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# Multi-criteria optimisation to align environmental impacts of industrial heat production with environmentally sustainable thresholds: case of the paper industry

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## Abstract

Human activities are currently at an unsustainable level and a significant reduction in greenhouse gas emissions is essential to limit global warming. Industry, which accounts for a large share of these emissions, has an important role to play, particularly in its energy consumption for heat production. One of the issues of this transformation is to assess, among all the possible energy solutions, those that are most likely to achieve the objective of reducing emissions of greenhouse gases without incidentally increasing other environmental impacts. The study proposes a method for classifying non-dominated solutions found using an optimisation model based on life cycle analysis (LCA), energy and economic indicators. This is complemented by integrating constraints represented by sustainability limits, i.e. an acceptable level of impact defined by planetary boundaries. A case study of a paper industry process in Italy is presented to highlight the capability of the method. For this example, the ranking shows that - with the current LCA weighting factors - waste heat recovered using a heat pump powered by electricity has the highest ranking. However, a scoring for which exceeding sustainable levels is penalized gives a higher ranking to solutions composed of a mix of several energy sources. Moreover, if one focuses only on the global warming indicator, the most effective solutions far exceed sustainable levels for other indicators. It is therefore necessary to adopt a comprehensive environmental approach to avoid shifting environmental burdens to other impact categories. On the other hand, no solution compatible with all sustainable levels has been found. It is therefore necessary to go further by proposing a global approach detailing the level of impact that each sector can have while ensuring an overall sustainable level.

## Key words

Optimisation, Industrial energy process, Planetary boundaries, Sustainability, Environmental assessment

## Nomenclature

| | | | | | |
|---|---|---|---|---|---|
| C | Corrective factor | | R1 | Ranking method 1 | |
| C’ | Weighting score | | R2 | Ranking method 2 | |
| C* | Corrected weighting factor | | R3 | Ranking method 3 | |
| D | Process demand | (MW) | S | Energy stored | (MWh) |
| $\varepsilon$ | Final energy losses | (%) | $S_{eff}$ | System efficiency | |
| $E_{in}$ | Final energy consumption | (MWh) | Sr | Sustainability ratio | |
| $E_{out}$ | Process enery demand | (MWh) | T | Process temperature | (K) |
| I | Impact intensity | (kgCO2eq/FU) | Ws | Weighting score | |
| P | Heat generation | (MW) | | | |

| **Acronym** | | **Subscripts** | |
|---|---|---|---|
| CCS | Carbon Capture & Storage | j | Heat production technology |

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| | | | |
|---|---|---|---|
| LCA | Life Cycle Assessment | rec | Recovered from waste heat |
| MHP | Mechanical Heat Pump | sto | Storage |
| GHG | GreenHouse Gas | sustainable | Environmentally sustainable thresholds |
| i | Impact category | up | Upgraded to be used by process |

# 1. Introduction

*It is unequivocal that human influence has warmed the atmosphere, ocean and land since pre-industrial times*, which *is a consequence of more than a century of net greenhouse gas (GHG) emissions from unsustainable energy use, land-use and land use change, lifestyle and patterns of consumption and production* [1], [2]. There are now a large number of climate scenarios that attempt to estimate the consequences of human activities on future global mean surface temperature (GMST), which are compiled in the last intergovernmental panel on climate change (IPCC) assessment report [3]. The higher the increase in GMST, the larger the irreversible changes in natural cycles and the consequences on livelihoods of people, which is why it is essential to hold this temperature increase well below 2 °C above pre-industrial levels. The latest Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services report [4] shows that global warming is not the only concern at the moment, and that other issues (land use, direct exploitation, pollution etc.) are at unsustainable levels leading to a huge decrease in biodiversity. This conclusion is also highlighted by the Stockholm Resilience Center in their proposed definition of planetary boundaries [5].

Many global warming mitigation options are already technically and economically viable or are going to become so in the near future [2]. Nevertheless, they can have other environmental impacts, which are necessary to evaluate. Therefore, an increasing number of studies, often called the 4E study, combined energy, exergy, economic and environmental approaches to reach this goal. For example, Chen et al. [6] proposed a comprehensive 4E approach applied to cascading systems, which has been shown to be beneficial in reducing greenhouse gas emissions. Yu et al. [7] go further in the environmental assessment by conducting a full life cycle analyses (LCA) to evaluate the most significant environmental impacts. Although these studies quantify the environmental impacts of a technical solution and the elements that significantly contribute to it, they do not relate them to sustainable thresholds, i.e. the maximum level of impact generated by the process that can be achieved without causing significant adverse effects on the environment, society or the ability of future generations to meet their own needs. Indeed, Bjørn et al. [8] have pointed out that one solution that is better than another from an environmental point of view is not necessarily an acceptable solution in the face of global limits..

In this study, we propose a 4E assessment framework including the sustainable levels defined by Vargas et al [9] to analyse the issue of sustainable heat production in industry. Starting with an industrial need defined by dynamic heat requirements at a certain temperature level, a set of mature solutions are compared to analyse the best compromise according to different energy, environmental and economic constraints. The main purpose of this article being to present the method, a simple case study is used for this purpose. It takes as example the paper production, which is a continuous industrial process, located in Italy, being able to benefit from a continuous flow of waste heat at a temperature lower than the process temperature. A period of one year is considered.

# 2. Methods and Material

## 2.1. Overall methodology

This study deals with the heat production for an industrial process at a defined temperature T, for a variable hourly demand. The objective is to define the best way to meet the dynamic heat demand by using combinations of different possible technologies like electric, gas and biomass boilers or heat pumps fed with waste heat or thermal storage. All the energy sources used to cover this need (including those used to generate grid electricity, with or without carbon capture and storage) have different environmental impacts and different costs that can vary at each time step. The aim is to analyse what is the best possible solution to produce this industrial heat according to environmental and economic criteria. The analysis being multicriteria, it is possible to find a set of possible solutions answering the optimization problem. The general assessment framework used to calculate and rank the optimal solutions is presented in Fig. 1.

From environmental, technological, energy, process-related and economic input data, it is possible to feed the economic, energy (yearly performance simulation) and environmental (LCA) models used in the optimization algorithm. The latter produces a set of non-dominated solutions capable of meeting the needs of the process. Note that for the sake of brevity, this article focuses only on the environmental impact presentation. The set of non-dominated produced solutions, also called Pareto front, is such that

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there is no one solution that exhibits a best performance in all dimensions. Eventually, these solutions are ranked based on considerations related to global limits and economy. The different steps of this general assessment framework are detailed in the following sections.

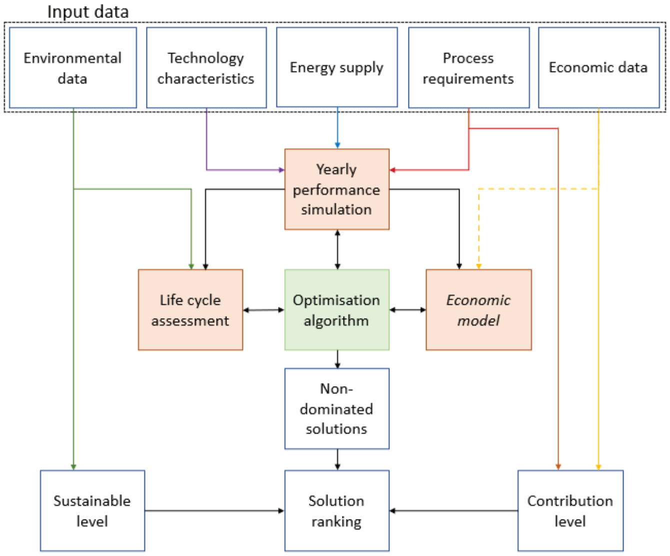

**Fig. 1 -** Assessment framework; dotted arrows and the block in italics are not presented in this study.

## 2.2. Input data

### 2.2.1. Environmental data

The environmental data are derived from Ecoinvent 3.7.1 LCI database [10]. This assessment considers the marginal process for all environmental data, which is defined by Hauschild et al. [11] as the transformation on the economy caused by the introduction of a new product system, i.e. the product system's consequence. For the proposed application, namely the heat production in industry sector, 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 assess the environmental impacts caused by the change in energy supply over the average values.

### 2.2.2. Efficiency of the technologies

The efficiencies of the technologies considered in the study are summarised in Table 1. They include the heat loss to the environment due to the generation of heat and consider a reduction of the efficiency when the system operates in partial load. In addition to these efficiencies, a ramp-up power is considered for biomass production with a limited ramp-up equal to 4.2% per hour of the maximum available power as defined by Veyron et al.[12]. For the Mechanical Heat Pump (MHP), the power is limited according to the available waste heat at the considered time step. In this study, the source of waste heat is external to the process and corresponds to a contribution equivalent to 80% of the process requirement.

A thermal storage facility is also modelled to allow a phase shift between production and use. There are currently many options for thermal energy storage as reviewed by Sarbu et al [15]. As this work focuses on industrial applications, only short-term storage (water tank) is considered as a first step. Storage losses are estimated at 5% of the stored energy for a charge cycle of 8 hours and a discharge cycle of 16 hours [16]. Considering the charging and discharging times, the hourly storage efficiency is equal to $\varepsilon_{sto} = 0.996$.

**Table 1 –** Final energy consumption $E_{in,T}$, Process energy demand $E_{out,T}$ at temperature T, for the four technologies considered in the study. $S_{eff,T}$ is the system efficiency for a process temperature T in °C, with $T_{up}$ the process temperature level and $T_{rec}$ the waste heat temperature level, ε is the share of final

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energy losses by the system in % which represents the heat losses to the environment of the heat generation technology as proposed by Bülher et al. [13].

| Technologies | Final energy consumption $\mathrm{E}_{in,\mathrm{T}}(\mathrm{t}) = \frac{\mathrm{E}_{\mathrm{out,T}}(t)}{\mathrm{S}_{\mathrm{eff,T}}(t).(1-\varepsilon)}$ | Partial load efficiency |
|---|---|---|
| Electric boiler | $\mathrm{S}_{\mathrm{eff,T}}(t) = 1$<br>$\varepsilon = 0.00096(\mathrm{T} + 273.15) - 0.115$ | No partial load efficiency losses |
| Natural gas boiler | $\mathrm{S}_{\mathrm{eff,T}}(t) = 1$<br>$\varepsilon = 0.001154(\mathrm{T} + 273.15) - 0.138$ | No partial load efficiency losses |
| Biomass boiler | $\mathrm{S}_{\mathrm{eff,T}}(t)$ depends on the partial load<br>$\varepsilon = 0.001154(\mathrm{T} + 273.15) - 0.138$ | Regression from [12]<br>At 100% design load:<br>$\mathrm{S}_{\mathrm{eff,T}}$ = 86.5%<br>At 50% design load:<br>$\mathrm{S}_{\mathrm{eff,T}}$ = 83.0% |
| MHP | $\mathrm{S}_{\mathrm{eff,T}}(t) = 1.91(\mathrm{T}_{\mathrm{up}}\text{-}\mathrm{T}_{\mathrm{rec}}+0.0884)^{0.89094}(\mathrm{T}_{\mathrm{up}}+0.0442)^{0.67895}$<br>$\varepsilon = 0.00096(\mathrm{T} + 273.15) - 0.115$ | Linear regression from [14]<br>At 100% design load:<br>$\mathrm{S}_{\mathrm{eff,T}}$ = COP<br>At 50% design load:<br>$\mathrm{S}_{\mathrm{eff,T}}$ = 0.985COP |

### 2.2.3.Energy supply

The electricity production considered in this study is scenario BL2050 for Italy from the heat road map Europe [17]. Italy is a relevant study case to assess the impact of Carbon Capture & Storage (CCS) option because of its large share of thermal generation of electricity. The new installed electricity production relative to the current electricity mix is described in Table 2.

**Table 2 –** New installed electricity production sources in scenario BL2050 for Italy

| Dammed hydro | Geothermal | Offshore wind | Onshore wind | Solar | River hydro | CHP Biomass | Condensing powerplants | Nuclear |
|---|---|---|---|---|---|---|---|---|
| 5.7% | 3.8% | 0% | 20.9% | 23.9% | 0% | 2.1% | 43.6% | 0% |

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 publish by Riahi et al. [18] from IPCC AR6 [3]. The data are presented in Table 3.

**Table 3 –** 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 captured efficiency, which is defined as the share of $CO_2$ not rejected by the CCS, is set at 88% according to García-Freites et al. [19]. The environmental impact of CCS is based on the LCA carried out by Bisinella et al. [20]. The efficiency penalty of CCS, which is the relative change on energy output, is set at 15% for gas [21] and 22.6% for BECSS and oxy-fuel [22]. For the gas boiler, a feed with 100% of conventional gas is assumed (no shale gas).

### 2.2.4.Process requirements

The consumption profile of the study is based on average data from a continuous paper production process [23]. The typical week is shown in Fig. 2 and is repeated throughout the year. The process temperature requirement is set at 130°C and the waste heat temperature is recovered at 80°C. The continuous heat requirement profile of the paper industry has the advantage of presenting a minimum of operating constraints for the heat production technologies. A batch profile would have higher constraints such as the ramp-up time of a biomass boiler or lower efficiencies at partial load. The same method can of course be applied to more complex profiles, but the lack of space does not allow to deal with them in this article.

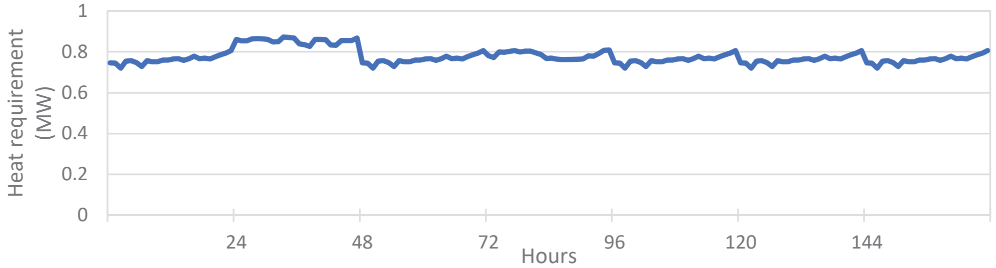

**Fig. 2 -** Weekly heat requirement profile for paper production process at a temperature level of 130°C

## 2.3. Yearly performance simulation

The energy model creates solutions that verify all the operating conditions of the technologies to meet the process demand. These solutions give for each time step the heat produced by each of the technologies:

$$\sum_{j=1}^{n} P_j(t) = D(t) + \frac{\mathrm{S(t)} - \mathrm{S(t-1)} - \mathrm{S(t)} * (1 - \varepsilon_{sto})}{\Delta t} \qquad (1)$$

Where $P_j$ is the heat production from source j in MW, $D$ the process demand in MW, $S$ is the amount of energy in thermal storage at time step t in MWh and $\Delta t$ the time step. The size of the heat production facilities for CAPEX and LCA calculations is based on the maximum demand required for each technology over the year, no safety factor being considered.

## 2.4. LCA model

The LCA focuses on the generation and supply of heat to the industrial sector in Italy. The functional unit is therefore defined as the production of heat at 130°C to meet the industrial demand presented in part 2.2.4 over one year in Italy for both 2015-2040 and 2065-2090 periods. Background data specified in Sections 2.2-2.3 are used for the life cycle inventory modelling. The Life Cycle Impact Assessment method used is EF 3.0 [16] and the weighting scores (Ws) proposed by this method are presented in Table **4** as well as the 16 environmental indicators used in this study. The weighting scores are not used in the optimization algorithm but are considered to rank the obtained solutions in the final step of the assessment framework. Furthermore, as explained in section 2.2.1, this study considers consequential modeling.

**Table 4 -** Weighting score from LCIA 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% |

## 2.5. Optimisation algorithm

The non-dominated solutions are calculated using the genetic optimisation algorithm package from Matlab [24]. The genetic method works by combining initial solutions and adding mutations to test the solution space as efficiently as possible. This method is well suited to our case as the solutions with one single energy source can be combined to make any possible solution. The initial solutions are therefore easy to generate. The number of obtained solutions depends on the size of the studied population; in this study a population of 100 is considered which generates a number of 35 final non-dominated solutions. This method has been widely studied in the literature [25], [26] and is already applied for energy optimization [27], [28], although reproducibility may be a minor issue.

## 2.6. Ranking of the non-dominated solutions

### 2.6.1. Sustainable & contribution levels

The environmental sustainability limitfor each environmental impact category is derived from Vargas et al. [9], except for marine eutrophication which is based on Willett et al. [29] and climate change which is based on the scenario AIM/CGE 2.2 published by Riahi et al. [18] and used in IPCC AR6 as one of the reference scenario to limit warming to 2°C without overshoot [3].

In order to assess the sustainability of non-dominant solutions, it is necessary to evaluate the share of the considered industrial process in relation to all human activities, and this for all environmental impacts. The aim is to define the safe operating space for the process, that can be described as the maximum acceptable impact that a process can have to remain below sustainable thresholds [30]. Several methods can be used for that purpose. The allocation principle that is used in this study is derived from the economic value added of the process as described in Jovet et al. [31]. To evaluate the deviation of each impact category of a non-dominated solution with respect to the sustainable level, the sustainability ratio defined by equation (2) is used.

$$Sr_{\mathrm{i}}(x) = \frac{\mathrm{I}_i(\mathrm{x})}{\mathrm{I}_{i,sustainable}} \tag{2}$$

where $Sr_{\mathrm{i}}(x)$ is the sustainability ratio of solution x for impact category i, $\mathrm{I}_i(\mathrm{x})$ the impact of category i and $\mathrm{I}_{i,sustainable}$ the sustainable level for the impact category i for the considered industrial process, which is derived from the share of the process in relation to its value added as described in Jovet et al. [31]. Another criterion was introduced in [31] to assess the sustainability of an industrial process: the contribution level $C_i(x)$. This criterion compares the ratio of the impact $I_i$ to the total impact $I_{i\ tot}$ of the category i to the share of the economic value added of the process $EVA_{process}$ to the total economic added value $EVA_{tot}$:

$$C_i(\mathrm{x}) = \frac{I_i\,(x)}{I_{i\ tot}} \cdot \frac{EVA_{tot}}{EVA_{process}} \tag{3}$$

This criterion puts the importance of the sustainability ratio into perspective. Indeed, if the sustainability ratio is above 1 (i.e. non-sustainable), but the contribution level is below 1 (i.e. less than the average for human activity), reducing the environmental impact of this process may not have a major 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. As an example, Fig. 3 shows the sustainability ratio versus the contribution level for three different impact categories A, B and C. Impact category B has a high sustainability ratio but a small contribution level, while impact category C behaves in the opposite way. This work considers the contribution of impact categories B and C to be equivalent in their ability to achieve or maintain a sustainable level for their respective category. For this reason, we propose to use a corrective contribution level C* in this paper to consider the importance of a sector in the total contribution and not only the sustainable level. This corrective factor is based on the orthogonal projection of the impact category coordinate on the linear function y = x.

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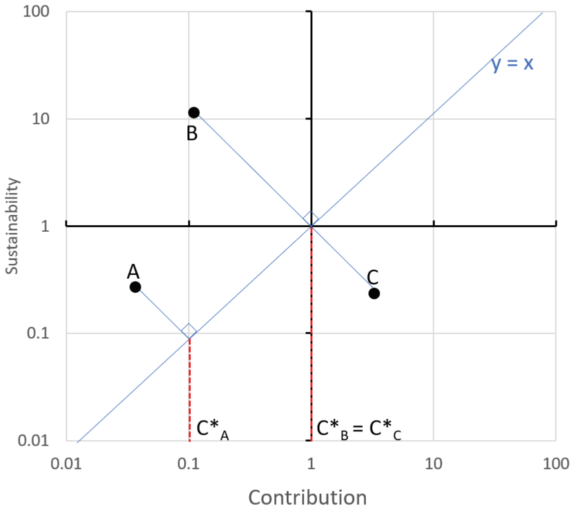


**Fig. 3 –** Contribution level corrected for each impact categories (A, B and C in this example) based on their sustainability level and contribution.

### 2.6.2. Classification

The classification of non-dominated solutions is realised using three different methods, (i) ranking 1 (R1) based on weighting the different impact categories with the EF 3.0 impact weighting scores $Ws_i$ ( Table 4), (ii) ranking 2 (R2) by adjusting the previous score with the C* factor, (iii) ranking 3 (R3) using the C* factor to calculate a penalty score C' which becomes more penalizing the more the sustainability threshold is exceeded, according to equation (4).

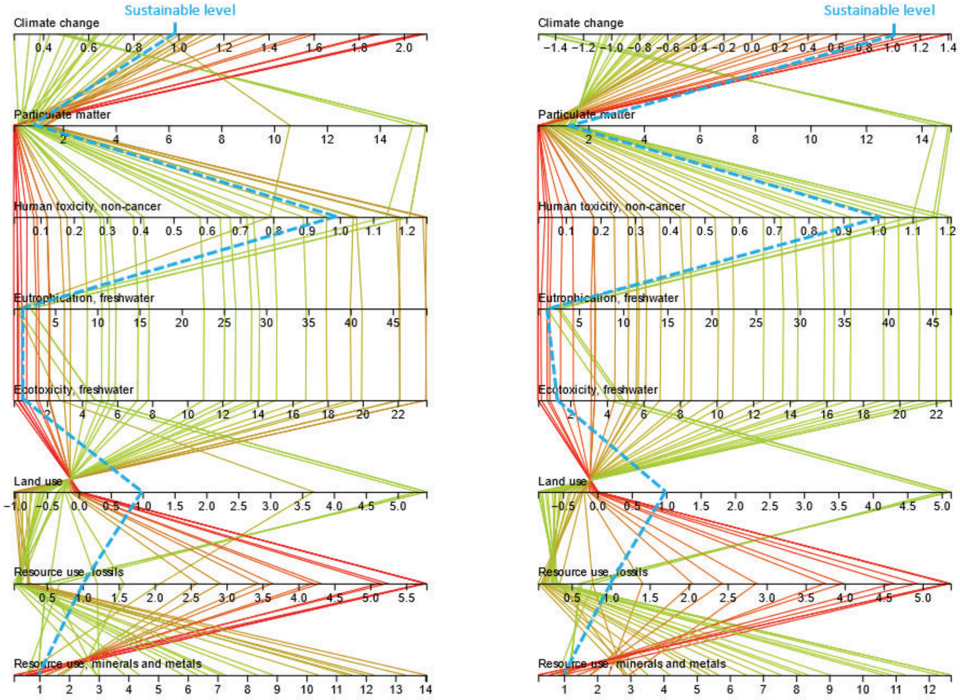
$$\begin{cases} C'_i(x) = e^{C^*_i(x)-1} & \text{if } C^*_i < 0 \\ C'_i(x) = C^*_i(x)^2 & \text{if } C^*_i > 0 \end{cases} \tag{4}$$

The final score for each non-dominated solution and the three different ranking methods is obtained using equation (5).

$$\begin{cases} R1 = \sum_i Ws_i . Sr_i(x) \\ R2 = \dfrac{\sum_i Ws_i . |C^*_i(x)| . Sr_i(x)}{\sum_i |C^*_i(x)|} \\ R3 = \dfrac{\sum_i Ws_i . C'_i(x) . Sr_i(x)}{\sum_i C'_i(x)} \end{cases} \tag{5}$$

## 3. Results & Discussion

The results of non-dominated solutions before ranking are presented in Fig. 4 for 2015 - 2040 and 2065 - 2090 periods for the impact categories that are not always sustainable. The following impact categories are always sustainable for the considered industrial sector whatever the technological solution studied and are not presented in Fig. 4: ozone depletion, Ionising radiation, photochemical ozone formation, human toxicity, cancer, acidification, marine eutrophication, terrestrial and water use. In this figure, each line represents the ratio between the impact of the process and the sustainable level of one heat production solution across all environmental impacts. Each value at the left of the blue line can be considered as sustainable while the value at the right is not. The changes between the 2015-2040 and 2065-2090 periods come from the development of CCS technology and the evolution of the sustainable climate change thresholds (which uses a budgeting approach). For the period 2065-2090, which presents greater uncertainties, it cannot be excluded that the current challenges will evolve according to the choices made by then. It is already possible to do some projection for climate change based on the willingness to limit the temperature increase. On the other hand, this approach helps to evaluate which impact categories could be an issue if the process were to continue as it does today.



(a) (b)

**Fig. 4-** Sustainability ratios of non-dominated solutions for periods (a) 2015-2040 and (b) 2065-2090 for impact categories exceeding the sustainable threshold value. The blue dotted line shows the sustainability limit corresponding to all values below 1. Each line is one of the 35 non-dominated solutions. The colour code varies from green to red, from the lowest to the highest value of climate change indicators to present the trades-off.

The first observation is that none of the 35 non-dominated heat production systems respects all the sustainable thresholds for both periods of time, i.e. all impact indicators lower or equal to 1 for a same heat production solution. The dispersion of the non-dominated solutions on the climate change indicator shows a result well above the sustainable level on indicators such as toxicity with a result up to 20 times the limit, freshwater eutrophication with a factor up to 50 or mineral resource use with a factor up to 13. The largest exceedances of sustainable levels are seen for solutions that meet the sustainable level for the climate change indicator. In contrast, the solutions that exceed the limit for climate change are below the sustainable levels for the other indicators, except for the fossil fuel consumption and freshwater eutrophication indicators.

Using the ranking method R1, the MHP technology performs the best achieving a ranking of 1 and 2 for both periods as presented in Fig. 5. As the environmental constraint increases over the period 2065-2090, it can be seen that the biomass solution ranks 7 to 10 times behind the MHP. The R1 score is very stable for all solutions combining MHP and gas boiler despite a high weight for climate change with over 20% of the ranking based on this indicator. Electrical boilers are heavily impacted by their lower electricity to heat conversion factor compared to MHP that results on a ranking of these solutions among the least efficient. It can be noted that the storage solution does not provide any gain with a ranking that decreases with the increase in storage use. This is due to different factors such as the low share of intermittent energy, which results to a low variation of the environmental impact of the electricity between the different time steps, but also due to the lack of process intermittency which is not sufficient to compensate for storage losses. However, this conclusion is specific to the profiles of electricity consumption and production chosen in this example. For electricity mixes with greater variations in environmental impact between time steps, non-dominated solutions will be more time-dependent and therefore storage will have a more important role.

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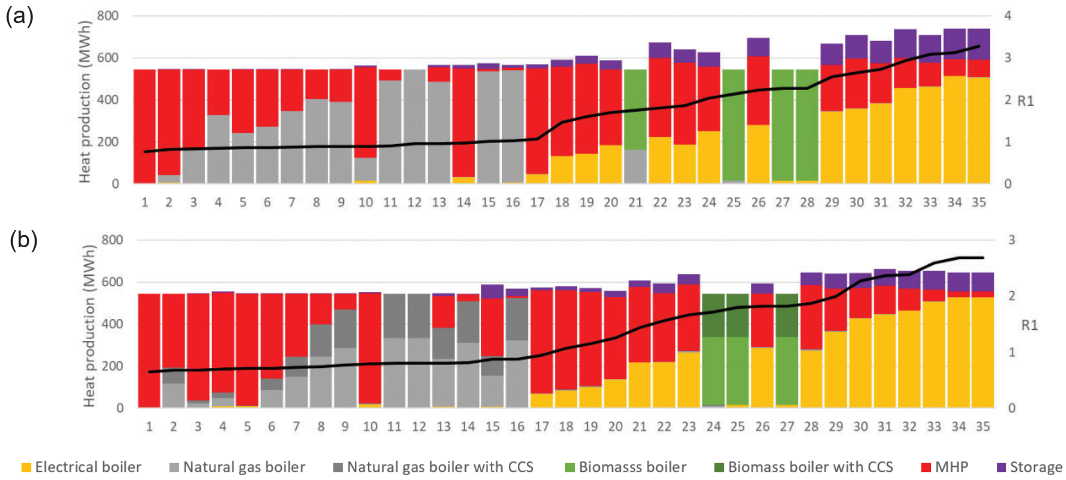
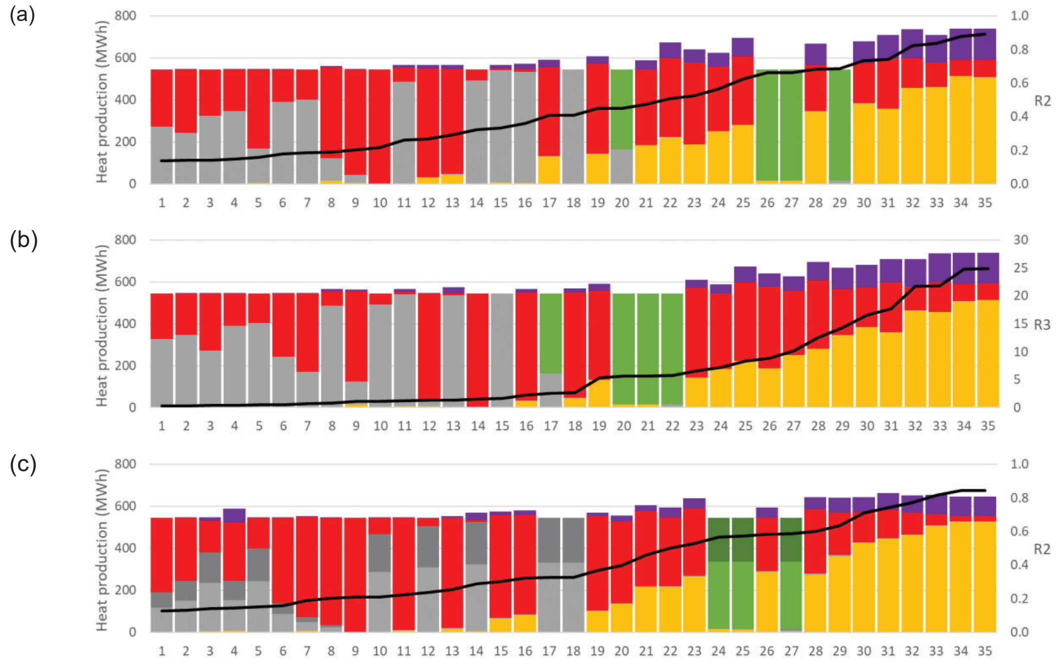


**Fig. 5 –** Non-dominated solutions ranked with method R1 using EF 3.0 ponderation factor for (a) years 2015-2040, (b) years 2065-2090. The score R1 is displayed with the black line.

The use of the R2 and R3 ranking methods, for which the higher the threshold exceedance, the higher the penalty, leads to significant changes compared to the R1 approach as presented in Fig. 6. The greater the penalty for exceeding global limits, the greater the share of gas combined with CCS development in the optimal solutions. Indeed, gas performs well in indicators for which electricity does not, and vice versa, which results to impacts closer to sustainable levels with fewer high-performing impact categories but simultaneously fewer categories far above the thresholds. Biomass boiler also benefits from these two-ranking methods but in a more limited way. On the other hand, the more we penalise exceeding the limits, the more the best ranked solutions exceed the threshold for the climate change indicator. For the period 2015-2040, among the 10 best solutions, only 2 meet the threshold for climate change whereas there were 4 with the R1 ranking method. The presence of CCS combined with the improvement of the carbon content of electricity increases this number to 7 solutions respecting the sustainable level for climate change over the period 2065-2090 while the R1 classification method is 9.



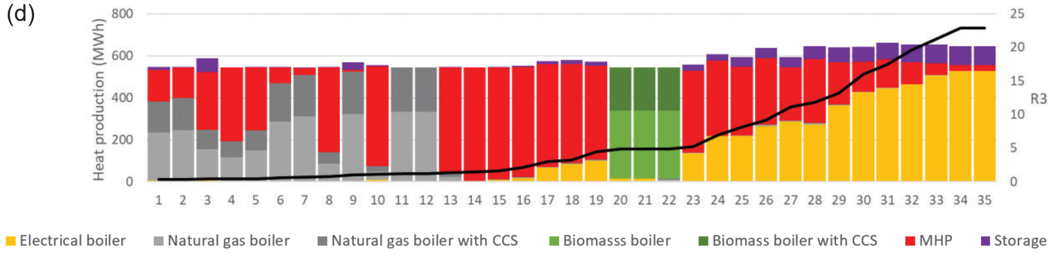


**Fig. 6 –** Non-dominated solutions ranked with method (a) R2 for the years 2015-2040, (b) R3 for the years 2015-2040, (c) R2 for the years 2065-2090, (d) R3 for the years 2065-2090. The score R2 and R3 are displayed with the black line.

Based on the results, it is possible to imagine two types of approaches to bring the industrial activity back to sustainable levels. The first approach requires each process to respect the global limits by defining a safe operating space for each process. This approach corresponds to the development of solutions where exceeding sustainable levels is strongly penalised, i.e. ranking method R3. The second approach requires each process to implement the best possible solution and therefore to adapt the process safe operating space for each impact category based and their ability to perform. However, this requires a comprehensive review of all human activities to ensure that the entire range of human activities is able to meet the thresholds of sustainability. The first method is simpler to implement because it is only necessary to allocate a share of the impacts to each process, whereas for the second method it is necessary to have a breakdown by impact category for each process. On the other hand, the first method will tend to ask for solutions as close as possible of the sustainable threshold (i.e. never the best but never the worst), which results in a multiplication of energy sources, and therefore in a multiplication of system for the industries to deal with, which increases the level of complexity on site.

However, if the transformation of industrial heat production means is oriented towards achieving the climate change objective, some impact categories are likely to exceed the sustainable limits. Fig. 7 shows that the best solutions with ranking method R3 are above the sustainable threshold for climate change for the period 2015-2040. The best solution for climate change indicator is ranked only 14th with the R3 method in 2015-2040 and 20th in 2065-2090, while the best solution with method R1 is also the best for the climate change indicator. However, high performing solutions on climate change exceed the sustainable levels on some other criteria, which explains their ranking with the R3 method, as can be seen in Fig. 7. Therefore, it is not possible to reach the sustainable level with the technology proposed and the safe operating space available for the process based on added value. This means that the safe operating space allocated to the process will not be sufficient to enable it to stay below the threshold. There are two ways to have sufficient safe operating space for the process:

(i) If the process needs to continue at the current level (e.g. for a vital process), other processes need to decrease in order for it to leave enough operating space.
(ii) this process must decrease

This will result in a modification of certain sectors of activity by reducing the operating space of some sectors that will be considered less essential or sufficiently efficient to leave enough safe operating space to sectors considered as essential. A reflection on this allocation is therefore essential to define the place of each sector in a sustainable world according to numerous technical parameters but also around political or sociological themes.

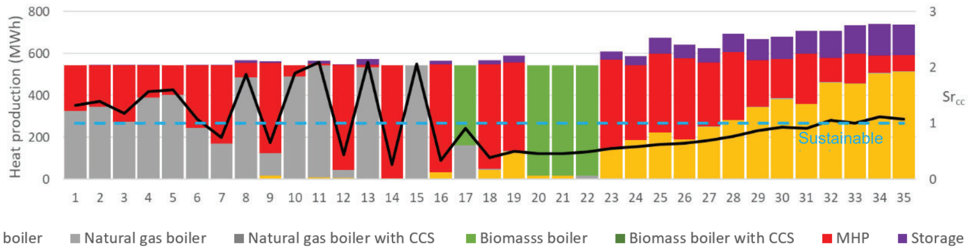


**Fig. 7 –** Non-dominated solutions ranked with method R3 for the years 2015-2040. The sustainable ratio for climate change is display in black and the sustainable level in blue.

## 4. Conclusions & Recommendations

In this paper, a method has been developed to optimize, from an energy, economic and environmental point of view, the combination of energy systems to be used to produce heat for a dynamic industrial process. The energy mix uses combinations of different possible technologies such as electric, gas and biomass boilers or heat pumps powered by waste heat or thermal storage. An optimisation model, based on LCA criteria, enables to obtain a number of non-dominated solutions. Even if some solutions enable to reduce some impact categories, no solution was found to reach sustainable levels for all impact categories. Thus, the best performing solutions on the climate change indicator also exceed the sustainable level for several other environmental impact indicators such as land use, toxicity, eutrophication or resource use fossil. By ranking the non-dominated solutions, using different weighting criteria, it can be seen that the more one penalizes the exceeding of sustainable levels for each impact category, the more mixed solutions are present and in particular the combination of MHP and gas boiler.

The results show that none of the studied solutions can reach a sustainable level regardless of the technology used and this, despite the use of resolution algorithms to highlight the best performing solution. This assessment shows that it is necessary to have a reflection on the share that each process can represent in human activities. It is possible to envisage this redistribution in two ways, (i) by requiring an identical effort from all sectors to reach the targeted level or (ii) by determining, according to the needs and potential of each sector, its maximum acceptable contribution for each impact category. The latter method requires in-depth knowledge of the potential of each sector, which could be determined using the optimization model presented in this paper but on a larger scale. For both approaches, it is essential to think holistically so that all human activities are taken into account and not to look at each sector individually to conclude about sustainability.

## References

[1] Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.), « IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change », doi: 10.1017/9781009157896.001.

[2] P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.), « IPCC, 2022: Summary for Policymakers. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change », doi: 10.1017/9781009157926.001.

[3] P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.), « AR6 Climate Change 2022: Mitigation of Climate Change — IPCC ». Consulté le: 11 octobre 2022. [En ligne]. Disponible sur: https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/

[4] IPBES, « Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services », Zenodo, mai 2019. doi: 10.5281/ZENODO.3831673.

[5] J. Rockström *et al.*, « Planetary Boundaries: Exploring the Safe Operating Space for Humanity », *E&S*, vol. 14, nº 2, p. art32, 2009, doi: 10.5751/ES-03180-140232.

[6] W. D. Chen et K. J. Chua, « Energy, exergy, economic, and environment (4E) assessment of a temperature cascading multigeneration system under experimental off-design conditions », *Energy Conversion and Management*, vol. 253, p. 115177, févr. 2022, doi: 10.1016/j.enconman.2021.115177.

[7] M. Yu, X. Liu, Z. Liu, et S. Yang, « Energy, exergy, economic and environmental (4E) analysis of a novel power/refrigeration cascade system to recover low-grade waste heat at 90–150 °C », *Journal of Cleaner Production*, vol. 363, p. 132353, août 2022, doi: 10.1016/j.jclepro.2022.132353.

[8] A. Bjørn, « Better, but good enough? », PhD Thesis.

[9] M. Vargas-Gonzalez *et al.*, « Operational Life Cycle Impact Assessment weighting factors based on Planetary Boundaries: Applied to cosmetic products », *Ecological Indicators*, vol. 107, p. 105498, déc. 2019, doi: 10.1016/j.ecolind.2019.105498.

[10] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, et B. Weidema, « The ecoinvent database version 3 (part I): overview and methodology », *Int J Life Cycle Assess*, vol. 21, nº 9, p. 1218-1230, sept. 2016, doi: 10.1007/s11367-016-1087-8.

[11] M. Z. Hauschild, R. K. Rosenbaum, et S. I. Olsen, Éd., *Life Cycle Assessment*. Cham: Springer International Publishing, 2018. doi: 10.1007/978-3-319-56475-3.

[12] M. Veyron, A. Voirand, N. Mion, C. Maragna, D. Mugnier, et M. Clausse, « Dynamic exergy and economic assessment of the implementation of seasonal underground thermal energy storage in existing solar district heating », *Energy*, vol. 261, p. 124917, déc. 2022, doi: 10.1016/j.energy.2022.124917.

https://doi.org/10.52202/069564-0258

[13] F. Bühler, « Energy efficiency in the industry: a study of the methods, potentials and interactions with the energy system », DTU Mechanical Engineering : DCAMM, Lyngby, 2018. [En ligne]. Disponible sur: https://orbit.dtu.dk/en/publications/energy-efficiency-in-the-industry-a-study-of-the-methods-potentia

[14] H. Pieper, I. Krupenski, W. Brix Markussen, T. Ommen, A. Siirde, et A. Volkova, « Method of linear approximation of COP for heat pumps and chillers based on thermodynamic modelling and off-design operation », *Energy*, vol. 230, p. 120743, sept. 2021, doi: 10.1016/j.energy.2021.120743.

[15] I. Sarbu et C. Sebarchievici, « A Comprehensive Review of Thermal Energy Storage », *Sustainability*, vol. 10, nº 1, p. 191, janv. 2018, doi: 10.3390/su10010191.

[16] B. Koçak, A. I. Fernandez, et H. Paksoy, « Review on sensible thermal energy storage for industrial solar applications and sustainability aspects », *Solar Energy*, vol. 209, p. 135-169, oct. 2020, doi: 10.1016/j.solener.2020.08.081.

[17] Susana Paardekooper, Rasmus Søgaard Lund, Brian Vad Mathiesen, Miguel Chang, Uni Reinert Petersen, Lars Grundahl, Andrei David, Jonas Dahlbæk, Ioannis Aristeidis Kapetanakis, Henrik Lund, Nis Bertelsen, Kenneth Hansen, David William Drysdale, Urban Persson, « Heat Roadmap Italy: Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps ». [En ligne]. Disponible sur: https://heatroadmap.eu/roadmaps/

[18] K. Riahi *et al.*, « Cost and attainability of meeting stringent climate targets without overshoot », *Nat. Clim. Chang.*, vol. 11, nº 12, p. 1063-1069, déc. 2021, doi: 10.1038/s41558-021-01215-2.

[19] S. García-Freites, C. Gough, et M. Röder, « The greenhouse gas removal potential of bioenergy with carbon capture and storage (BECCS) to support the UK's net-zero emission target », *Biomass and Bioenergy*, vol. 151, p. 106164, août 2021, doi: 10.1016/j.biombioe.2021.106164.

[20] V. Bisinella, T. Hulgaard, C. Riber, A. Damgaard, et T. H. Christensen, « Environmental assessment of carbon capture and storage (CCS) as a post-treatment technology in waste incineration », *Waste Management*, vol. 128, p. 99-113, juin 2021, doi: 10.1016/j.wasman.2021.04.046.

[21] S. Budinis, S. Krevor, N. M. Dowell, N. Brandon, et A. Hawkes, « An assessment of CCS costs, barriers and potential », *Energy Strategy Reviews*, vol. 22, p. 61-81, nov. 2018, doi: 10.1016/j.esr.2018.08.003.

[22] A. Babin, C. Vaneeckhaute, et M. C. Iliuta, « Potential and challenges of bioenergy with carbon capture and storage as a carbon-negative energy source: A review », *Biomass and Bioenergy*, vol. 146, p. 105968, mars 2021, doi: 10.1016/j.biombioe.2021.105968.

[23] L. Ramirez Camargo, « Hourly electricity load profiles of paper producing and food processing industries ». Mendeley, 19 mars 2021. doi: 10.17632/TTX9CHKDCG.1.

[24] « MATLAB Optimization Toolbox ». The MathWorks, Natick, MA, USA.

[25] A. Neumann, A. Hajji, M. Rekik, et R. Pellerin, « A Didactic Review On Genetic Algorithms For Industrial Planning And Scheduling Problems* », *IFAC-PapersOnLine*, vol. 55, nº 10, p. 2593-2598, 2022, doi: 10.1016/j.ifacol.2022.10.100.

[26] A. K. Kesarwani, M. Yadav, D. Singh, et G. D. Gautam, « A review on the recent applications of particle swarm optimization & genetic algorithm during antenna design », *Materials Today: Proceedings*, vol. 56, p. 3823-3825, 2022, doi: 10.1016/j.matpr.2022.02.200.

[27] R. C. Peralta, A. Forghani, et H. Fayad, « Multiobjective genetic algorithm conjunctive use optimization for production, cost, and energy with dynamic return flow », *Journal of Hydrology*, vol. 511, p. 776-785, avr. 2014, doi: 10.1016/j.jhydrol.2014.01.044.

[28] S. Elsoragaby *et al.*, « Applying multi-objective genetic algorithm (MOGA) to optimize the energy inputs and greenhouse gas emissions (GHG) in wetland rice production », *Energy Reports*, vol. 6, p. 2988-2998, nov. 2020, doi: 10.1016/j.egyr.2020.10.010.

[29] W. Willett *et al.*, « Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems », *The Lancet*, vol. 393, nº 10170, p. 447-492, févr. 2019, doi: 10.1016/S0140-6736(18)31788-4.

[30] A. W. Hjalsted, A. Laurent, M. M. Andersen, K. H. Olsen, M. Ryberg, et M. Hauschild, « Sharing the safe operating space: Exploring ethical allocation principles to operationalize the planetary boundaries and assess absolute sustainability at individual and industrial sector levels », *Journal of Industrial Ecology*, vol. 25, nº 1, p. 6-19, févr. 2021, doi: 10.1111/jiec.13050.

[31] Y. Jovet, A. Laurent, N. A. Kermani, F. Lefevre, B. Elmegaard, et M. Clausse, « Environmental assessment of electrification of food industry for Denmark and France », présenté à ECOS 2022 35th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, juill. 2022. Consulté le: 2 novembre 2022. [En ligne]. Disponible sur: https://hal-insa-lyon.archives-ouvertes.fr/hal-03715592