●), coal/hydro (●), gas/hydro (●) or wind/hydro (●) show very similar behaviour for all impact categories and thus some correlation with the CExD proxy. For other energy pairs, it is necessary to be more cautious in the use of such a proxy as there are significant differences between several energy sources. It is therefore preferable to carry out a 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. [18] remain valid for the energy pair gas/coal for which the pattern presents 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 study shows that the CExD indicator remains a good proxy for "resource use, fossil" indicator when adding decarbonized production sources. For this indicator, depending on the countries, only 2 to 6 energy sources do not evolve in the same direction as CExD, and this is the case for 5 in the French case. However, this is less valid for climate change, with 6 to 12 pairs that do not evolve in the same direction and 11 for the French case.

3.3. Generalising the French case to a global scale

A global approach is used to check the consistency of the results obtained for the French case with the data available for other available national countries. Indeed, the environmental and energy characteristics of each energy source [36] may vary from one country to another. For example, the energy potential of energy sources can differ greatly, particularly for coal and most renewable energies. The efficiency of the conversion systems used to produce 1 kWh of electricity may also be different, for example in the case of coal. As an example, Figure 6 shows the wide disparity of the climate change indicator for fossil fuels.

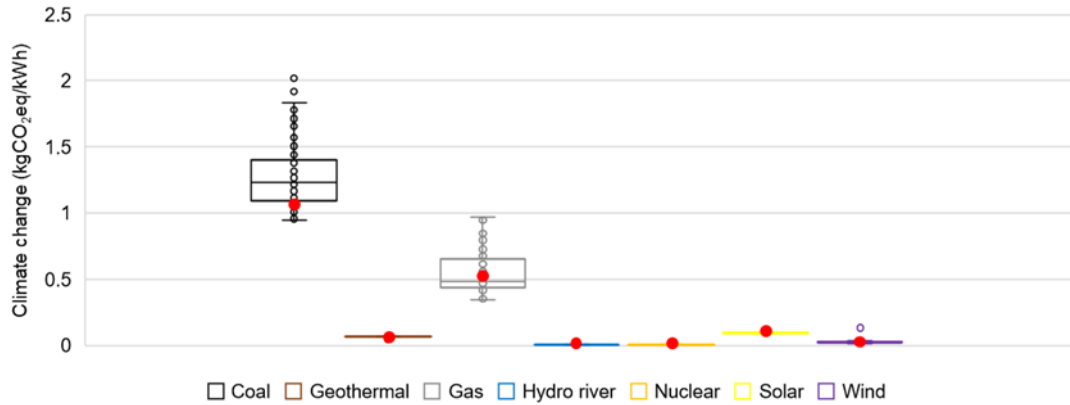


Fig. 6 – Distribution of climate change impact for the production of 1 kWh of electricity with different energy sources for all national data in the Ecoinvent database. The red dots are for the French case.

To generalize the approach obtained for France, the ratio of relative change is calculated for all the data available in the Ecoinvent database. The results for the cases of climate change and CExD are presented for all energy pairs in Fig. 7, showing the dispersion of this indicator between available countries. Three types of results can be observed: (i) energy pairs for which the country has no impact, such as gas/hydro (●), nuclear/gas (●), gas/wind (●), (ii) energy pairs with a significant variation in the relative change but always with the same sign, indicating that the trend is the same for all countries, such as solar/deep geothermal (●), solar/hydro (●), or nuclear/solar (●), (iii) energy pairs that are either positive or negative depending on the country, such as coal/gas (●) or coal/nuclear (●). This last category stems from both CExD indicators that are very close and may be better for one or other energy source depending on the country. This is a limitation of the $Rc_{i/j}$ indicator when comparing two energy sources that are very close one to the other. Anyhow, Fig. 7 shows that there is no correlation between climate change and CExD, when shifting from one energy to the other with 11 energy pairs systematically having negative values, 15 pairs systematically positive, and 2 pairs that can have either positive or negative values depending on the country.

Detailed results for the other impact categories and all energy pairs are provided in supplementary information SI2. The results vary among the 16 different categories, but the overall trends remain similar with a minimum of 4 couples with negative values and 8 with positive values. Consequently, this study carried out on a global scale, confirms the analyses and conclusions obtained for France.

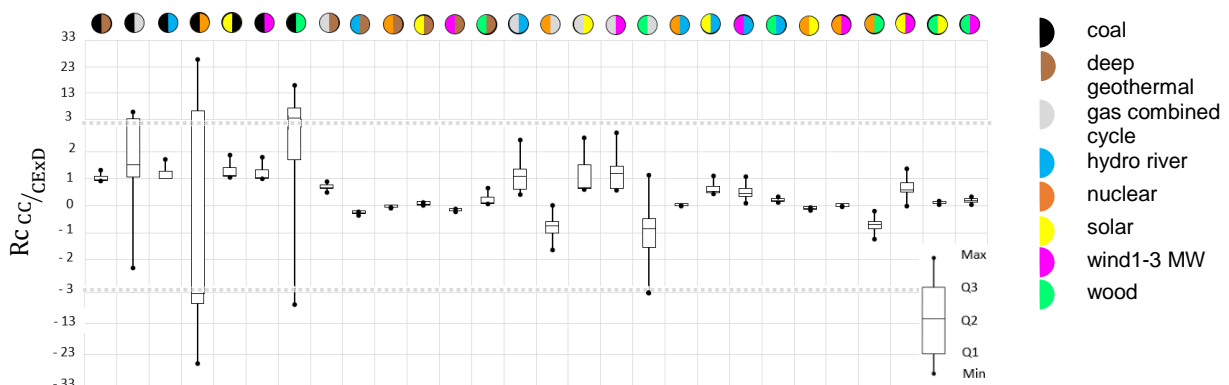


Fig. 7 - Ratios of relative change for climate change and cumulative exergy demand for all energy pairs studied and for all available data in Ecoinvent database (140 countries and regions).

3.4. Limitations of this work and future prospects

This work presents several limitations, such as considering average values for the different sources of electricity production or using a single indicator for exergy, while others are available. Furthermore, the ratio of relative change comparing an environmental indicator to the CExD indicator may lead to a very high sensitivity when two sources of energy have very close CExD. Nevertheless, this study points out that using the CExD indicator as sustainability screening metrics in the context of decarbonisation of industrial heat through electrification is generally not relevant, while this indicator is generally relevant in the current energy context, based mainly on fossil fuels on a global scale. This is due to the fact that industrial heat accounts for two-thirds of the total industrial energy, weighing therefore heavily on the final impact. In the context of energy transition, each country will decarbonise its electricity production using a variety of energy sources, depending on its own resources, that may have very different environmental impacts. As a consequence, the environmental impacts of the industrial heat will therefore vary greatly from one country to another, for the same amount of heat required to run the factories. This was highlighted in [18] for the case of nuclear power concerning the indicator "ionising radiation", which was thus not included in the study. Therefore, energy transition will lead to a shift of the impact that is today mainly climate change to other impact categories. It is then necessary to consider these new issues when thinking about the resulting transformation of the electricity system.

This work emphasizes the necessity of maintaining a multi-criteria approach, as proposed in 4E studies, to assess sustainability of industrial heat production. The exergy analysis is at the core of these methodology and is particularly appropriate to track the thermodynamic inefficiencies within a particular system or a process, and therefore reduce their footprint. The review paper of Soltanian et al. [25] on the exergetic analysis of municipal solid waste treatment systems and the one of Shahbeig et al. [36] on the exergetic analysis of biomass gasification processes clearly shows the potential and interest of these studies. However, when different sources of energies are available to decarbonize a process, including renewable and nuclear energies, it is necessary to consider all the environmental impacts in a multicriteria energy and environmental analysis to assess the sustainability of this transformation. The optimization process may lead to solutions that deteriorate the CExD indicator while simultaneously improving other environmental indicators.

Finally, it is also important to highlight that optimizing a process, like the industrial heat production, on both environmental and energy criteria does not necessarily lead to a sustainable solution. To this end, it is also necessary to integrate sustainability limits, in the environmental analysis. Different methods evaluate these sustainable limits such as the planetary boundaries, as proposed by the Stockholm Resilience Center [37], [38], the methods developed by Sala et al. [39] from Joint Research Center of European commission or from Vargas et al. [40]. The development and implementation of this type of multi-objective approach can help decision-making and the development of strategies but raises several challenges. The first of them is a methodological developments to define the "right to impact" of each sector as studied by Ryberg et al. [41]. This assessment may be controversial and requires collaboration between different technical, sociological, and even political sciences. It is also possible to identify possible synergies between different sectors, by identifying the strengths and weaknesses of each process from an environmental point of view, as in the work of Jovet et al [28]. This requires the identification of possible ways of distributing the various environmental impacts across the different sectors of human activity so as not to exceed sustainable limits.

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 includes enough information to make informed decision as it is the case for shifting between fossil fuels. For each possible shift in the means of electricity production, the proposed approach consists of estimating the relative change for each LCA indicator and their ratio.

For 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 of 100% is found for the exergy demand. As for ratio in relative changes, a large number of impact categories evolve in a non-proportional manner and sometimes even in opposite directions, i.e. a reduction in the impact of one category leads to an increase in that of another. Nevertheless, in some limited cases, a similar trend is identified (for coal/gas shifting for example), which confirms the results obtained in previous works but in other contexts (e.g. [18]). 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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