Environmental assessment of electrification of food industry for Denmark and France

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1. Abstract

To align energy demand with greenhouse gas emission reduction targets set by the COP21 or the EU Green Deal, electrification is one of the most promising options. Most studies on the electrification of industrial processes focus on energy and greenhouse gas emissions, while the other potential environmental impacts have often been overlooked. Hence, the proposed work aims to highlight the pros and cons of shifting to electricity thanks to a Life Cycle Assessment approach. Industrial heat productions for the Danish and French food industries are used as case study. The reference consists in heat production based on fossil fuel (i.e. gas and oil boilers mainly) while electrical boilers, mechanical heat pumps or mechanical steam recompression solutions are considered for shift to electricity. Different electrification scenarios are considered, including levels of electrification and technological development. To identify the most relevant environmental impacts, an assessment of the food industry sectors is performed. Different scenarios are evaluated according to the selected impact categories, allowing to assess the environmental trade-offs. Results show that an electrification of the food industry enables to meet a sustainable level for climate change in France and Denmark for the majority of industrial processes. However, several important drawbacks are identified with burden shifting to other impact categories that go beyond sustainable levels, e.g. particulate emissions impacting human health and mineral resource use. These findings highlight that it is difficult for one sector alone to be considered environmentally sustainable without looking at other sectors. Therefore, multi-sectoral studies should be carried out to assess the improvement potentials in each sector and identify the trade-offs between sectors in order to achieve sustainable industrial systems.

Key words

Sustainability; Environmental assessment; Planetary boundaries; Energy transition; Industrial systems

Nomenclature

BAU	Business as usual	**GVA**	Global value added
COP	Coefficient of performance	**MHP**	Mechanical heat pump
GHG	Greenhouse gases	**MVR**	Mechanical vapor recompression

2. Introduction

The 2021 IPCC report highlights the scientific consensus on the anthropogenic origin of global warming [1]. This report also emphasises that a massive reduction in greenhouse gases (GHG) emissions is required to limit the rise in temperature and its consequences for the environment and human life. This need to reduce the impact of human activity is currently at the centre of policy, such as the Paris Agreement signed by all UN parties in 2015. Despite recent attention to this issue, the current level of emissions is not sufficient to achieve the objective of limiting temperature increase to 2°C [2].

To achieve these goals in a European context, the EU strategy is based on several pillars such as process optimisation, the evolution of energy systems towards more virtuous systems and the circular economy. The reduction of industrial GHG emissions is one of the pillars of the European strategy to achieve its defined objectives [3]. Among these solutions, energy system transformation has been studied to assess the potential for reducing GHG emissions in industry [4], [5]. These studies show that achieving the targets depends on a variety of solutions depending on the constraints of each industry. However, electrification of heat production seems to be one of the most important options to achieve the reduction for two main reasons: (i) electrification represents the major part of the energy used in the compatible scenario [4], [5]; and (ii) electrification has a high technology readiness level [3]. Studies on the transformation of energy systems focusing on environmental impact are relatively recent and mainly focus on the potential reduction of GHG emissions [4], [6]–[9]. As shown by da Costa et al. [10], the transformation of an energy system can have benefits in terms of reducing greenhouse gas emissions but at the same time an increased impact 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 [11], [12].

The aim of this study is to evaluate the environmental impacts of the electrification of industrial processes in order to highlight the ability of the change in energy system to achieve the GHG reduction objectives but also the trade-offs of such a change in the system on other environmental indicators. To evaluate these different environmental criteria, these values are put into perspective with the planetary boundaries [13] and thresholds for human health damages [14] as well as with the objectives set by the Paris Agreement. This assessment methodology is applied to the Danish and French food industry taken as illustrative cases. Finally, this work aims to classify the different environmental impacts in order to rank the criteria among themselves and thus facilitate decision-making between different technical solutions.

3. Methods and Material

3.1. Assessment framework

The methodology used aims to define the environmental impact of three scenarios based on the study of the electrification of the Danish food industry by Elmegaard et al. [15] on the basis of the work of Bülher et al. [16]. The first scenario, called "business as usual" (BAU), represents the current state of the industry. This scenario is complemented by two electrification scenarios: the Li scenario includes a massive electrification of the processes with the use of heat pumps for temperatures up to 150°C and the Hi scenario goes further by assuming a technological improvement allowing the use of heat pumps for temperatures up to 300°C. Following the methodology developed by Bülher et al. [16], each industry is broken down by process type and temperature level in order to define the appropriate process electrification technology. These scenarios assess for each process and temperature which technology is the most appropriate. Mechanical heat pump (MHP) are used when the process is compatible and below the scenario temperature threshold except for mechanical vapor recompression (MVR), which is used for evaporation processes. Above the temperature threshold, heat is produced with electric boilers and if this is not possible with gas boilers as a last option. However, the site-specific integration constraints cannot be integrated and the study is based on standard integration.

This assessment considers marginal process for the evaluation of both energy and environment. Marginal process are defined by Hauschild et al. as "the changes to the economy caused by the introduction of the studied product system, i.e. the product system's consequence" [17]. For the proposed application, namely the food industry, which represents a significant share of the energy market, the change of energy system will lead to a change in electricity production to satisfy this new demand. Considering marginal process requires to study the impact of the new sources of electricity production. For the environmental part, the so-called "consequential" approach as embedded in the ecoinvent database (i.e. consequential version) is considered.

3.2. Energy model description

3.2.1. Energy efficiency

The energy model is based on the current energy consumption of the industry. Assessing the total energy consumption (Ec_T) of the process requires considering the efficiency of the heat generation technology and the system losses, which depends on the type of fuel and the temperature level of the process as described in eq. (1).

$$Ec_T = \frac{Ep_{x,T}}{Seff_{,x,T}.(1-\eta)}$$ (1)

Where $Ep_{x,T}$ is the heat requirement of the industry for a specific process at temperature T, $Seff_{x,T}$ the system efficiency for a fuel x and a process temperature T and η the thermal losses of the system, presented in Tab. 1, which represent the heat losses to the environment of the heat generation technology as defined by Bülher et al. [16].

Tab. 1 – System efficiency by fuel and temperature level from [16]

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

The system efficiency depends on both the type of technology and the process temperature. The efficiency used is this work are from [16]:

1. Mechanical heat pump (MHP) are assumed to be transcritical CO_2 heat pump with an efficiency

$$COP_{MHP} = \eta_{Lorenz} \frac{\bar{T}_{lm,sink}}{\bar{T}_{lm,sink} - \bar{T}_{lm,source}}$$ (2)

where η_{Lorenz} is a Lorenz efficiency and a value of 0.45 is assume in this study. $T_{lm,sink}$ and $T_{lm,source}$ are defined in eq (3) and (4):

$$\bar{T}_{lm,sink} = \frac{T_{sink,out} - T_{sink,in}}{ln(T_{sink,out}) - ln(T_{sink,in})}$$ (3)

$$\bar{T}_{lm,source} = \frac{T_{source,in} - T_{source,out}}{ln(T_{source,in}) - ln(T_{source,out})}$$ (4)

Where $T_{sink,in}$ and $T_{sink,out}$ are respectively the input and output temperatures of the sink, $T_{source,in}$ and $T_{source,out}$ are respectively the input and output temperatures of the source.

2. A mechanical vapour recompression (MVR) COP of 5 is assumed.
3. Electric, gas, oil or coal boilers have an efficiency of 1.

3.2.2. Danish & French consumption scenarios

The BAU, Lo and Hi scenarios are based on energy consumption per energy source of the Danish food industry; the data are from the Danish Energy Agency (Energistyrelsen) [18] corrected with efficiency of eq. (1). The energy distribution of the Danish food industry is presented in Fig. 1**Erreur ! Source du renvoi introuvable.**. The main energy consumption of the current food industry is gas following by oil and coal. After electrification, electricity can cover all the demand except for slaughterhouses and the share of MHP depends on the electrification scenario. The category "other food industry" includes all industries not covered by the other four categories and will be the focus of this study because it is composed of a number of different processes to be representative of the average performance.

The details of energy demand by energy source of the French food industry, presented in Fig. 2**Erreur ! Source du renvoi introuvable.**, are taken from the French statistical office (INSEE) [19]. Due to lack of detailed data of the distribution between the different processes and their temperature within a sector for French industry, we assume that this distribution is the same as the Danish industry. However, the type and quantities of energy are country specific.
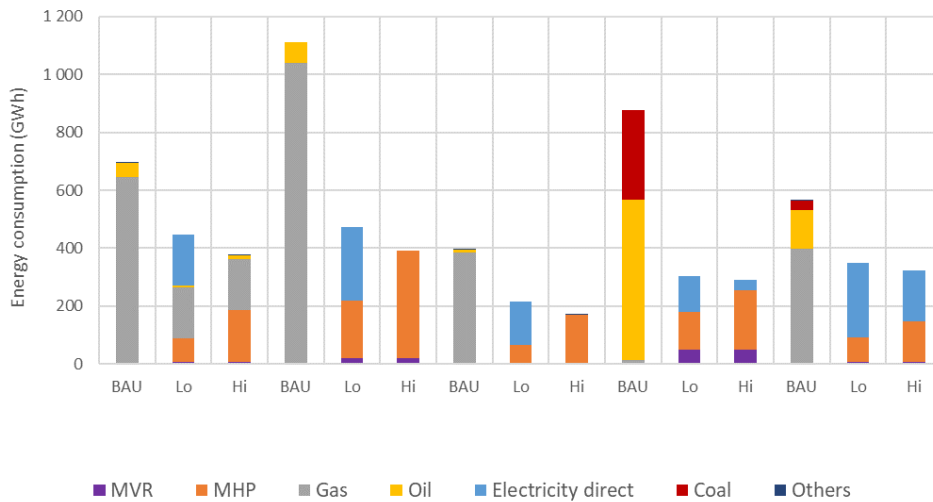
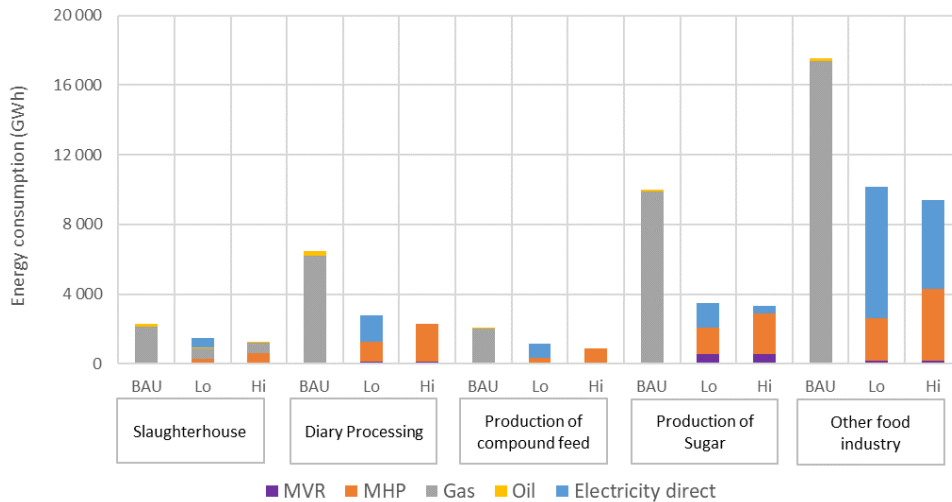*Fig. 1 – Danish food industry energy consumption by source*

Fig. 2 – French food industry energy consumption by source

3.2.3. Energy mix

The environmental impact assessment for the electricity is correlated to the electricity production mix for each country. As the French and Danish electricity production systems are different, the study considers the specificities of each type of production. The marginal electricity mix for Denmark comes from the consistent Ecoinvent 3.7.1 database and is allocated as follows: less than 0,1 % from hydro river production, 61.0 % from wind power and 39.0 % from biomass [20]. For the marginal electricity mix for France, we have chosen to consider three different scenarios from the French Transmission System Operator (RTE) whose allocation is described in Tab. 2 [21], [22]. The values used here are medium-high voltage electricity mixes, which explains the absence of solar, which is mostly low voltage and therefore used by industry to a negligible extent. These three different scenarios propose variants of a low GHG emission mix with a highly variable share of nuclear and renewable energy, ranging from nuclear-free production (scenario M0) to a maximum share of 56.8 % (scenario N03) and an intermediate scenario N1. The French electricity projections is used to assess the sensitivity of the electricity mix to environmental impacts. Storage to regulate the grid, which is essential for scenarios with a high share of renewable energy, is included in the model.

Tab. 2 – Marginal energy distribution in French electricity mix

	Sc. N03	Sc. N1	Sc. M0

	(%)	(%)	(%)
hydro alpine	0.5	0.5	0.4
hydro river	0.5	0.5	0.4
nuclear	56.8	22.7	0
wind power	41.6	75.7	98.5
biomass	0.1	0.1	0.1

RTE has carried out scenarios including the storage required to balance the French electricity grid [7]. As only marginal processes are considered here, the main contributor to electricity storage is the battery, in the absence of a significant increase in pumping station storage in the scenarios. 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 is considered in this work. This choice was made because electricity storage is the main type of storage in the scenarios and is the only type of regulation which has a direct impact on national electricity. Others flexibility factors like flexibility or interconnection have an impact that is accounted elsewhere.

Assuming a daily storage cycle and a discharge time of a few hours, an energy-to-power ratio of 10 and a life time of 10 years can be assumed [23]. Therefore, with a density of 300 Wh/kg, a ratio of battery mass per unit of electric energy can be calculated as presented in Tab. 3.

Tab. 3 – Electricity storage assumptions with batteries for France

	Battery storage capacity (GW)	**Battery mass /energy (kg/GWh)**
Sc. N03	1	0.05
Sc. N1	9	0.45
Sc. M0	26	1.22

3.3. Environmental model description

The environmental assessment is based on a life cycle assessment of the energy systems including energy consumption, refrigerant characteristics, and the heat production technology. This analysis is performed using the Ecoinvent 3.7.1 LCI database for modelling background processes [20], based on the marginal process defined in the assessment framework. The life cycle impact assessment methodology used to assess the environmental impact is the EF 3.0 methodology [25]. The assessment boundaries are set from cradle-to-grave including transport and conversion losses for the life cycle of energy and the equipment life cycle with the exception of materials needed to adapt the system to the new technology like the connections to the existing current grid. For the refrigerant, a charge by power unit ratio of 2.0 kg/kW [26], an annual leakage rate of 5 % [26] and an end of life leakage rate of 15 % [27] are considered.

3.3.1. Sustainability assessment

The life cycle assessment is expanded to include the sustainability assessments of the proposed transition scenarios. 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 [17]. Sustainable levels are defined using equation (5) on the basis of the current impact, which is corrected with a reduction factor from Vargas et al. [14].

$$Sl_x = \frac{I_{BAU,x}}{Rf_x}$$ (5)

Where Sl_x is the sustainable level of the studied entity for environmental impact x, $I_{BAU,x}$ the impact of the studied entity for environmental impact x using BAU as a reference, Rf_x the reduction factor presented in Tab. 4 to reach a sustainable level of environmental impact x. I_x units depend on the category x. 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. For example a reduction factor of 9.4 is estimated by Vargas et al. [14] for climate change impacts. This value can be compared to the work by Bjørn and Hauschild [28] who estimated the steady-state emissions of greenhouse gases to stay below 2°C at 6.8 Gt-CO_2eq/yr, hence a reduction factor of 8.2 compared to the EF 3.0 reference value [25]. The sustainability ratio (Sr_x) defined in eq. (6) is use to assess the gap between the process and the sustainable level for each impact category.

$$Sr_x = \frac{I_x}{Sl_x} \tag{6}$$

Where Sl_x is the sustainable level defined in eq. (5) and I_x the contribution of BAU, Lo or Hi scenarios for impact category x. A value of less than 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.

Tab. 4 – Reduction factor for all environmental categories in the EF 3.0 methodology

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
9.36	0.28	0.01	0.54	5.97	0.90	0.26	0.30	3.22	- [a]	0.30	0.85	9.33	0.51	4.08	4.08

[a] Value not given in Vargas et al. [14]

3.3.2. Share of the contribution in the global economy

To put food industry emissions into perspective with respect to global emissions, a downscaling methodology is used to compare the emission of the different scenarios with the current global environmental impact. There are many principles of downscaling, i.e. moving from global to process level impacts [29], [30]. The sharing principle used in this work is the economic value added (EVA), which has been the most used sharing principle until now [29]. Although many biases may distort this coupling, this approximation allows the share of environmental impact for each industry to be estimated. As these data are readily available, it makes the study reproducible and transferable to other sectors. To define whether a process has a significant impact within an impact category, we use eq. (7). The economic share of global value added (GVA) of this process is compared to its share of emissions for that impact category relative to global emissions for that same category. The higher the share of environmental impact in relation to the share of GVA, the more significant the contribution of the sector studied to this impact category. On the contrary, when the value is low, it means that the sector is not a contributor to the global impact.

$$Cl_x = \frac{I_x}{I_{tot}} \cdot \frac{EVA_{tot}}{EVA_x} \tag{7}$$

Where Cl_x is the contribution level of the studied entity for the environmental impact x, I_x/I_{tot} the share of impact of the studied perimeter for environmental impact x in relation to total emissions (%), EVA_x/EVA_{tot} is the share of economic value added of the studied perimeter for category x in relation to total economic value added (%). Data for Denmark are from [31], data for France are from [19] and the world data are from [32]. As the Danish GVA value includes several "Production of compound feed", " Production of Sugar" and " Other food industry", the distribution of the GVA is made in proportion to the energy consumption between these 3 sectors. A value 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.

4. Results and discussion

4.1. Environmental impact analysis

As presented using logarithmic scale in Fig. 3(a) for France and Fig. 3(b) 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. However, the reduction of the climate change indicator through electrification leads to the unsustainability of some other categories concerning human health or resource use. The assessment of these indicators shows that electrification reduces the impact of 7 indicators for France and 8 for Denmark, but only reaches 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.
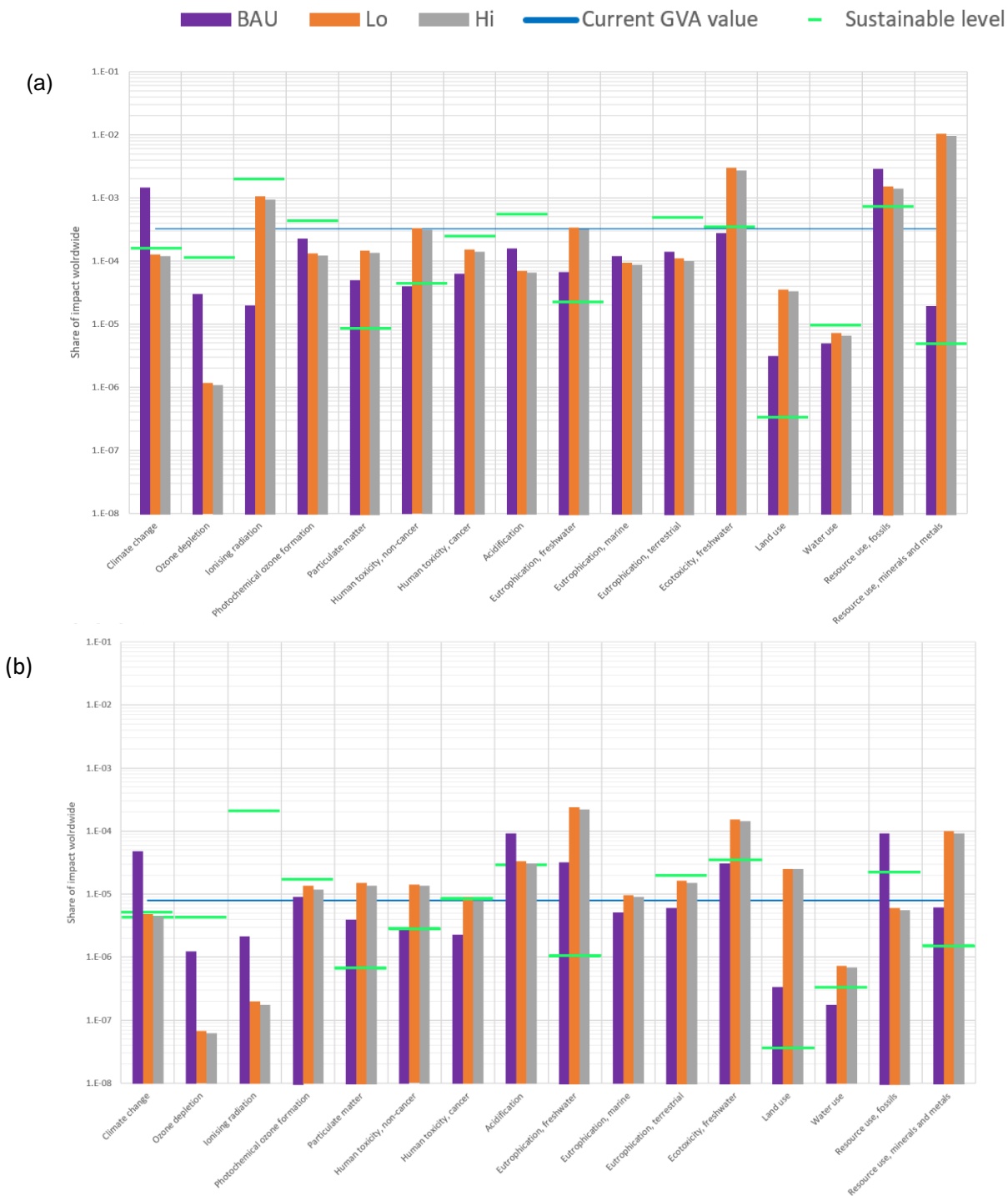
Fig. 3 – Results of the different impact categories for the other food industry scenarios for (a) France and (b) Denmark using logarithmic scale. The level defined as sustainable is represented with a green line for each impact category; the current share of GVA ($\frac{EVA_x}{EVA_{tot}}$) value is represented with the blue line.

The main differences between France and Denmark for the studied sector after electrification 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 fossil" 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". The methodology used has two main limitations: (i) for the category "resource use, minerals and metals" recycling is not considered in the definition of the limit [33], [34]. The sustainable level is therefore underestimated because it only considers the reserve present in the ground; (ii) the reduction factor is based on global level emissions and these factors are applied to BAU impacts. Therefore, for sectors with a

low contribution, the reduction target may not be appropriate, e.g. gas production for land use indicator is probably the most efficient solution, so it is not possible to reduce for equal consumption.

In order to assess the environmental impact of a solution, it is interesting to go beyond the study of the sustainable level itself by integrating the share of the contribution of the process in relation to the global economy. Fig. 4 evaluates the contribution of each environmental impact for the category "other food industry" for France and Denmark in 2 electrification configurations, namely BAU and Lo. It can be noted that the differences between Lo and Hi scenarios remain limited for this industry category.

(a) BAU - France

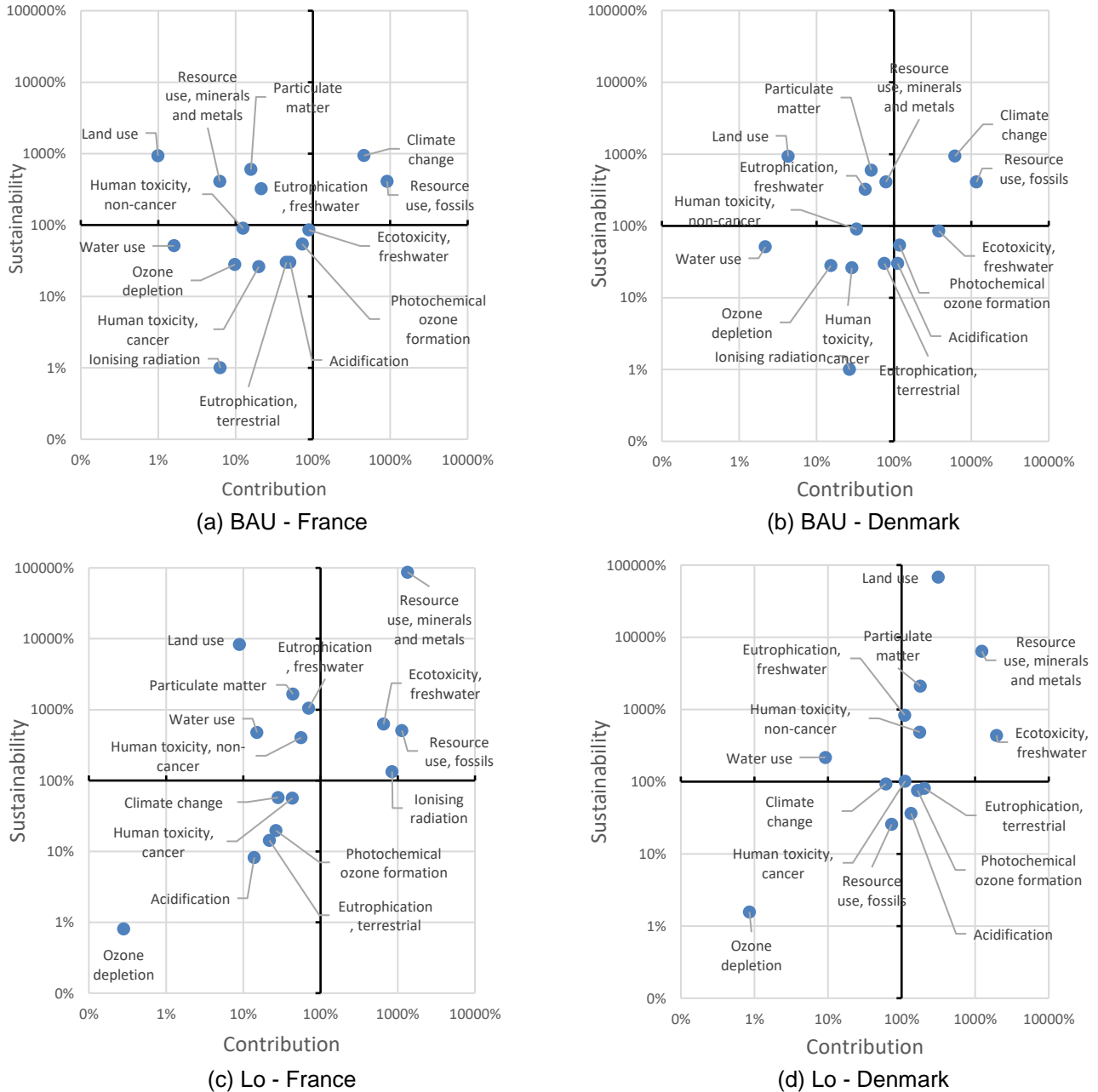(b) BAU - Denmark

(c) Lo - France

(d) Lo - Denmark

Fig. 4 – Level of environmental impact category and contribution of the environmental indicators studied for the scenarios (a) BAU–France, (b) BAU–Denmark, (c) Lo–France, (d) Lo–Denmark

Four trends emerge from Figure 4:

(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 and is hence of less 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 implies to consider them. While no impact category is

present in this zone for France, some can be found for Denmark because the importance of the agri-food sector has a larger share of GVA.

(iii) The upper left-hand area is for impacts that are unsustainable, but where the impact share is less 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.

Fig. 4 shows that there is not a general improvement in all environmental impact categories related to electrification: some indicators reflect impact decreases while others demonstrate impact increases. Therefore, to achieve GHG emission reduction targets, trade-offs have to be made with other environmental indicators such as land use or mineral and metal use. This impact/contribution classification highlights which categories need to be considered more specifically. In particular, impact categories located in the top-right zone are estimated to be within unsustainable ranges and may limit the growth of one sector and/or require a trade-off with other sectors of the economy to achieve economy-wide environmental sustainability.

4.2. Influence of electricity grid mix

A sensitivity analysis was carried out on the French electricity grid mix in order to study its influence on the results (see Figure 5). Results show a large variability in the sensitivity of the impact indicator scores to the electricity grid mix and in particular to the share of nuclear power and renewable energy sources (see also Methods, Section **Erreur ! Source du renvoi introuvable.**; share of biomass not considered here because not reported as predominant source in the French scenarios). Regarding the use of mineral resources and metals, which is associated with the largest impact share, the electricity mix may play a predominant role due to a strong increase in several impacts when assuming a completely renewable energy mix resulting from the use of metals in the manufacture of renewable energy technologies, e.g. wind power, batteries, etc. It should be noted for this specific point that, as for the previous part, recycling is not considered in the method, which overestimates the share of this impact category. This means, however, that there will be a large quantity of metals available in this sector and that it is essential to make progress on recycling these materials. The second indicator with a high degree of uncertainty is the use of fossil resources, including uranium ore, which leads to an increase in this impact if nuclear power is used.

The impact categories "climate change" and "resource use, fossils" are found to be the only impact categories where the impact scores may exceed or remain below the sustainability thresholds depending on the electricity mix. For the use of fossil resources, the shift to a 100 % renewable mix enables to reach a sustainable level. This trend could be seen in

Fig. 5 (a) with the sustainable level represented with a green line. The variability, which can be defined as the difference between the maximum value and the minimum value (upper and lower bounds in

Fig. 5) divided by the reference value, shows a high magnitude for this indicator with a value of 219 % due to the low use of fossils for the 100 % renewable mix and a high use for the mix with a high nuclear share. For the climate change indicator, however, the electricity mix with 100 % renewable exceeds this threshold as shown in

Fig. 5 (b). For the climate change indicator, the variability remains limited with a value of 63 %. This low variability is explained by the fact that both solutions result from low GHG emissions strategy.
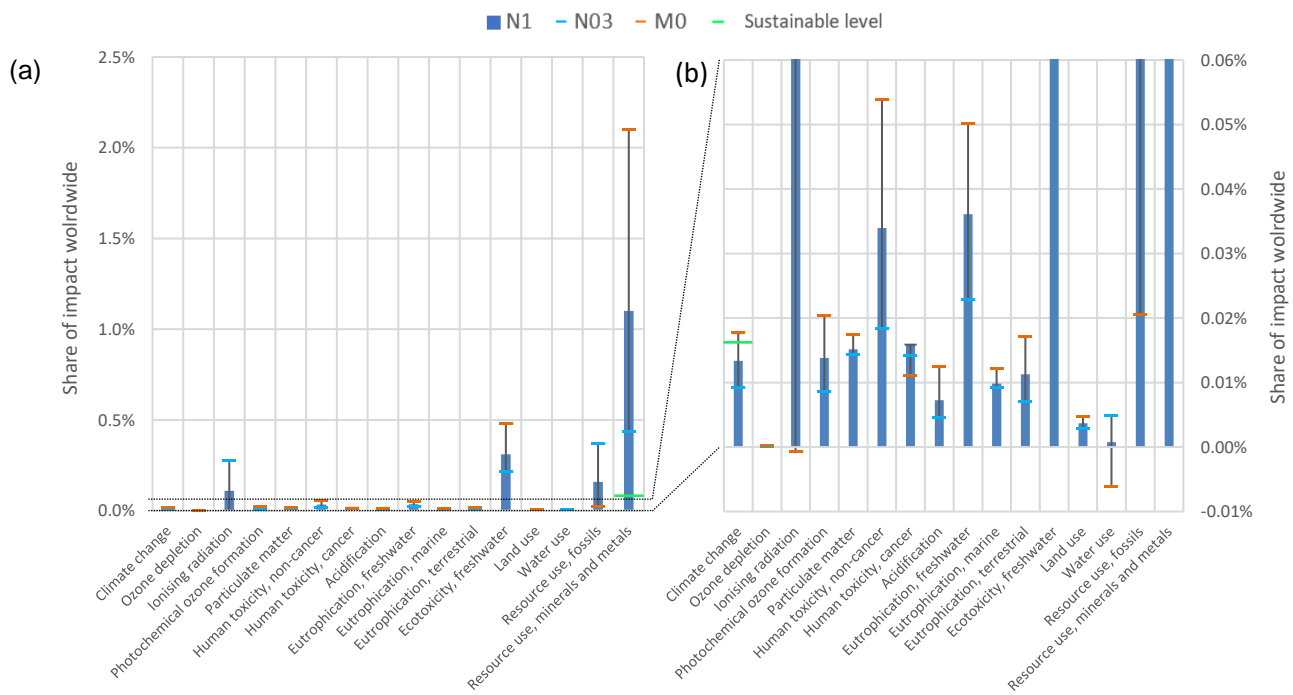
Fig. 5 – Environmental impact sensitivity to different electricity generation scenarios for France; (a) full scale (b) focus on lower value. The green lines indicate the sustainable level for climate change (b) and "resource use, fossils" impact categories (a).

5. Conclusions and recommendations

This study proposes a methodology for analysing the environmental impacts of an energy transformation with respect to sustainable levels based on planetary limits and the impact on human health. The methodology applied to the case of the electrification of the food industry assesses environmental externalities that are expected to happen when reducing the GHG emission to achieved targets. These environmental counterparts exist for both French electricity grid mix based on a renewable and nuclear mix as well as for the Danish mix composed of renewable and biomass energy sources. Electrification reduces the environmental impacts of 7 out of 16 categories studied in France and 8 in Denmark. Of these categories, climate change is the only one that remains potentially below sustainable levels. At the same time, electrification will increase the impact of several impact categories and notably some categories related to human health which might then exceed their thresholds.

The study of sustainability thresholds is not sufficient to show the impact of the transformation on the global system. To assess the overall impact of a system and its future evolution, it is important to evaluate its contribution from a global perspective. The greater the contribution of a sector to an impact category, the greater the impact of reducing it at the global level. In the study, we have identified and classified impact categories into 4 groups based on their threshold crossing and relative contribution. This classification indicates that for the industry studied, there is a large disparity between the different impact categories. This suggests that a breakdown using another indicator than GVA might be more relevant to allow for the assessment of the relative critical impact categories (i.e. strongly above or below the threshold) of each industry.

When changing the energy consumption of an industry, the identification of the most sensitive impact categories can help in the decision-making process. In order to plan a global transformation of industrial energy systems, it would therefore be necessary to assess the environmental externalities of each process within a broader perspective, accounting for sectoral interactions. Once these externalities have been assessed, the ability of industrial systems to remain within the planetary boundaries and below acceptable human health damage thresholds could be evaluated in terms of technical and political choices.

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