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Economic and Environmental considerations for the deployment of VHTHPs in European markets

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Abstract

This paper provides an overview of the most important economic and environmental considerations when deploying very high temperature heat pumps (VHTHPs) in the European region. One of the state-of-the-art heat pumps, a process based on the reversed Stirling cycle, can achieve temperatures of up to 200 °C, and temperature lifts over 150 °C. The coefficient of performance (COP) suffers during such large temperature lifts, and thus the relationship between the price of electricity and alternative fuels becomes a crucial factor when determining the feasibility of replacing existing boilers in industrial settings. The environmental impact is quantified using life cycle assessment and mainly depends on the electricity source used to run the heat pump as well as the construction and decommissioning of the heat pump itself.
It was found that factors such as low electricity prices and/or carbon pricing mechanisms are crucial in order to operate low COP heat pumps profitably. Additionally, it was determined that VHTHPs can significantly reduce the environmental impact of steam generation compared to equivalently sized fossil fuel boilers, provided that renewable sources of electricity are used.

Keywords: VHTHP; Life Cycle Assessment; Europe; Electricity mix

1. Introduction

Very high temperature heat pumps (VHTHPs) capable of delivering temperatures of up to 200 °C (392 °F) are beginning to emerge on the market and offer an alternative process for generating high temperature process heat for industries which have traditionally relied on the combustion of fossil fuels [1]. While there is no generally accepted definition of what constitutes a VHTHP, Arpagaus et al. presents a definition for in Figure 1 which involves operating conditions where sink temperatures exceed 100 °C and/or source temperatures exceed 60 °C. Traditional heat pumps operate with sink temperatures below 80 °C and source temperatures below 40 °C, and high temperature heat pumps occupy the space between traditional heat pumps and VHTHPs [2].

The coefficient of performance (COP) decreases due to the high temperature lifts, and as such the economic feasibility of the technology becomes highly dependent on the price ratio between electricity and fossil fuels, typically natural gas. The environmental benefit of replacing fossil fuels boilers with VHTHPs is also largely dependent on the source of the electricity used to power the heat pump. Countries where electricity grid mixes consist mostly of nuclear power and/or renewable energy sources such as wind, solar, and hydropower produce a significantly smaller environmental footprint when operating VHTHPs compared to grids consisting mostly of fossil fuels. This footprint can be quantified using life cycle assessment (LCA).

In this study, a way to estimate the environmental and economic outcomes associated with installing VHTHPs in different European regions is determined using electricity data from ENTSO-E [3], environmental impact data from ecoinvent v3.8 [4], and real-world data from VHTHPs in industrial settings. Two separate

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breweries in Spain utilizing high temperature steam are investigated, and the economic and environmental impacts of replacing existing natural gas boilers with VHTHPs are estimated.

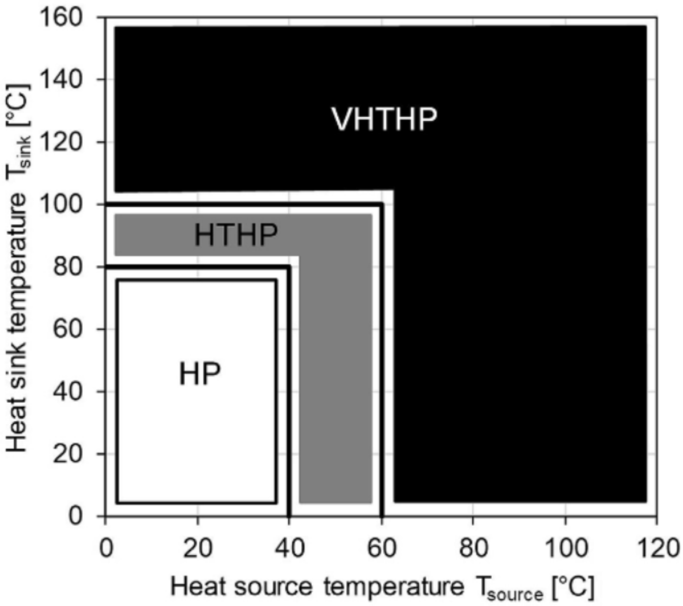

Fig. 1. Temperature operating ranges for heat pumps (HP), high temperature heat pumps (HTHP), and very high temperature heat pumps (VHTHP) [2].

2. Economic considerations

The efficiency of a heat pumps is limited by the theoretical Carnot efficiency, which decreases as the temperature difference between the heat source and the heat sink increases. The VHTHP analyzed in this study, a heat pump based on the reverse Stirling cycle which uses helium as the working medium, can deliver temperature lifts over 150 °C. During these temperature lifts, the COP tends to drop under 2.0 in practice [1, 5]. This means that the price ratio between electricity and fossil fuels, commonly natural gas, becomes a deciding factor when comparing different heating technologies.

Compared to natural gas boilers, industrial VHTHPs are still an emerging technology and therefore tend to have higher upfront costs, as well as potentially higher maintenance costs. Table 1 presents the initial investment and maintenance costs for a natural gas boiler and the VHTHP included in this study. The investment cost of the VHTHP is calculated according to a 1 200 €/kW figure from a product datasheet [6], while the maintenance cost is an internal estimate from the heat pump manufacturer. The values for the reference natural gas boiler are obtained from case study 2 in the EU Commission report *Ecodesign preparatory Study on Steam Boilers* [7], as it is of roughly appropriate size. The values for the natural gas boiler have been adjusted for inflation to 2022 prices.

Table 1. Investment and maintenance cost comparison of a VHTHP and a natural gas boiler

	VHTHP	NG Boiler
Thermal capacity (kW)	750	1 700
Investment cost (k€)	900	76
Maintenance cost (k€/yr)	10	5.5

All European Union member countries as well as Iceland, Liechtenstein, and Norway are participants in the European Union Emissions Trading System (EU ETS), which is a cap-and-trade scheme in which companies purchase emission allowances for the CO_2 they emit. Depending on the industry, companies get a certain number of allocations by default, and must thereafter either purchase enough allowances to cover their carbon dioxide emissions or reduce their overall emissions [8]. Companies always have an incentive to reduce their emissions, as the allowances can be bought and sold on an open market. Therefore, any reduction in CO_2 emissions can be directly tied to a monetary gain. At the time of writing, allocations were trading at 80 €/ton CO_2 [9].

3. Environmental considerations using LCA

A significant portion of the environmental footprint associated with a VHTHP is tied to the electricity generation used to run the heat pump. The European electricity market consists of a diverse set of energy sources that varies between bidding zones. In order to accurately determine the environmental impact of installing and operating a VHTHP, one needs to know the electricity mix in the region in question along with the environmental footprint associated with each energy source.

3.1. Life Cycle Assessment

LCA allows one to estimate the environmental impact of building, operating, and decommissioning a product at a specific location. The overall impact gets categorized into fifteen or so midpoint categories depending on the methodology used, and includes categories such as land use, carcinogenic substances, and ecotoxicity. These factors can be summarized into wider damage categories covering the impact on human health, ecosystem quality, climate change, and resource usage.

The life cycle impact of the VHTHP in this article has been studied and quantified before and will serve as a basis for further analysis [10].

3.2. Methodology and Impact categories

Depending on what methodology is used, one can group the environmental impact into three or four damage categories. The IMPACT 2002+ V2.15 [11] method was chosen in this analysis, as it separates climate change into its own category alongside human health impact, ecosystem quality, and resource usage. These four damage categories can be normalized in order to compare them against each other, and they can also be combined into a single total environmental impact estimate. This impact is measured in points, which are equal to person years (pers×yr) and represent the average impact associated with a single European citizen per year in a given category.

At the midpoint level, life cycle impacts are typically expressed as kg substance $s_{\text{-eq}}$, which is an equivalent amount of a reference substance s appropriate for the impact category in question. Examples of these reference substances are chloroethylene emissions into the air for the human toxicity category, sulfur dioxide emissions into the air and water sources for terrestrial acidification/nutrification and aquatic acidification, and carbon dioxide emissions for global warming. Other units are used where a reference mass equivalent substance is not appropriate, such as Becquerel carbon-14 into $\text{air}_{\text{-eq}}$ for the category ionizing radiation.

These emissions are then normalized into the damage category units Disability-Adjusted Life Years (DALY) for human health, Potentially Disappeared Fraction of species over a certain amount of m^2 during a certain amount of years (PDF×m^2×yr), and Mega Joules (MJ) for resource usage. The normalization factors used to further estimate the total environmental impact measured in points are 0.0071 DALY/point for human health, 13 700 PDF×m^2×yr/point for ecosystem quality, 9 950 kg CO_2e into air/point for climate change, and 152 000 MJ/point for resource usage [11].

3.3. Environmental impact of different electricity sources

Table 2 contains a summary of the environmental impact associated with the most common electricity generation sources in Europe and the most relevant midpoint categories expressed in damage category units. The inventories for each electricity source were taken from the database ecoinvent v3.8, and the method IMPACT 2002+ V2.15 was used to assess the life cycle impact. The impact of some electricity sources such as solar power differs considerably between regions. The total amount of solar irradiance received is lower in regions further from the equator and the weather conditions may be harsher, resulting in reduced equipment lifespans. As a result, the environmental impact associated with each individual kWh electricity produced over the panel's lifetime is increased in regions that receive less solar irradiance. The impact of other energy sources such as nuclear power is more consistent across European regions.

The figures in Table 2 are modeled after the "Electricity, *source*, at power plant/UCTE" modules in ecoinvent v3.8, which represent the average impact across power generation stations across Europe. In reality, these figures vary between power plants, with more modern units being more efficient and producing a smaller environmental footprint for a given amount of electricity.

Table 2. Environmental impact assessment per kWh delivered electricity from different electricity sources

Category	Unit	Hard coal	Lignite	Natural gas	Nuclear	Hydro	Solar*	Wind	Pulp**	Wood chips
Human health impact										
Carcinogens	DALY	2.81×10^{-9}	1.2×10^{-9}	1.62×10^{-8}	6.52×10^{-10}	2.56×10^{-10}	5.17×10^{-9}	1.38×10^{-9}	1.4×10^{-8}	9.3×10^{-9}
Non-carcinogens	DALY	1.5×10^{-8}	4.53×10^{-9}	9.43×10^{-10}	4.32×10^{-9}	2.35×10^{-10}	9.38×10^{-9}	1.44×10^{-9}	1.52×10^{-8}	9.53×10^{-8}
Respiratory inorganics	DALY	5.11×10^{-7}	8.48×10^{-7}	8.17×10^{-8}	1.81×10^{-8}	4.32×10^{-9}	4.98×10^{-8}	1.05×10^{-8}	2.54×10^{-7}	2.24×10^{-7}
Ecosystem quality										
Aquatic ecotoxicity	PDF × m^2 × yr	2.23×10^{-3}	7.67×10^{-5}	2.73×10^{-4}	1.85×10^{-3}	1.03×10^{-5}	6.03×10^{-4}	6.41×10^{-5}	2.47×10^{-3}	1.32×10^{-2}
Terrestial ecotoxicity	PDF × m^2 × yr	8.69×10^{-2}	6.46×10^{-3}	1.03×10^{-2}	2.41×10^{-2}	6.19×10^{-4}	2.25×10^{-2}	4.74×10^{-3}	0.12	0.77
Terrestial acid/nutri	PDF × m^2 × yr	1.65×10^{-2}	1.54×10^{-2}	4.19×10^{-3}	2.19×10^{-4}	8.45×10^{-5}	1.38×10^{-3}	1.79×10^{-4}	5.41×10^{-3}	1.25×10^{-2}
Land occupation	PDF × m^2 × yr	8.35×10^{-3}	1.46×10^{-4}	2.51×10^{-5}	2.15×10^{-4}	4.09×10^{-5}	9.73×10^{-4}	7.6×10^{-4}	0.21	0.26
Climate change										
Global warming	kg CO_2e	1.03	1.22	0.619	7.54×10^{-3}	3.64×10^{-3}	8.5×10^{-2}	1.08×10^{-2}	0.13	4.05×10^{-2}
Resources										
Non-renewable energy	MJ primary	12.4	13.8	11.2	12.7	4.32×10^{-2}	1.38	0.17	2.0	0.53
Mineral extraction	MJ primary	1.82×10^{-3}	1.11×10^{-3}	8.32×10^{-4}	2.98×10^{-3}	1.14×10^{-3}	2.18×10^{-2}	1.45×10^{-2}	5.77×10^{-3}	1.86×10^{-3}

* Modelled after solar power generated in German climate conditions
** Modelled after electricity generated from bleached softwood pulp production using the kraft process

3.4. European grid mixes

The European electricity market consists of a diverse mix of energy sources that varies greatly between bidding zones. Table 3 contains the average electricity consumption mixes for the year 2022 in some of the largest economies in Europe which were estimated using data from the ENTSO-E transparency platform [6]. The average consumption mix was estimated as the sum of the electricity generated within a region and the consumption mix of any imported electricity. The mix of any exported electricity was excluded in order to only account for the domestic demand. As ENTSO-E provides hourly updates regarding electricity production across the EU, it is possible to create up-to-date predictions regarding the consumption mixes. By combining the consumption mixes in Table 3 with the environmental impact associated with each electricity source in Table 2, one can estimate the environmental impact of operating a VHTHP with a specific COP in any given country. This estimate is performed in chapter 5.

The ENTSO-E transparency platform does not provide additional details regarding the composition of electricity generated from biomass which makes it difficult to estimate the environmental impact. This electricity might be generated by combusting black liquor from pulp production, biogas from silage, biodegradable waste, woodchips, or other sources.

Table 3. Average electricity consumption mixes for the year 2022

Country	Hard coal	Lignite	Natual gas	Nuclear	Biomass	Hydro	Solar	Wind	Other	Unaccounted Imports
Austria	3.4%	9.5%	16.8%	7.3%	2.8%	39.3%	3.8%	14.7%	2.4%	0 %
Belgium	1.7%	0.7%	22.4%	42.4%	2.2%	0.3%	6.9%	12.5%	8.4%	2.5%
Czech Republic	7.6%	36.3%	7.1%	31.9%	3.3%	2.5%	4.0%	4.1%	3.2%	0 %
Denmark	11.0%	0.9%	5.7%	2.8%	8.5%	12.5%	5.8%	45.7%	7.1%	0 %
Finland	4.7%	0 %	2.3%	31.8%	7.2%	27.3%	0 %	16.4%	5.9%	4.4%
France	1.0%	0.4%	10.4%	60.6%	1.0%	9.6%	4.5%	8.9%	0.9%	2.7%
Germany	12.4%	19.9%	11.2%	7.4%	7.6%	4.0%	10.6%	24.4%	2.5%	0 %
Italy	6.9%	0.8%	45.5%	7.2%	2.3%	12.9%	8.3%	8.5%	7.6%	0 %
Netherlands	20.9%	1.2%	36.7%	5.8%	0.9%	1.9%	1.0%	17.6%	11.6%	2.4%
Norway	0.3%	0.2%	1.0%	1.6%	0.2%	83.5%	0.3%	12.3%	0.6%	0 %
Poland	44.1%	25.5%	5.9%	0.3%	1.3%	1.4%	6.0%	13.4%	2.1%	0 %
Slovakia	8.6%	14.5%	6.8%	45.5%	2.8%	9.5%	3.1%	3.1%	6.1%	0 %
Spain	3.0%	0 %	29.3%	22.1%	1.5%	8.4%	11.6%	22.4%	1.7%	0 %
Sweden	0.1%	0 %	0.1%	29.3%	0.1%	44.7%	0.5%	20.0%	5.2%	0 %
United Kingdom*	2.0%	0 %	38.9%	22.0%	7.1%	2.2%	4.6%	22.1%	1.1%	0 %

* Data from the year 2020

4. Assessment of two breweries

Two different industrial cases were assessed in this study, and the most important case data presented in Table 4. The first case involved a brewery in Spain utilizing high temperature steam at 170 °C (7 barg). 680 kW of heat was available in the form of ammonia condensation at 26 °C during the winter and 32 °C during the summer, and there were expected to be 6 350 operational hours annually. The COP was estimated to be 1.8, which is 58% of the theoretical maximum Carnot COP of 3.1. The second case involved a different Spanish brewery with steam at 162 °C (5.5 barg) as a heat sink. 425 kW of waste process heat was available at 85 °C. The smaller temperature lift results in a higher COP which was estimated to be 2.3, 41% of the Carnot COP of 5.6.

Table 4. Data for the two cases investigated

	Case 1	**Case 2**
Hot sink temperature	170 °C (7 barg)	162 °C (5.5 barg)
Cold source temperature	26 °C (winter) 32 °C (summer)	85 °C
Cold source availability	680 kW	425 kW
Operational hours	6 350 h	5 200 h

The COP was estimated based on an internal model provided by the heat pump producer. The performance of the heat pump in several different operating conditions can be viewed in the products datasheet [6]. Electricity was to be available in the form of guarantee of origin solar power priced at 70 €/MWh, the price of natural gas was 27 €/MWh, and the ETS carbon price was 90 €/ton CO_2 at the time. The boiler efficiency was estimated to be 90%.

For the first case, two 750 kW heat pumps utilizing the entire cold heat source and delivering 1 370 kW heat while consuming 760 kW electricity was proposed. The second brewery case had enough waste heat to operate one heat pump delivering 690 kW of high temperature steam while consuming 300 kW electricity.

The reduction in on-site CO_2 emissions from combustion were estimated as follows:

$$m_{CO_2} = \frac{q_{NG} Q}{\eta_{boiler} LHV_{NG}}. \tag{1}$$

Here m_{CO2} is the CO_2 mass, q_{NG} is the specific natural gas CO_2 emission factor of 2.75 kg_{CO2}/kg_{NG}, Q is the heat produced, η_{boiler} is the efficiency of the boiler, and LHV_{NG} is the lower heating value of natural gas which is 13.06 kWh/kg_{NG}. Both the economic assessment and the environmental impact assessment assumed a 15-year lifespan.

4.1. Economic assessment

Table 5 presents the estimated annual cost of operating one or multiple VHTHPs in both cases under the conditions described in the previous chapter. It also includes an estimate of the cost of operating the reference natural gas boiler as well as the annual running cost savings if VHTHPs are used in place. The estimated running cost savings were calculated as the cost of natural gas for the boiler, the cost of maintenance, as well as the cost of the ETS allowances needed to cover the CO_2 emissions minus the cost of electricity needed to operate the heat pump as well as maintenance costs.

Table 5. Annual running cost estimates for the two cases

	Case 1	**Case 2**
	2 VHTHPs	1 VHTHP
VHTHP costs		
Maintenance (k€/yr)	20	10
Electricity (k€/yr)	338	109
Natural gas boiler costs		
Maintenance (k€/yr)	5.5	5.5
Natural gas (k€/yr)	261	108
ETS allowances (k€/yr)	183	76
Running cost savings (k€/yr)	**91.5**	**70.5**

One factor that limits the running cost savings are the relatively few operational hours in both cases, namely 6 350 and 5 200 hours respectively. When estimating the simple payback period as the cost of investment divided by the annual running cost savings, a VHTHP is assumed to have a retail price of 900 000 €, and the natural gas boiler is assumed to cost 76 000 € in accordance with Table 1. With these figures the simple payback periods for both cases are calculated to be 20 years and 13 years respectively.

A sensitivity analysis on the simple payback period provides more insight into how uncertainty in the price of electricity and natural gas affects the economic viability of an installation. One approach is to conduct Monte Carlo simulations which rely on a large number of random samplings of variable values in order to estimate the probability of different outcomes. These simulations were performed with electricity, natural gas, and ETS prices as independent variables. In practice, these variables are not truly independent, as for example grid electricity prices will be affected by changes in natural gas prices if the grid in question partially operates on fossil fuels.

Figure 2 depicts the results of two Monte Carlo simulations, one for each investigated case. 1 000 000 price conditions were simulated with the relative outcome probability on the y-axis. The price of electricity and natural gas was varied with a standard deviation of 10%, while the price of the ETS allowances had a standard deviation of 15%. Outcomes with payback periods longer than 50 years and outcomes with negative payback periods (i.e., unprofitable outcomes) are not included in the figure. These amounted to 13% of the outcomes in the first case and less than 1% of the outcomes in the second case.

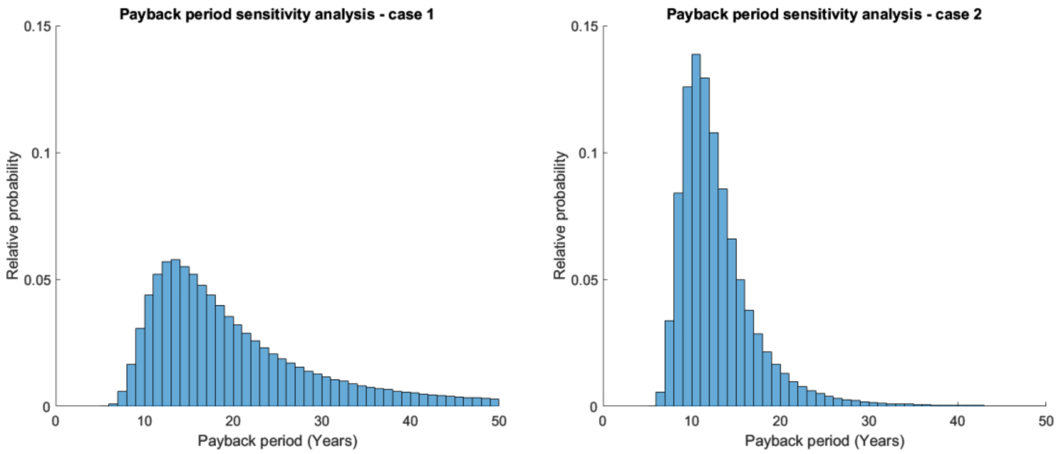

Fig. 2. Sensitivity analysis on the simple payback periods for two different cases using Monte Carlo simulations.

Analysis shows that the first case is more sensitive to price changes compared to the second case. This is likely due to the lower COP and, as a result, higher electricity consumption. Overall, 54% of the outcomes in the first case and 93% in the second case end up with a payback period below 20 years, with median values of 19 and 12 years, respectively.

4.2. Environmental impact

Table 6 contains the estimated environmental impact for the proposed solution of two VHTHPs and an equivalently sized natural gas boiler for the first case, and Table 7 contains the results for the second case. The damage categories are presented in bold text while their most impactful constituent midpoint categories are in roman. An estimated total environmental impact is also included.

In both cases, VHTHPs operating under the previously described conditions and utilizing renewable solar energy in Spain show a significantly smaller total environmental footprint, with large reductions in the damage categories climate change and resource usage. The impact on human health shows a slight improvement, while the impact on ecosystems is slightly increased. Case two shows more significant improvements due to the higher COP.

Table 6. Estimate of the environmental impact of two VHTHPs and a natural gas boiler in the first case

	VHTHP	Natural gas	Reduction
Total environmental impact (kPt)	**1.26**	**7.66**	**84 %**
Climate change (ton CO_2e)	**3 630**	**32 200**	**89 %**
CO_2 emissions on site (ton/a)	0	2 030	
Human health impact (DALY)	**2.84**	**3.67**	**23 %**
Carcinogens (DALY)	0.22	0.85	74 %
Non-carcinogens (DALY)	0.42	0.06	-600 %
Respiratory inorganics (DALY)	2.17	2.74	21 %
Ecosystem (PDF × m^2 × yr)	**1.14×10^6**	**7.44×10^5**	**-53 %**
Land occupation (PDF × m^2 × yr)	4.24×10^4	1.24×10^4	-242 %
Aquatic Ecotoxicity (PDF × m^2 × yr)	2.66×10^4	1.54×10^4	-73 %
Terrestrial Ecotoxicity (PDF × m^2 × yr)	1.01×10^6	5.92×10^5	-71 %
Terrestial acid/nutri (PDF × m^2 × yr)	6.00×10^4	1.24×10^5	52 %
Resources (MJ primary)	**6.16×10^7**	**5.83×10^8**	**89 %**
Non-renewable energy (MJ primary)	6.05×10^7	5.83×10^8	90 %
Mineral extraction (MJ primary)	1.07×10^6	5.23×10^4	-1 946 %

Table 7. Estimate of the environmental impact of one VHTHP and a natural gas boiler in the second case

	VHTHP	Natural gas	Reduction
Total environmental impact (kPt)	**0.41**	**3.16**	**87 %**
Climate change (ton CO_2e)	**1 170**	**13 300**	**91 %**
CO_2 emissions on site (ton/a)	0	840	
Human health impact (DALY)	**0.92**	**1.52**	**39 %**
Carcinogens (DALY)	0.07	0.35	80 %
Non-carcinogens (DALY)	0.14	0.03	-367 %
Respiratory inorganics (DALY)	0.70	1.13	38 %
Ecosystem (PDF × m^2 × yr)	**3.74×10^5**	**3.07×10^5**	**-18 %**
Land occupation (PDF × m^2 × yr)	1.38×10^4	5.10×10^3	-171 %
Aquatic Ecotoxicity (PDF × m^2 × yr)	8.69×10^3	6.33×10^3	-27 %
Terrestrial Ecotoxicity (PDF × m^2 × yr)	3.32×10^5	2.44×10^5	-36 %
Terrestial acid/nutri (PDF × m^2 × yr)	1.95×10^4	5.13×10^4	62 %
Resources (MJ primary)	**2.02×10^7**	**2.40×10^8**	**92 %**
Non-renewable energy (MJ primary)	1.98×10^7	2.40×10^8	92 %
Mineral extraction (MJ primary)	3.68×10^5	2.16×10^4	-1 603 %

The 89% and 91% reductions in CO_2e emissions are almost entirely due to the smaller carbon intensity of solar energy compared to natural gas. Spanish solar electricity is modeled as the "Electricity, production mix photovoltaic, at plant/ES" module in ecoinvent 3.8 which has a carbon intensity of roughly 50 g CO_2e per kWh electricity while natural gas is modeled as the "Heat, natural gas, at boiler modulating >100kW" module in ecoinvent 3.8 which has a carbon intensity of roughly 247 g CO_2e per kWh heat.

A network analysis of the LCA results was conducted in order to identify the sources of the emissions. The lessened impact on human health mostly comes down to a reduction of inorganic emissions causing respiratory illnesses as well as reduced carcinogenic emissions. Particulate matter smaller than 2.5 µm in diameter ($PM_{2.5}$) is the reference substance for the midpoint category respiratory inorganics, and in the case of the natural gas boiler, roughly two-thirds of the $PM_{2.5}$ emissions originated from the production and transport of natural gas while most of the remaining one-third occurred during the combustion process. In the VHTHP case, these emissions stemmed from a mix of copper and aluminum refining, glass production, and freight shipping.

The increased impact on ecosystems consists almost entirely of increased terrestrial ecotoxicity. The process of copper extraction and refining accounted for over half the impact on terrestrial ecotoxicity in both heat pump cases.

The use of non-renewable energy resources sees a substantial reduction as no fossil fuel combustion occurs. At the same time, considerably more energy is needed for the extraction of minerals such as copper, nickel, and aluminum. The extraction of copper accounted for roughly half the energy used for mineral extraction in the VHTHP cases.

5. VHTHPs in different electricity grid mixes

In this section the environmental impact of deploying a VHTHP in the different European countries grid mixes listed in Table 3 is investigated. The operating conditions of the VHTHP is modeled to be similar to that of case 2. Electricity generated from biomass is assumed to consist of natural wood chip combustion as no further insight is provided by ENTSO-E, and the category *Other* is modeled as a mix of waste combustion and biomass, as well as peat in the case of Finland. The *Unaccounted imports* in the case of Finland consists of Russian electricity. These imports have since halted and have been replace with imports from the Swedish grid since the 15th of May 2022. Russian electricity production is also not available in ENTSO-E. As a result, the category *Unaccounted imports* in the case of Finland is modeled after the Swedish electricity mix. The unaccounted imports in the case of Belgium, France, and the Netherlands consist of imports from the United Kingdom, whose production data is not included in the ENTSO-E database for the year 2022. These imports were therefore modeled after the United Kingdom 2020 mix in Table 3.

The total environmental impact of a VHTHP in the second case using grid electricity in the listed countries as well as the total environmental impact of an equivalently sized natural gas boiler is presented in Figure 3, where the red horizontal line indicates the total environmental impact of the natural gas boiler. The four damage categories human health impact, ecosystem impact, climate change, and resource usage have been recalculated into points using the normalization factors in chapter 3.2.

Countries under the red line would see a net environmental benefit by operating a VHTHP instead of a natural gas boiler, while countries over the line would not. The results show that the environmental impact associated with operating a VHTHP across all damage categories is highly dependent on the source of electricity used. In electricity grids reliant on fossil fuels such as Poland or the Czech Republic, the total environmental impact can be greater for a VHTHP compared to an equivalently sized natural gas boiler. This is clearly shown in the damage categories climate change and human health impact, where electricity from the Polish grid results in a significantly larger impact compared to a natural gas boiler. Countries whose grids mostly consist of renewable energy sources, such as Norway or Sweden, would see a significant environmental benefit to installing and operating VHTHPs in place of a natural gas boilers under the conditions described in case 2.

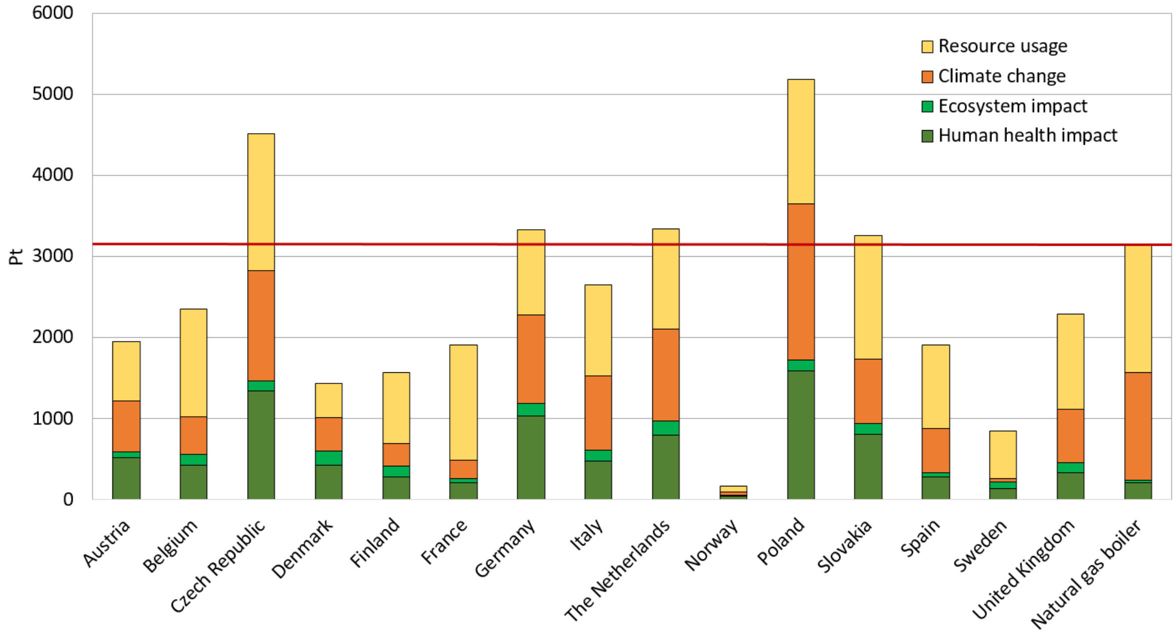

Fig. 3. Estimate of the total environmental impact of one VHTHP with a COP of 2.3 utilizing grid electricity in different European countries and a similarly sized natural gas boiler. The red line indicates the total environmental impact of the natural gas boiler.

6. Conclusion

This article summarized the most important economic and environmental factors that should be considered when assessing the feasibility of introducing VHTHPs in the European region. A way to quantify the environmental impact using LCA and up-to-date data regarding electricity consumption mixes in distinct regions was presented.

Two cases involving breweries in Spain with a demand for steam at 170 °C and 162 °C respectively were considered, and the economic and environmental impacts of replacing natural gas boilers with one or multiple VHTHPs were investigated. Analysis showed that the running cost savings and payback periods are highly dependent on the price ratio between electricity and natural gas as well as the price of CO_2 emission permits. The first case was estimated to have a simple payback period of 19 years and was shown to be more sensitive to utility price changes compared to the second case which was estimated to have a payback period of 12 years.

It was determined that the first case could operate two VHTHPs with an estimated COP of 1.8 which resulted in an 84% reduction in the total environmental impact over a natural gas boiler if solar power was used as an electricity source. The second case could facilitate a single VHTHP with an estimated COP of 2.3 which would reduce the total environmental impact by 87%. The environmental impact of operating VHTHPs in a number of different European settings using grid electricity was also studied, and it was determined that the environmental benefit of replacing natural gas boiler with VHTHPs is highly dependent on the source of electricity used. VHTHPs operating in electricity grids consisting mostly of renewable energy sources showed a substantial reduction in the total environmental impact compared to natural gas boilers, while VHTHPs operating in grids consisting mostly of fossil fuels showed an increase.

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