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Highlights:

- Climate change footprint is studied taking the life cycle of the whole energy system
- Mechanical heat pumps (MHP) are considered as alternatives to natural gas boilers
- MHP can help to achieve the Paris Agreement targets in EU countries by 2050
- Energy price ratios to make MHP competitive are identified for different performance
- Impact of carbon tax on MHP competitiveness is assessed for several EU members

Abstract

The recovery of waste heat represents a promising opportunity to reduce greenhouse gas (GHG) emissions from industrial sectors. The current development of heat recovery technologies can provide industries with several options for retrofitting their heat generation systems. Although past studies estimated the resulting savings in GHG emissions for specific industries or facilities, work is still needed to fully substantiate the expected benefit and the competitiveness of these alternatives, taking into account data at country scale (e.g. long-term reduction targets, energy cost, etc.). Hence, in this study, a new methodology is developed to determine the minimum conditions for waste heat recovery solutions to enable compliance with the targets from the Paris Agreement, taking 2030 and 2050 as reference years. It is applied to several industrial sectors for 24 EU countries, focusing on mechanical heat pump solutions (MHPs). Results indicate that all countries are compliant in 2050 for MHP integration with low temperature lift (like ammonia production) and 21 countries are compliant for high temperature lift (like food industry). The main constraint to the development of the MHP technology in 2030 is found to be economic, while in 2050, the main barrier for countries that do not reach the reduction targets is a too high carbon intensity of electricity generation. To accommodate the relatively long lifetime of the heat production system, the future MHP roadmap should therefore anticipate these potential barriers including carbon footprint of electricity network, working fluids and gas to electricity price ratio. In addition to meeting the 2030 requirements by a large margin, this strategy would factor in constraints associated with the long-term investments in MHPs. To further expand such foresight analysis, our methodology can be duplicated to other technologies than MHPs, so it can help industry decision-makers select the most suitable waste heat recovery options for a given industrial process in a specific country.

Nomenclature

Latin letters

Bcc	Climate change balance ($kgCO_2eq$)
C	Cost per unit of energy (€/MWh)
$C_{ng,min}$	Gas price for economic profitability (€/MWh)
h	Operating hours per year (h/year)
If_{el}	Impact intensity of electricity ($kgCO_2eq$/MWh)
$If_{el,max}$	Impact intensity of electricity for environmental conformity ($kgCO_2eq$/MWh)
If_{MHP}	Impact intensity of mechanical heat pump ($kgCO_2eq/MW_{el}$)
If_{ng}	Impact intensity of natural gas ($kgCO_2eq$/MWh)
If_{wf}	Impact intensity of working fluid ($kgCO_2eq$/kg)
La	Annual refrigerant leakage (%)
Le	End of life refrigerant leakage (%)
n	Heat pump lifespan (years)
m_{wf}	Mass of refrigerant (kg)
$\dot{Q}$	Heat flow (MW)
R	Target reduction of the environmental footprint (%)
T	Temperature (K)
$\dot{W}_{el}$	Electrical power (MW)

Acronym

CAPEX	Capital expenditure (€)
COP	Coefficient of performance
EU	European union
GHG	Greenhouse gas
IPCC	Intergovernmental Panel of Climate Change
MHP	Mechanical heat pump
OPEX	Operational expenditure (€/year)
PBP	Payback period (years)

Subscripts

el	Electrical
EoL	End of life
lift	Temperature lift
MHP	Mechanical Heat Pump
ng	Natural gas
rec	Recovered
ref	Reference case
up	Upgraded to be used by process
wf	Working fluid

1. Introduction

Anthropogenic emissions of greenhouse gases (GHG) are currently at unsustainable levels [1]. The Paris Agreement, ratified by most UN parties in 2015, is still far from being fully implemented, and efforts are still needed to keep the increase in global average temperature below 1.5 or 2 degrees compared with pre-industrial levels. Industry has been recognised as a major contributor of GHG emissions, reported to be associated with about 25% of total energy and process-related CO_2 emissions [2]. Industry thus represents the second largest GHG emission reduction potential after the energy sector with a total of 5.4 $GtCO_2eq$ in 2030 [3]. The related decarbonisation objectives can be achieved at several levels. The Sustainable Process Industry through Resource end Energy Efficiency (SPIRE) association thus classified four different objectives [4]: (i) increase energy and resource efficiency; (ii) create industrial symbiosis (e.g. cross-sectoral application of technologies); (iii) integrate new processes and materials for market applications; and (iv) avoid, valorise and re-use waste streams.

There are several alternatives to gas generation systems. The solutions that currently have the most potentials are biomass production, district heating production from waste incineration and electrification [5], [6]. For biomass production, according to environmental data from the Ecoinvent database [7], a potential GHG emission reduction of between 5% and 93% can be expected, depending on the type of biomass, plant capacity and system efficiency. This may be a viable option for meeting GHG reduction targets under specific conditions, but there are other environmental issues, such as land or water use, that might be inadvertently increased and should be investigated for such systems [8]. For the waste incineration system, the associated GHG emissions of the combustion can be almost 3 times higher than the natural gas solution, considering data from Ecoinvent database [7]. As the majority of European countries currently recover heat from incineration, a factor of 50% of the impact should therefore be attributed to heat production as defined in the European Commission's circular footprint formula [9]. This allocation results in an impact of the same order of magnitude as the natural gas solution. Factoring in the above considerations and limitations, the current study is therefore intended to focus on the recovery of waste heat using MHP.

Among several possible actions, waste heat valorisation is key to achieve these SPIRE objectives. Waste heat as a resource is defined by Bendig et al. [10] as the “exergy that unavoidably leaves a process or is lost within it, independent of the technological choices made within the process“. As reported in the literature, energy savings from waste heat recovery are highly dependent on the industrial sector, ranging from 5 to 30% [11], [12]. Taking Europe as an example, the potential of waste heat recovery in industry has been estimated to range between 300 and 375 TWh/year [12]–[15]. When put into perspective with a total heat requirement in Europe estimated at 1820 TWh/year, this demonstrates the relative importance that waste heat recovery in industry could bring to the energy sector and its contribution to achieving more sustainable energy systems. Papapetrou et al. [14] have proposed a temperature-dependent breakdown of the European waste heat potential and have estimated that one-third of this energy is available between 100 °C and 200 °C. Among the different possibilities of using heat within the site, in-process reuse seems the most relevant because it accounts for more than half of the total energy consumption of the industrial sector [14]. In this study, the focus is therefore on heat reused in industry. Although electricity production may also be relevant to some industries, it is considered outside the scope of the study.

From a technical perspective, the valorisation of waste heat often requires a temperature upgrade of the heat. Several heat pump technologies have been developed to comply with the industry requirements in terms of heat capacity and operating temperatures. They can be classified in three types: (i) Mechanical Heat Pump (MHP), (ii) absorption heat transformer, (iii) thermochemical heat transformer. While thermochemical heat transformers are largely immature technologies at present, absorption heat transformers and MHPs are already used at commercial scale with operating temperatures up to 165 °C [16], [17]. The next challenge for these two technologies is however to increase the operating temperature, and several research works are ongoing in this regard, e.g. Danish SuPrHeat project aiming to reach 200 °C with natural refrigerants by 2024 [18]. Brückner et al. [19] have shown that MHP have many advantages that can facilitate their development in industry compared to the absorption solution. The advantages highlighted include their level of development in the market, their small size facilitating integration into existing sites and greater ease of control to adjust production as required. With regard to GHG emission savings, while the implementation of absorption heat transformers or thermochemical heat transformers directly leads to GHG emission reductions (due to limited electricity consumption compared to the achieved heat capacity), the relevance of MHP is highly dependent on the CO_2 content of the electricity driving the system, which must be taken into account in an appropriate manner.

Until now, the majority of studies have focused on the economic and energy aspects when choosing or sizing a process heating technology. This pool of studies can be separated into 2 main categories:

- *Micro-level studies.* Several studies have focused on assessing the performance of MHP integration in specific contexts, e.g. at single technology and process levels [20]–[27]. They often adopt an exergo-economic approach for this purpose. Oluleye et al. [28] modelled the energy and economic savings as a function of MHP operating conditions for a refinery application. In another example, Wallerand et al. [22] proposed to combine Pinch analysis and exergo-economy analysis to derive the performance from process parameters (e.g. heat load). Although these studies provide a good insight into technical and economic performance, they rarely address sustainability considerations (e.g. the ability to reduce GHG emission which are a key element in the SPIRE roadmap for industrial transformation. Some studies, such as Oluleye et al. [28] and Zuberi et al. [24] carry out such assessments for MHP technology, suggesting that MHP solution can lead to GHG reductions in this specific context. These studies do not assess the replicability potential of a technology which is context-dependant and therefore it is not possible to deduce the impact of a large scale deployment at sectoral level..

- *Macroscale studies*. Several large-scale studies have been performed to estimate the potential of heat pumps for waste heat recovery at national or international levels [12], [15], [29], [30]. These studies have established the potential of MHP on the market and have shown a significant potential to reduce fossil fuel consumption. Although they describe the relevance of MHP, all these macroscale studies have however two major limitations as (i) they do not consider the specific constraints of each industry (e.g. specific heat load, implementation into the existing process, specific heat losses, etc.), (ii) they only consider energy and economic performance and dismiss environmental considerations.

Micro-level studies are not necessarily transferable or scalable from one context to another, hence macro scale studies, which address the aforementioned limitations of existing studies, are needed to identify and prioritise sectors where the integration of MHP technologies is the most relevant. These studies could therefore be used by decision-makers to target the implementation of MHP in sectors with energy, economic and GHG emission mitigation benefits. With regard to the latter, no studies have quantified the GHG emission reduction potential of MHP at the national and international levels while relating to climate change objectives such as those specified in the Paris Agreement. It is indeed important not only to reduce GHG emissions, but to ensure that these reductions are consistent with national and international GHG emission reduction targets [31], [32].

Hence, the purpose of this study is to bridge the gaps in these past studies and to fully explore the economic, technical and climate change mitigation potentials of MHPs. To this end, we aim to (i) convert the environmental constraints of GHG emission reductions into performances required for waste heat recovery, (ii) study the economic conditions that would allow the waste heat recovery technologies to replace current ones, and thus set minimum requirements for industry, and (iii) apply the proposed methodology to the replacement of natural gas heat production by waste heat valorisation with MHP in European countries. Although replicable to other countries and regions or others technologies, the methodology is applied in a European context, owing to its clearly defined GHG emission reduction targets, i.e. 35% reduction in 2030 and 85% reduction in 2050. A macroscopic approach is used to determine the requirements for the different EU countries using current and 2050 trends for economic, energy and environmental aspects such as energy prices, carbon footprint of electricity, carbon tax, etc.

2. Methods and Material

2.1. Assessment framework

Fig. 1 presents the energy, environment, and economic assessment methodology for determining the minimum requirements for MHP technologies to be in line with both industrial demands and European GHG reduction strategies. The energy consumption is based on the reference configuration (or current configuration) to calculate the technology to be evaluated, here heat recovery technology but can be adapted to others technologies. This assessment provides the energy consumption and power of the systems, which are used as inputs for the economic and carbon footprint models. From these inputs, the model evaluates the required conditions for achieving the economic and GHG reduction targets. It is then possible to conclude with the energy performance to be achieved to meet the objectives.

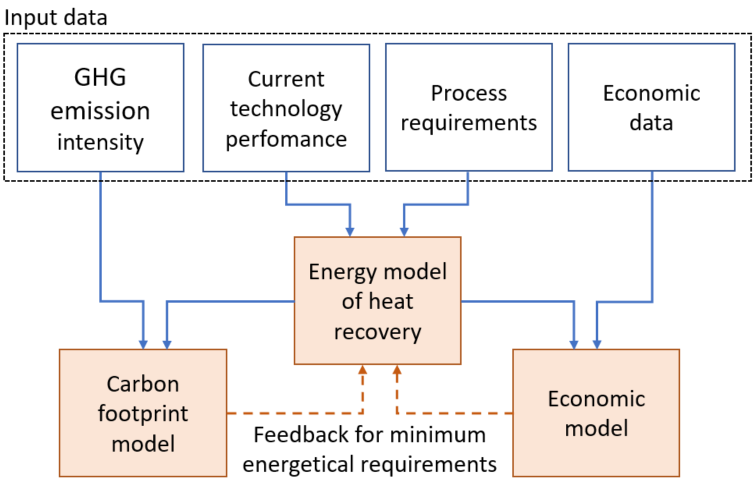


Fig. 1 – Proposed assessment framework to add carbon footprint and economic constraints within the energy model

2.2. Energy model description

To keep the energy model as simple as possible, Eq. 1 and Eq.2 are used to assess the performance of the heat pumps:

$$\dot{W}_{el} = \dot{Q}_{up} - \dot{Q}_{rec} \tag{1}$$

$$\dot{Q}_{up} = \dot{Q}_{rec} \frac{COP}{COP - 1} \tag{2}$$

where $\dot{Q}_{up}$ is the upgraded heat flow ready to be used in the industrial process and $\dot{Q}_{rec}$ is the waste heat flow.

Schlosser et al. [33] provide a relationship for the coefficient of performance (COP), which is a regression obtained on the basis of MHPs currently available on the market:

$$\mathrm{COP} = 1.9118 \times (T_{\mathrm{up}} - T_{\mathrm{rec}} + 0.088378)^{-0.89094} \times (T_{\mathrm{up}} + 0.044189)^{0.67895} \quad (3)$$

where T_{up} is the industrial process temperature in K. This equation was obtained for a temperature of waste heat T_{rec} between 80 °C and 160 °C and a temperature lift, $\Delta T_{lift} = T_{\mathrm{up}} - T_{\mathrm{rec}}$, between 25 K and 95 K.

As it is not possible to integrate the specificity of the processes into this macro study, the energy consumption is estimated assuming that the system is adiabatic and that the power consumption of the auxiliaries (circulation pumps, control system) can be neglected compared to that of the MHP compressor [34]. MHP electricity consumption is assumed to come 100 % from the national grid, so that intermittency of supply is not an issue. All systems are considered as adiabatic and operating at steady state, and upgraded heat covers 100 % of the process demand. These favourable assumptions imply that the solutions that are not viable in this study will not meet the targets without a technology breakthrough and that the solutions that do meet the targets still requires specific studies to ensure their feasibility. Nevertheless, the model could easily be adapted to a specific industrial case.

2.3. Carbon footprint model

Carbon footprint was carried out to quantify the impact of climate change stemming from the life cycle of heat production technologies. Carbon footprint can be regarded as a truncated life cycle assessment [35], where GHG emissions are inventoried over the entire life cycle of the system and translated into impact indicator scores (expressed here in [$kgCO_{2eq}$]) by means of the global warming potentials (GWP) issued by the IPCC [36]. The climate change impact indicator (Bcc, expressed in $kgCO_{2eq}$) can therefore be calculated as the difference between the carbon footprint of the current heat production and the carbon footprint of the recovered heat system, as developed in Eq. 4:

$$\begin{aligned}\mathrm{Bcc} = &\left(\dot{Q}_{\mathrm{up}} \cdot \mathrm{If}_{\mathrm{ref}} - \dot{W}_{\mathrm{el}} \cdot \mathrm{If}_{\mathrm{el}}\right) \cdot \mathrm{h} \cdot \mathrm{n} - \dot{W}_{\mathrm{el}} \cdot \mathrm{If}_{\mathrm{MHP}} \\ &- \mathrm{m}_{\mathrm{wf}}\left(\mathrm{If}_{\mathrm{wf}} \cdot (\mathrm{La} \cdot \mathrm{n} + \mathrm{Le}) - \mathrm{If}_{\mathrm{EoL}} \cdot (1 - \mathrm{Le})\right)\end{aligned} \quad (4)$$

Where If_{ref} indicates the climate change impact intensity of reference (or current) energy source in [$kgCO_{2eq}$/MWh], If_{el} is related to the energy used by the MHP during operation expressed in [$kgCO_{2eq}$/MWh], If_{wf} [$kgCO_{2eq}$/kg] to the working fluid, m_{wf} being the refrigerant charge in [kg]. If_{MHP} is the impact of production and disposal of MHP in [$kgCO_{2eq}/MW_{el}$], which is based on its electrical power $\dot{W}_{el}$. If_{EoL} is the impact of end-of-life treatment in [$kgCO_{2eq}/kg$] of the mass of working fluid, *La* is the annual leakage rate in percentage of total mass, *Le* the end of life leakage rate in percentage of total mass, *h* is the number of working hours per year, *n* is the lifetime of the heat recovery system in years. The impact intensity *If* were derived using the ReCiPe 2016 life cycle impact assessment methodology (v. 1.04 ; Huijbregts et al. 2017 [37]), which contains the GWP from the IPCC for assessing climate change impacts, combined with emission intensities from the ecoinvent database (v. 3.6, [38]).

It should be noticed that compared to the TEWI (Total Equivalent Warming Impact) indicator, which is widely used in assessing the CO2 impact of mechanical heat pumps [39], the proposed methodology goes further to assess MHP impact by integrating imported emissions: refrigerant on its whole life cycle, MHP manufacturing, etc.

By integrating eq. (1) and (2) into eq. (4), Bcc can thus be expressed as a function of COP and $\dot{Q}_{rec}$:

$$\mathrm{Bcc} = \frac{\dot{Q}_{rec}}{\mathrm{COP}-1}\left[\mathrm{h}\cdot\mathrm{n}\cdot(\mathrm{COP}\cdot\mathrm{If}_{ref}-\mathrm{If}_{el})-\mathrm{If}_{MHP}\right] - \mathrm{m}_{wf}\left(\mathrm{If}_{wf}\cdot(\mathrm{La}\cdot\mathrm{n}+\mathrm{Le})-\mathrm{If}_{EoL}\cdot(1-\mathrm{Le})\right) \quad (5)$$

From this equation, it is possible to calculate the maximum value of the carbon content of the electricity ($If_{el,max}$) consistent with the target percentage reduction of the carbon footprint *R*:

$$\mathrm{If}_{el,max} = \frac{1}{\dot{Q}_{rec}\cdot\mathrm{h}\cdot\mathrm{n}}\Big[(1-\mathrm{R})\cdot\dot{Q}_{rec}\cdot\mathrm{h}\cdot\mathrm{n}\cdot\mathrm{COP}\cdot\mathrm{If}_{ref}-\dot{Q}_{rec}\cdot\mathrm{If}_{MHP} - (\mathrm{COP}-1)\,\mathrm{m}_{wf}\left(\mathrm{If}_{wf}\cdot(\mathrm{La}\cdot\mathrm{n}+\mathrm{Le})-\mathrm{If}_{EoL}\cdot(1-\mathrm{Le})\right)\Big] \quad (6)$$

For a given target of GHG reduction *(R)* and a given *COP*, Eq. 6 provides the minimum electricity carbon content ($If_{el,max}$) to be achieved. It should be noted that the carbon footprint impact of the auxiliaries related to the operating of the MHP is not included in the environmental model to be consistent with the energy model. At EU level, GHG emission reduction targets have been defined between 34% and 40% in 2030 and between 83% and 87% in 2050 compared to 1990 [40]. When addressing country-specific evaluations, an even distribution of these targets is assumed across EU countries, meaning that each country is subject to the same reduction targets of 35% in 2030 and 85% in 2050.

2.4. Economic model

The economic criterion used for this study is the payback period (*PBP*). The flexibility requirements of industrial production sites make investments over long periods more complex. The choice to focus on the payback time rather than net present value is intended to address the potential lack of long-term visibility for the industries. The economic equations (7) and (8) consider the costs of installation (CAPEX) and the maintenance (OPEX), the purchase of electricity and the savings on the current source of energy.

$$\mathrm{PBP} = \frac{\mathrm{CAPEX}}{\mathrm{savings}} = \frac{\mathrm{CAPEX}}{\dot{\mathrm{Q}}_{\mathrm{up}} \cdot \mathrm{h} \cdot \mathrm{C}_{\mathrm{ref}} - \dot{\mathrm{W}}_{\mathrm{el}} \cdot \mathrm{h} \cdot \mathrm{C}_{\mathrm{el}} - \mathrm{OPEX}} \tag{7}$$

Where *C* is the price per unit of energy used to calculate the annual price of the energy consumption for the reference solution, or the electricity price for the heat pump. *CAPEX* and *OPEX* are respectively the capital and operational expenditure.

By introducing Eq. (1) and (2) into Eq. (7), the following equation for PBP depending on COP and available waste heat is obtained:

$$\mathrm{PBP} = \frac{\mathrm{CAPEX}}{\frac{\dot{\mathrm{Q}}_{\mathrm{rec}}}{\mathrm{COP} - 1} \cdot (\mathrm{COP} \cdot \mathrm{C}_{\mathrm{ref}} - \mathrm{C}_{\mathrm{el}}) \cdot \mathrm{h} - \mathrm{OPEX}} \tag{8}$$

By rearranging Eq. (8), the minimum price of the current energy production, below which heat recovery is not compatible with the payback time is given by:

$$\mathrm{C}_{\mathrm{ref,min}} = \frac{1}{\mathrm{COP}} \left[\mathrm{C}_{\mathrm{el}} + \frac{(\mathrm{COP} - 1) \times \left(\frac{\mathrm{CAPEX}}{\mathrm{PBP}} + \mathrm{OPEX} \right)}{\dot{\mathrm{Q}}_{\mathrm{rec}} \cdot h} \right] \tag{9}$$

For a given industrial process, this equation shows that the minimum price of the current energy production ($C_{ref,min}$) is an affine function of the electricity price.

The energy costs for both natural gas and electricity depend on the considered European members. They are given by Eurostat data for costs with non-recoverable taxes for the second half of 2020 [41], [42]. The values used are those currently in force in Europe. No changes in energy prices are considered in the following because the projections show no significant evolution in the near future [43].

2.5. Case study

Since it is widely used in the industry, gas is taken as the reference energy source for heat production. Indeed, it represents 34% of the total energy consumed in European industries and its replacement by a less carbon-intensive form of energy would have a significant impact on the achievement of the Paris

Agreement targets [33]. For the sake of simplicity, an efficiency of 100% is assumed for the gas boiler. Therefore, If_{ref} and C_{ref} can be replaced by If_{ng} and C_{ng} in Eq. (6) and (8).

As it can be seen in Table 1, both high-temperature and very high-temperature heat pumps are considered to replace the gas boiler. The temperature ranges were set according to the survey performed by Schlosser et al. [33], and their value reported in Table 1.

Table 1 - Range of variation of the parameters

	LOWER VALUE	HIGHEST VALUE
T_{REC} [°C]	70	130
T_{UP} [°C]	90	150
ΔT_{LIFT} [°C]	20	60

Because of confidentiality issues, available data on temperature requirements in industrial processes are scarce. For the present work, values given by Cudok et al. [44] are considered (Table 2). For this case study, we assume an even GHG reduction requirement for all the industrial processes.

Table 2 - Process temperature levels used in this study based on [44]

	FOOD INDUSTRY	ALCOHOL PRODUCTION	POLYCRYSTALLINE SILICON	POLY FILM MANUFACTURING	AMMONIA PRODUCTION	CHEMICAL INDUSTRY
T_{UP} [°C]	144.5	158	144	157	125	125
ΔT_{LIFT} [K]	48.4	38	39	49	28	44

The reference values used for the carbon footprint study are presented in

Table 3. The current carbon content of electricity for each country is based on data from the European Environmental Agency [45], and the evolution of the carbon content is estimated for 2050 from the scenarios proposed by European Commission in ref. [46]. Only the EU countries for which all data are available for both the economic and GHG study are retained, representing 24 out of 27 EU countries.

The case study focuses on two working fluids, based on the work of Arpagaus et al [47]. The choice was made to compare fluids used in high temperature MHPs. The reference considered is R134a which is currently widely used and has a high GWP (i.e. 1300 $kgCO_{2eq}$/kg [36]). R1336mzz(Z) is considered as a very low GWP alternative fluid (2 $kgCO_2eq$/kg [36]).

Table 3 - Climate change impact intensities

Parameters	Impact intensity	Units	Ref.
Heat pump production and disposal, If_{MHP}	14.6	$kgCO_{2eq}/kW_{el}$[a]	[38]
Electricity 2018	varies by country[b]	$kgCO_{2eq}/kWh$	[45]
Electricity 2030 to 2050	varies by country[c]	$kgCO_{2eq}/kWh$	[46]
Heat from gas life cycle, If_{ng}	247	$kgCO_{2eq}/kWh$	[38]
Including operation, $If_{ng,comb}$	213	$kgCO_{2eq}/kWh$	[38]
R134a life cycle, If_{wf}	2361	$kgCO_{2eq}/kg$	[38]
Including operation stage	1300	$kgCO_{2eq}/kg$	[48]
Including end of life, If_{EoL}	776	$kgCO_{2eq}/kg$	[38]
R1336mzz(Z) life cycle, If_{wf}	12.1	$kgCO_{2eq}/kg$	[38]
Including operation stage	2	$kgCO_{2eq}/kg$	[48]
Including end of life, If_{EoL}	1.4	$kgCO_{2eq}/kg$	[38]

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

[b] Ranging from 9 to 922 kgCO2eq/kWh for 24 EU countries

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

Two scenarios are considered, including or excluding the imported emissions. When imported emissions are considered, all emissions across the life cycle are included. For the configuration without imported emissions, only emissions during operation are considered: CO_2 content of consumed electricity and refrigerant direct emission for MHP, and natural gas combustion for the reference boiler. These choices were made based on heat pump process from the ecoinvent life cycle inventory database [38].. The electricity carbon intensity values were extrapolated from the expected sources of electricity [22] and the current value of the GHG intensity of each generation source for all countries studied from ecoinvent database [15].

Additional reference values used for the application of the methodology are presented in Table 4. The number of annual operating hours was set at 8000 hours per year. This represents industries working 24 hours a day, 7 days a week with an annual closure of one month for maintenance. This choice is consistent with operations in countries like France, where, according to the French Environment and Energy Management Agency, 69% of industries in France operate at this rate [49].

Table 4 - Case study parameters

Parameters		Ref.
Operation hours, *h*	8000 hours	[49]
MHP Lifespan, *n*	20 years	[50]
Refrigerant load by power unit, m_{wf}	2 kg/kW	[51]
Annual leakage rate, *La*	5%	[51]
End of life leakage rate, *Le*	15%	[52]
CAPEX by power unit	0.7 M€/MW	[53]
CAPEX used in case study	3.5 M€	
Annual fix OPEX by power unit	3 k€/MW_{th}	[54]
Annual variable OPEX by energy unit	1.8 €/MWh_{th}	[54]
OPEX used in case study	87 k€/year	
Return time	5 years	[33] [55] [56]

A MHP installation cost of 0.7 M€/MW is chosen following Pieper et al. study [53]. It covers the full installation costs (machine, electrical and thermal connections, engineering, etc.) for heat pumps including low GWP refrigerants and for a capacity of 5 MW. The MHP share is about 40% of the total price according to [53] and about 50% according to [54]. This CAPEX value is higher than the range of 0.38 to 0.5 M€/MW_{th} found in [12], [28], [33], [57], which have only taken into account the CAPEX of the heat pump. The variation in installation costs according to the income level of the country does not necessarily seem to have a major impact. For example, the value estimated for Denmark [53] seems consistent with that proposed by Fleiter et al. [50] for Poland in 2015. Payback period is set at 5 years corresponding to the most favourable objective for an industrial project as reported in the literature [33], [55], [56].

3. Results and discussion

3.1. Carbon footprint analysis

3.1.1. Ability to reach the GHG reduction targets

Fig. 2 shows the maximum climate change impact of electricity as a function of the COP of the MHP to enable alignment with the European targets of 2030 and 2050. By comparing the 2030 target with and without imported emissions (Figs. 2b vs. 2a), it can be observed that GHG emissions are mainly territorially-based, and imported emissions only play a secondary role without being fully negligible in the total carbon footprint. This can be seen in the graph with the maximum carbon footprint of electricity being 11 to 14% higher when considering imported emission but electricity production is also impacted with an increase that differs according to the electricity mix, Poland for example sees its electricity carbon footprint increased by 6% in 2030 and 15% in 2050. It is worth noting that the excluded climate change impacts of non-territorial emissions for electricity generation (associated with, e.g., manufacturing of wind turbines components or photovoltaics outside Europe) are partially or even completely compensated by the increased climate change impacts stemming from the gas transport and extraction, heat pump production and disposal and refrigerant production and disposal (relative to electricity).

Not all EU countries, for which the grid mix performances in 2030 and 2050 are illustrated by the blue and red areas in Fig. 2a, are found to be capable of meeting the Paris Agreement targets (i.e. portions of the blue and red areas standing above the blue and red curves, respectively). The maximum allowable values of carbon footprint electricity differ depending on the type of fluid and his share on overall GHG impact. The share of R1336mzz(Z) on overall impact is lower than 1‰ in 2030 and 5‰ in 2050. For this low GWP refrigerant, the energy is driving the overall performance which is reflected by a significant gradient in Fig. 2. For R134a, on the other hand, which has a higher GWP, the refrigerant has a much higher share between 12% and 16% in 2030 and 53% and 69% in 2050. This fixed share, as it does not depend on the efficiency of the system, leads to a lower relative importance of energy and therefore a lower gradient. Based on the carbon footprint thresholds (blue and red curves in Fig. 2), a classification can be done for the different European countries, depending on the carbon footprint of their electricity grid mixes in 2030 and 2050 (

Table 5 :

- Those with a low electricity carbon intensity are compliant with the European targets for any COP (blue-marked cells in Table 5). This for example corresponds to 22 EU countries in 2030 and 16 EU in 2050 in the configuration with a low GWP refrigerant (e.g. R1336mzz(Z));
- Those with a medium electricity carbon intensity allowing the solution to be compliant with the European targets if the COP is high enough (yellow-marked cells in Table 5); This corresponds to 2 countries in 2030 and 7 in 2050 in the configuration with a low GWP refrigerant (e.g. R1336mzz(Z));
- Those with a carbon intensity of electricity too high for any solution to be compliant with the European targets regardless of the COP (red-marked cells in Table 5). No country is in this case in 2030 and only Belgium in 2050 when using a low GWP refrigerant (e.g. R1336mzz(Z)).

As the European GHG emission reduction targets for 2030 and 2050 do not include imported emissions, it is fair to compare this target with the configuration without imported emissions. Although imported emissions should always be considered, the following will exclude imported GHG emissions to keep the analysis consistent with climate change objectives (i.e. Figure 2a).

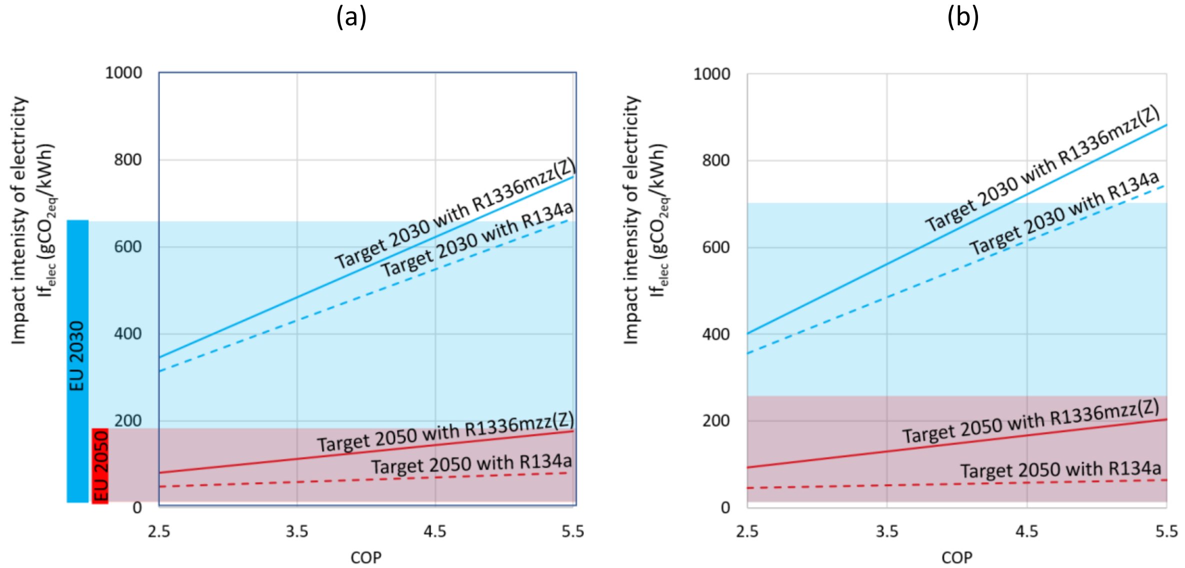


Fig. 2 – Maximum impact intensity of electricity to achieve the GHG reduction targets of 35% in 2030 and 85% in 2050, a) without imported emissions b) with imported emissions. The curves represent the maximum grid mix impact intensity for different coefficient of performances (COP) to comply with targets. The blue and red areas capture the range of carbon footprints of the electricity grid mix of all considered EU countries for 2030 (21-663 gCO_2eq/kWh and 17-704 gCO_2eq/kWh without and with imported emissions, respectively) and 2050 (7-191 gCO_2eq/kWh and 26-263 gCO_2eq/kWh without and with imported emissions, respectively).

3.1.2. Influence of refrigerant

Table 5 shows that the majority of the EU countries surveyed will be compatible with the reduction targets in 2030 regardless of the COP or the nature of the refrigerant. Poland and Estonia, with a projected electricity carbon intensity above 400 gCO_2/kWh, will only be compatible for COP above respectively, 5.8 and 3.9 for R134a and 4.8 and 3.2 for R1336mzz(Z). The influence of the refrigerant is limited in 2030 because the carbon content of electricity is low enough that the targets are met even with high GWP refrigerants. In contrast, in 2050, a larger influence is observed. Table 5 shows that 7 of the 24 studied countries cannot meet GHG reduction target with a fluid like R134a regardless of the COP within the MHP range (see method section). With low GWP refrigerants, all EU countries, except Belgium, can consider the integration of MHP to achieve the EU targets. Among these countries, 7 of them do not achieve the targets for all processes with the integration of MHP, so case-by-case studies need to be carried out to assess their suitability.. However, as observed in Fig. *3*, which presents the minimum COP required for each country to meet the targets in 2050, MHP integration in some process are still not able to reach the GHG reduction target due to the carbon footprint of electricity. This implies that for MHP to be relevant in the future, the transition to a low-GWP working fluid for all MHP must be continued. Switching from a refrigerant with a GWP of 50 $kgCO_2eq/kg$ to a refrigerant with a GWP of 2 $kgCO_2eq/kg$ provides a gain equivalent to a reduction in energy-related carbon footprint between 1.5% and 2%.

Table 5 - Impact intensity of electricity and analyses of the environmental requirements for EU countries without imported emissions in 2030 and 2050 for R134a and R1336mzz(Z)

[blue] Low electricity intensity compliant with the European targets regardless of the COP
[yellow] Medium electricity intensity compliant with the European targets if the COP is high enough
[orange] High electricity intensity not compliant with the European targets regardless of the COP

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

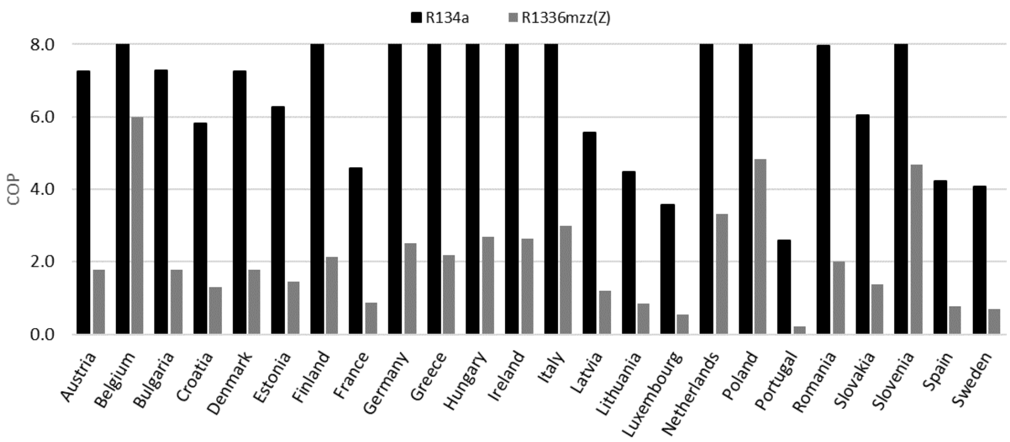


Fig. 3 – Minimum COP in 2050 to comply with the 2-degree target of the Paris Agreement for each EU members (without imported GHG emissions). Projected electricity grid mix compositions stem from ref. [46]. *Note that COP values above 8 are not represented.*

3.2. Economic analysis

3.2.1. Current economic viability

The minimum gas prices required for MHP to be competitive with gas boiler, vs. electricity price and as a function of COP are plotted on Fig. 4. Furthermore, the energy prices of different EU countries are reported as well allowing to identify for which of them competitiveness is achieved (i.e. country mark above the considered curve).

The results highlight the low economic competitiveness of MHP compared to heat produced by a gas boiler in most of the European countries, with the current prices of gas and electricity (2019 data). Even with a high COP of 5.5, only Denmark, Finland, France, Serbia and Sweden have an energy price that could make the waste heat solution competitive with gas.

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

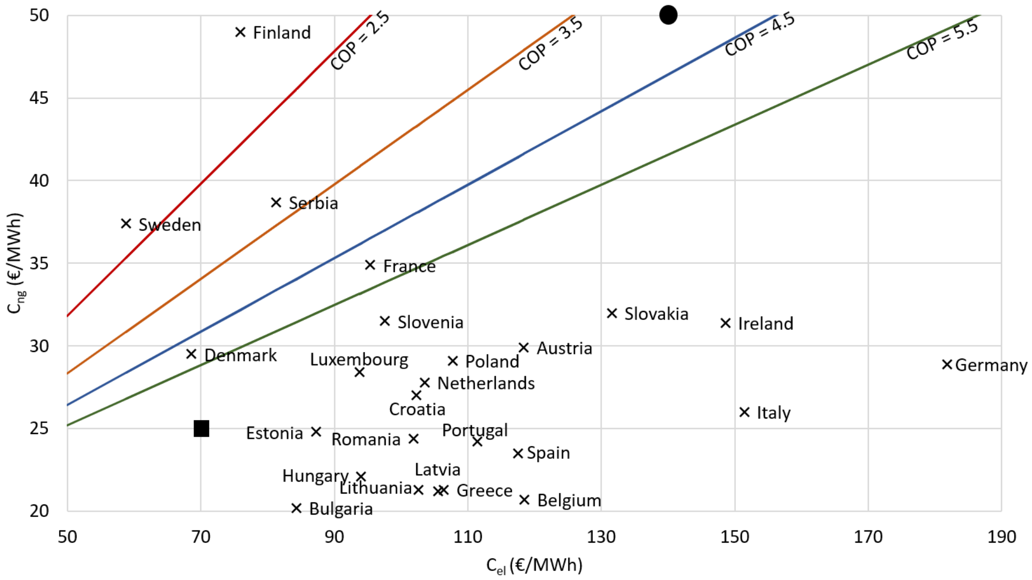


Fig. 4 – Positioning of European countries according to the gas price limits ($C_{ng,min}$) allowing the economic profitability for current COP range of MHPs. Coloured lines indicate the minimum gas cost ($C_{ng,min}$) that makes heat recovery cost-effective compared to a gas boiler for a given COP (see Eq. 9 in Methods). Cyprus, Malta, Czech Republic missing on the graph due to lack of economic data.

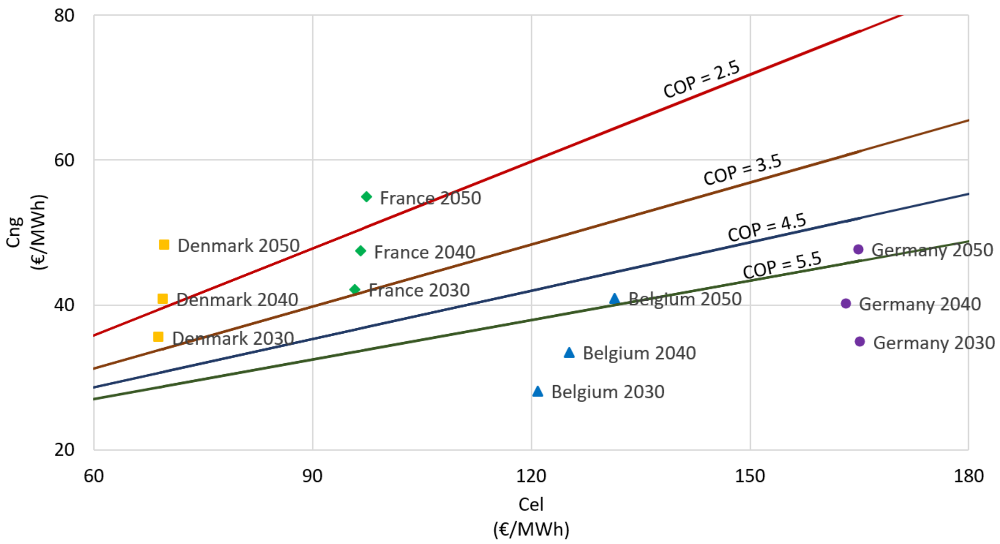
3.2.2. Influence of carbon tax and grid mix composition

To simulate a change in electricity and gas prices, the impact of the evolution of the carbon tax and that of the electricity grid mix carbon footprint have been quantified, taking representative countries with contrasting characteristics. Four EU members are thus considered, namely Belgium (low gas price and average electricity price), Denmark (low electricity price and average gas price), France (high gas price and average electricity price), and Germany (high electricity price and average gas price). The evolution of the carbon footprint of electricity was taken from the European commission scenario [46]. Two cases were considered for the evolution of the carbon tax with a first scenario, termed “Reference scenario”, based on the EU Reference Scenario 2016 (i.e. tax of 25 €/tCO_{2eq} in 2030, 50 €/tCO_{2eq} in 2040 and 85 €/tCO_{2eq} in 2050; see Fig. 5a) and a more constraining scenario, termed “Constrained scenario ”with a tax of 50 €/tCO_{2eq} in 2030, 100 €/tCO_{2eq} in 2040 and 200 €/tCO_{2eq} in 2050 (Fig. 5b) [50].

Results presented in Fig. 5 (a) show that for the reference scenario, France and Denmark can expect that profitability can be achieved between 2030 and 2040 for most MHP industrial integration (where

COP are typically all above 2.5). Germany and Belgium, in contrast, are not found to meet the same cost efficiency, even by 2050. For the second scenario presented in Fig. 5 (b), France and Denmark can expect profitability before 2030 for most processes, Belgium between 2040 and 2050 and Germany after 2050. Because the competitiveness of the waste heat recovery solutions follows the energy prices (see Section 3.2.1), the carbon tax can play a major role to MHP development by making heat recovery solutions more cost-effective than gas solutions. This tax results in a change in the ratio gas to electricity price from 0.44 to 0.52, 0.59 and 0.69 in Denmark, from 0.39 to 0.44, 0.49 and 0.56 in France, from 0.20 to 0.23, 0.27 and 0.31 in Belgium, from 0.19 to 0.21, 0.25 and 0.29 in Germany for years 2030, 2040 and 2050 respectively. This financial mechanism is less effective in countries with a high carbon footprint of electricity, while the ratio is increased by 56% by 2050 for Denmark, it is increased by only 23% for Germany. This could stimulate spontaneous uptake of the technology within industries, which could then anticipate GHG reduction regulatory requirements to enter into force by 2050.

(a)



(b)

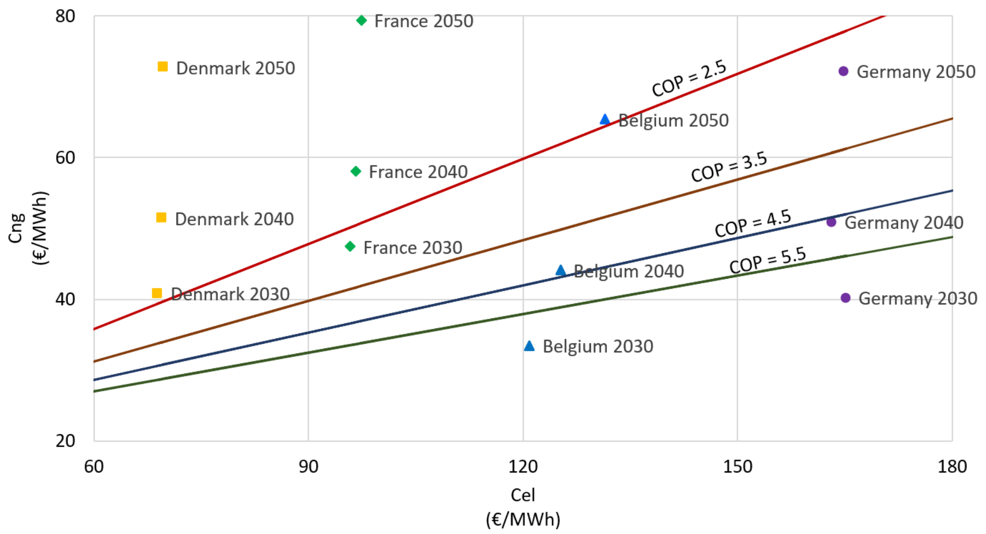


Fig. 5 – Projection of the evolution of energy cost and compatibility with natural gas price limit ($C_{ng,min}$) for current COP range of MHP a) Reference scenario *b) Optimistic scenario*

3.3. Combined energy, economic, and environmental assessment within industrial processes

Tables 6 and 7 show for 6 different industrial processes (Food industry, Alcohol production, Polycrystalline silicon, Poly film manufacturing, Ammonia production, Chemical industry) which countries solutions of waste heat recovery by MHP technologies enable to reach the climate change and economic objectives in 2030 and 2050. The environmental performance becomes the main limiting factor for 3 countries namely Belgium, Poland, and Slovenia. For the projected electricity mix intensity, policy focusing on the development of these systems in these countries would not achieve the environmental objectives as presented in the section 3.1. For most countries, unmet conditions are largely economic (brown-marked cells in Table 7), suggesting that economic constraints tend to be a major barrier for the deployment of the MHP technologies in 2030 and that all the studied countries except Poland are able to meet the targets for climate change impact. In contrast, in 2050, the profitability of MHP is no longer an obstacle except for Germany and Italy despite carbon tax. Others policies in the short term (by 2030) are needed to accelerate the development of heat recovery

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

As far as the studied processes are concerned there are also large differences across industries in 2030. The most favourable industrial processes for MHP integration based on table 6 and 7, i.e. resulting in an integration of MHP with a low temperature lift, have great potential in all countries. These industries are more favourable from both an economic and environmental perspectives. In contrast, for less favourable processes such as food industry or poly film manufacturing, both economic and GHG constraints are more demanding. It is therefore likely that heat recovery will not be installed spontaneously by these industries in the short term.

Table 6 - Environmental and economic compliance of different processes for European countries in 2030. The study is carried out with the refrigerant R1336mzz(Z), with a carbon tax following the EU Reference Scenario 2016.

■ Conditions for MHP development are met ■ Conditions for MHP development are not met

2030 projection	Food industry		Alcohol production		Polycrystalline silicon furnaise		Poly film manufacturing		Ammonia production		Chemical industry	
COP[a]	3.6		4.6		4.4		3.7		5.7		3.8	
	Envi. compl.	Eco. compl.	Envi. compl.	Eco. compl.	Envi. compl.	Eco. compl.	Envi. compl.	Eco. compl.	Envi. compl.	Eco. compl.	Envi. compl.	Eco. compl.
Austria												
Belgium												
Bulgaria												
Croatia												

	Envi. compl.	Eco. compl.	Envi. compl.	Eco. compl.	Envi. compl.	Eco. compl.	Envi. compl.	Eco. compl.	Envi. compl.	Eco. compl.	Envi. compl.	Eco. compl.
Denmark	met	met	met	met	met	met	met	met	met	met	met	met
Estonia	met	met	met	met	met	met	met	met	met	met	met	met
Finland	met	met	met	met	met	met	met	met	met	met	met	met
France	met	met	met	met	met	met	met	met	met	met	met	met
Germany	met	not met	met	not met	met	not met	met	not met	met	met	met	not met
Greece	met	not met	met	met	met	met	met	not met	met	met	met	not met
Hungary	met	met	met	met	met	met	met	met	met	met	met	met
Ireland	met	not met	met	met	met	met	met	not met	met	met	met	not met
Italy	met	not met	met	not met	met	not met	met	not met	met	met	met	not met
Latvia	met	not met	met	met	met	met	met	not met	met	met	met	not met
Lithuania	met	not met	met	met	met	met	met	not met	met	met	met	not met
Luxembourg	met	met	met	met	met	met	met	met	met	met	met	met
Netherlands	met	met	met	met	met	met	met	met	met	met	met	met
Poland	not met	not met	not met	met	not met	met	not met	met	met	met	not met	met
Portugal	met	not met	met	met	met	met	met	not met	met	met	met	not met
Romania	met	met	met	met	met	met	met	met	met	met	met	met
Slovakia	met	met	met	met	met	met	met	met	met	met	met	met
Slovenia	met	met	met	met	met	met	met	met	met	met	met	met
Spain	met	not met	met	met	met	met	met	not met	met	met	met	not met
Sweden	met	met	met	met	met	met	met	met	met	met	met	met

[a] *Based on table 2 and equation 3*

Table 7 - Environmental and economic compliance of different processes for European countries in 2050. The study is carried out with the refrigerant R1336mzz(Z).

■ Conditions for MHP development are met ■ Conditions for MHP development are not met

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

4. Conclusions and recommendations

In this study, a methodology is developed to assess the competitiveness of industrial waste heat recovery solutions. It combines energy, economic and environmental aspects with the aim of reducing greenhouse gas emissions in line with the Paris Agreement. Focusing on Mechanical Heat Pump (MHP) case, carbon footprint was highlighted as a major indicator in addition to the economic one in feasibility studies. Indeed, through its assessment, it was possible to identify the required parameters that allow a technology to be viable for the economic demand of the industry but also to be aligned with the GHG reduction trajectory set at the European level. The impact of imported emissions was also assessed, resulting in a 13% increase in the carbon footprint for natural gas and a 50% increase for MHP refrigerant. Imported emissions impact also the electricity mix carbon footprint. Indeed, each type of electricity generation has a highly variable share of imported emissions, depending on the resources used and where they are produced. While being of interest, imported emission were not considered further in the study to keep consistency with EU objectives in terms of GHG reductions that do not include them.

At EU scale, MHP can be a relevant option to meet the GHG emission reduction targets set by the EU for both 2030 and 2050 for 21 out of 24 assessed EU members. When using sensitivity analysis with carbon tax schemes, it was found that among these 21 countries, energy prices favour gas in lieu of MHPs in 10 countries in 2030 and 2 in 2050, regardless of the stringency of the tax scheme. In all 21 countries, MHP are a solution already capable to meet GHG reduction commitments. Economic profitability of the MHPs is therefore the main obstacle, and only few countries are viable with current energy price. For countries identified as not meeting GHG emission reduction targets, the results are strongly related to the carbon footprint of the electricity grid mix. With the available projections, although reducing the carbon footprint of the delivered industrial heat in comparison to current gas fired solutions, MHP based solutions do not achieve the GHG reduction targets in Belgium, Poland and Slovenia. Carbon footprint of electricity in these three latter countries is clearly a barrier to their deployment.

The methodology can also be applied to assess other technologies dealing with waste heat recovery like the Organic Rankine Cycle system, which have so far been studied using climate change footprints but not linked to GHG emission reduction targets [58], [59]. This would enable to identify optimal solutions tailored to each industry in a specific context. While doing so, it is essential to go beyond climate change impacts and assess all relevant environmental impacts including for example chemical releases impacting ecosystems and human health, mineral resources use or land use [60]. Existing tools, like the ISO-standardized life cycle assessment methodology [35], may be useful to meet such objectives.

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