Environmental impact of high temperature industrial heat pumps – from a global warming potential (GWP) perspective

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Abstract

Several factors drive the increased utilisation of heat pumps in industry. Two important factors are the drive to reduce the negative environmental impact of industrial processes and the general trend of electrification ("de-fuelling") of energy systems. Much of the heat demand in the process industry is at temperature levels above 100 °C, which is above the temperature achievable with conventional heat pumps. Heat pump manufacturers are developing new heat pump technologies that can meet the demand of high sink temperatures and high temperature lifts. These heat pumps are often referred to as High Temperature Heat Pumps (HTHP) or Very High Temperature Heat pumps (VHTHP). The new heat pump technologies operate under conditions different from conventional heat pumps used for domestic heating, and it is not obvious how to evaluate the environmental impact of the installations. It depends very much on the technology being replaced what the various efficiencies of the heat pump system are (e.g. Coefficient of Performance (COP), system efficiency or exergy efficiency), and what the emissions are from generating the electricity used to drive the heat pump. In this paper we are investigating ways of evaluating the conditions where a heat pump installation will be an improvement and under which conditions it will not, where the focus will be on reducing global warming. We will look at basic thermodynamic considerations and modern thermodynamics tools, e.g. exergy and pinch analysis using data from the European energy systems as practical examples. To give a fuller picture of the impact, a life cycle impact assessment (LCA) is given, comparing a Stirling engine- type VHTHP with more conventional heaters. The paper is also using a current VHTHP installation as an example throughout the paper.

Introduction

Lowering the environmental footprint of industrial heating and cooling utilities resulted in heat pump technology entering this field, as part of a general trend of "de-fuelling" energy systems. Although the maximum temperatures reached with so-called Very High Temperature Heat Pumps (VHTHPs) are in the range 150–200 °C, significant advantages from the viewpoint of greenhouse gas (and pollutant) emissions follow when electricity from a renewable source is available. An overview of high temperature heat pump development up to 2018 can be found in the work by Arpagaus et al. [1].

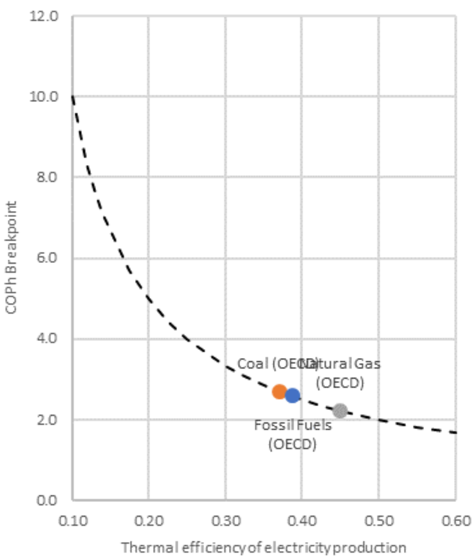
As discussed below, analysing the real benefit of VHTHPs must start with the heat generation equipment it replaces, followed by an evaluation of the energy efficiency and environmental footprint of the electricity source. For both, a life cycle assessment (LCA) sheds light on a range of aspects that affect sustainability, besides CO_2 emissions. For optimal implementation of a heat pump it needs to be properly integrated with respect to the heating and cooling demands of the process it will support. For this purpose, pinch analysis can be used [2]. Heating and cooling demands for a process can be plotted as two curves in a heat vs. temperature diagram in which, for a cost-minimised smallest temperature difference ΔT a pinch point is found. While heating and cooling equipment can be operated either above or below the pinch point, heat pumps allow for transferring heat across the pinch – in fact the heat pump *must* transfer heat across the pinch as it would otherwise act as an electrical heater [3]. Challenging for heat pumps is to reach temperatures above the pinch temperature, as discussed below, combined with proper positioning of heat exchangers. But, as noted above, besides energy efficiency an LCA comparing a heat pump with gas- or oil-fired boilers gives a more complete picture of the environmental footprint, covering both construction and operation of equipment. The direct application of what is reported here is the use of a series of 500 kW heat output heat pumps based on Stirling engines located at the pharmaceutical research facility of AstraZeneca in Gothenburg, Sweden, substituting for natural gas-fired boilers. A simplifying factor there is that heat demands have little variations. The environmental impact of heat pumps should also be compared to alternative technologies. For steam production it is natural to compare to natural gas- and oil-fired boilers. The potential impact of all the technologies are related to the production, transportation and use of the equipment.

The objective of this paper is to lay out several approaches to estimating the environmental impact of heat pumps with focus on high to very high temperature applications. A VHTHP from Olvondo Technology will be used as an example throughout the paper.

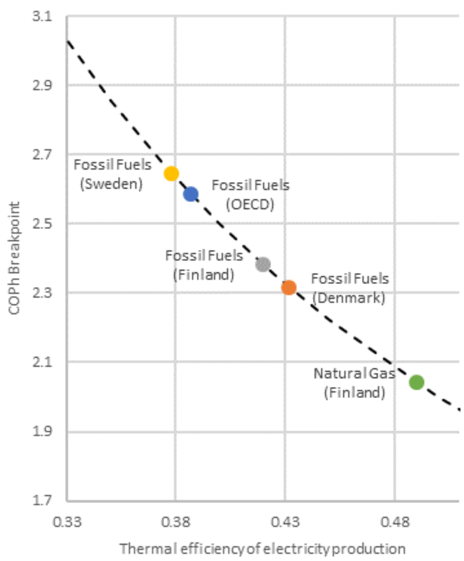
Thermal efficiency of electricity generation and heat pump COP

For a heat pump, the most basic analysis of the usefulness of the installation is to compare the thermal efficiency of power generation with the efficiency of the heat pump, Coefficient of Performance (COP). For instance, if the heat pump is using electricity generated using natural gas, it would make more sense to generate heat by directly burn the natural gas. This applies when the COP is not high enough to deliver more heat than is consumed by the power plant to generate the electricity used by the heat pump. The thermal efficiency of a power plant, η, is defined as the amount of electricity the power plant generates, W, divided by the amount of heat needed for that, Q. That is; $\eta = W/Q$. Compared with traditional, low temperature, heat pumps, high temperature heat pumps usually have lower COP, but with higher exergy efficiencies. The COP of a heat pump is defined as the amount of useful heat output, Q, divided by the amount of electricity consumed by the heat pump, i.e. $COP = Q/W$. This means that the COP of the heat pump must be higher than the inverse of the power plant efficiency, $COP > 1/\eta$. Figure 1 shows graphs illustrating the breakpoint for a heat pump.

However, the current European electricity systems are comprised of diverse power plants based on new or old technology, ranging from hydro, nuclear and wind energy with low environmental impact, to oil, anthracite and lignite fired thermal power plants with high environmental impact. The electricity generation mix for Europe in 2018 can be seen in Figure 2. It is also possible for end users to buy guarantees of origin of the electric power, making sure that the specific power consumption is generated by the same amount of more environmentally friendly production than the average or residual mix. This means that the impact of a heat pump installation is strongly dependent on the source of the electric power in addition to the COP. It is also important to consider the heat source being replaced in the case of retrofit installation, or the alternative



a) Breakpoint line for the COP as a function of thermal efficiency of thermal power plants. OECD averages for fossil fuels indicated.



b) Close-up of COP breakpoint line with Nordic averages for fossil fuel thermal powerplants.

Figure 1. COP breakpoint for heat pumps using electricity from thermal power plants. Source for the efficiencies are taken from the IEA publication "Energy Efficiency Indicators for Public Electricity Production from Fossil Fuels" [4].

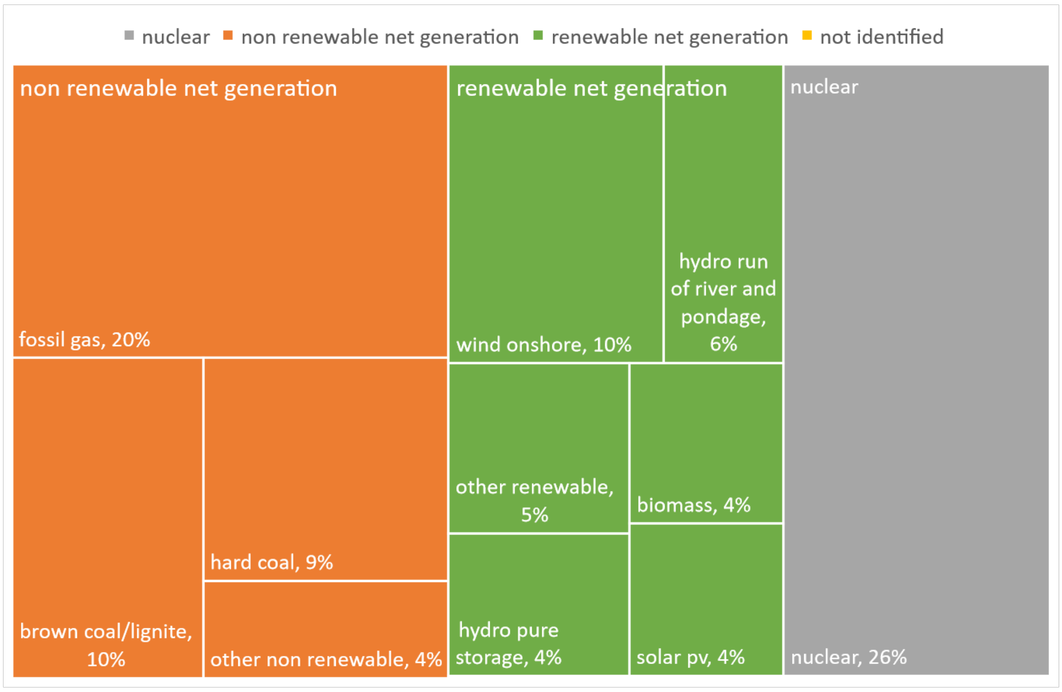


Figure 2. The electricity generation mix for Europe in 2018. The total net generation capacity was 1,163 GW. Nuclear power accounts for 26 % of the generation, non-renewable 42 % and renewable 32 %. The data is adapted from [5].

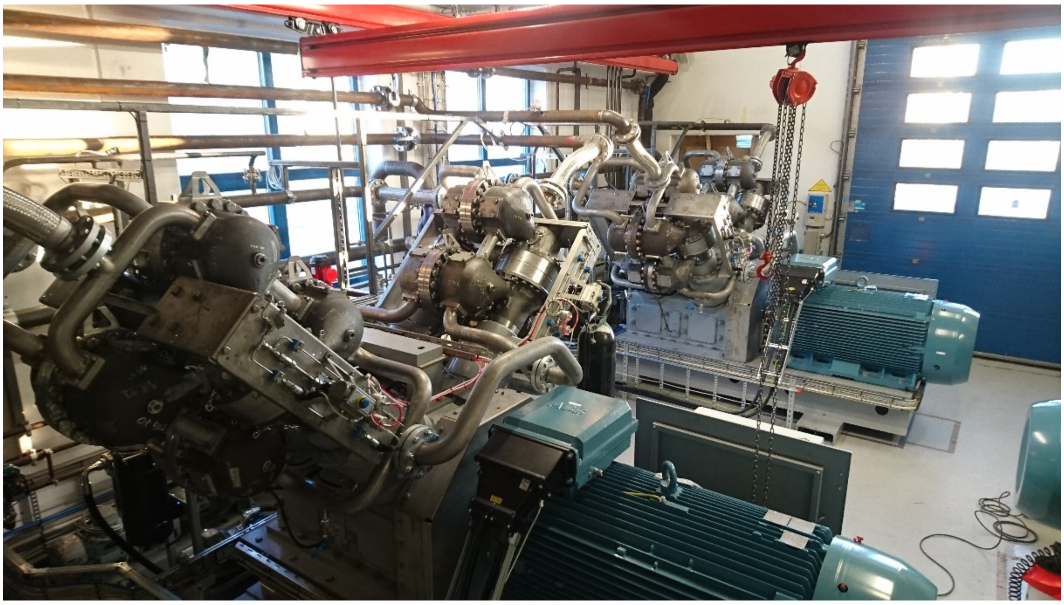


Figure 3. Two of three Highlift HTHP heat pumps from Olvondo Technology installed at the dairy plant used in this example. The heat pumps are replacing steam generation by natural gas fired boilers.

heat source(s) in case of a new installation. If the heat generation being replaced is an electric boiler, any COP greater than 1 will have a positive impact.

This means that a basic efficiency analysis is not sufficient to give a proper analysis of the impacts of a heat pump installation. In previous work by the authors [6] a comparison between the CO_2 emissions of a heat pump for steam generation and natural gas-fired boiler was made.

The heat pump was using district heating as a heat source and the heat sink was steam at 10 bar. The coefficient of performance, COP_h, for this set-up is approximately 2.1. The working medium for the heat pump is Helium (R704). The natural gas fired boiler and the heat pump were assumed to run at 500 kW heat load for 3,900 hours. The CO_2 emissions of the heat pump are strongly dependent on the source of electricity, being either about 380 ton $CO_{2,eq}$ per year less than the natural gas fired boiler or 30 ton $CO_{2,eq.}$ per year higher than that. Comparing these older values with the latest available emission factors for electricity (data from 2018 [5]), the emissions from the high temperature heat pump are decreasing. Figure 4 shows the earlier results of the analysis together with calculations based on the new data available.

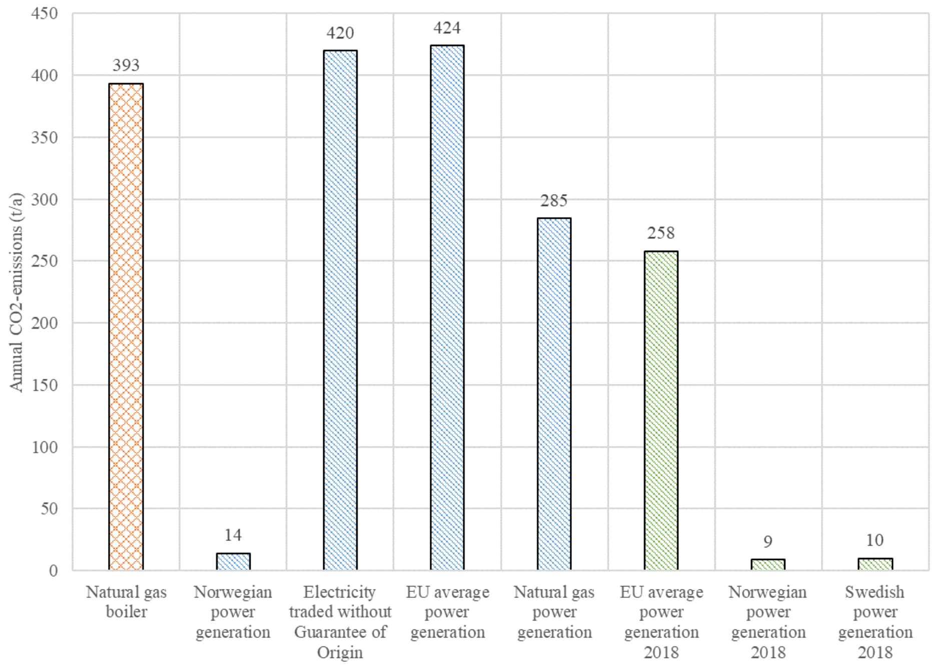


Figure 4. Updated graph of calculated annual CO_2-emissions for generation of 10 bar steam compared to a natural gas fired boiler. Old data in blue and new data in green. The total steam generation for all cases is 1,753 MWh/a. The old calculations are taken from previous work [6].

As can be seen in the figure, the emissions based on electricity consumption with the EU average power generation is considerably lower than with data from 2014.

Heat pump process integration and pinch analysis

Another method for analysing a heat pump installation for industrial processes, is to check whether the heat pump is properly integrated into the process using pinch analysis [2]. A pinch analysis will group all the process' streams into two groups, hot or cold, depending if the stream is being cooled or heated. The so-called 'pinch temperature', then divides the process into regions of heat surplus or heat deficit. A properly integrated heat pump is used for heat transfer "across the pinch" and will reduce both the heating demand and the cooling demand on a site, at the cost of increased electricity consumption. A poorly integrated heat pump will increase the cooling demand with the additional penalty of increased electricity consumption if used "below the pinch". There is also an intermediate integration, where the heat pump in the system used "above the pinch" in fact acts as an electrical boiler [4].

The total heating and cooling demand of the process can be plotted as a single graph, the Grand Composite Curve (GCC). Figure 5 shows an example of a GCC for processes with heating and cooling demands. Hot streams can for instance be streams for pasteurization, evaporation or CIP, while cold streams can be streams for cooling of buildings, process equipment (e.g. chillers) and condensation.

A challenge for many industries is to find a heat pump that can increase the temperature to a temperature above the pinch temperature, as this can often be above the regular operating temperatures of traditional heat pumps. The HTHP described in this paper allows for this.

Exergy analysis of heat pump installation vs. alternative heaters

Analysis of the efficiency of energy use in thermal systems where different types of energy are used can be based on the exergy concept which "normalizes" all energy streams or resources to their capacity to do work [7]. For this work the physical exergy of power and heat and the chemical exergy of fuel is needed when making a comparison of a heat pump with a fuel-fired boiler. For power P, its exergy Ex(P) = P, while for heat Q at temperature T with ambient surroundings temperature T° (K) the exergy is readily calculated via the Carnot factor Ex(Q) = Q · (1 - T° / T). Slightly more complicated is the exergy of hydrocarbon fuel which relies on the chemical conversion to CO_2, H_2O and emission of this and other gases to the atmosphere where all chemical species involved have a reference chemical exergy. To summarise, it was shown by Szargut et al. [7] that the chemical exergy of natural gas and liquid hydrocarbon fuels are quantified by 1.04× and 1.07× the lower heating value, LHV, respectively. Thus, for a heating system with an output of 500 kW heat at 180 °C (exergy 182.1 kW) three energy input exergies considered are, for heating a 30 °C input water (250 kW, exergy 12.3 kW):

- A heat pump using (effectively) 250 kW electricity
- A natural gas-fired boiler (LHV natural gas 47 MJ/kg), 250 kW after 90 % efficiency
- An oil-fired boiler (LHV light fuel oil 41 MJ/kg), 250 kW after 90 % efficiency

For the fuel-fired boilers, the amounts of natural gas and fuel oil needed are 21.3 kg/h and 24.4 kg/h respectively. Exergy efficiency calculation, defined as exergy efficiency = exergy of hot output divided by sum of all exergy inputs gives efficiency values 69.4 %, 60.4 % and 58.8 % for the heat pump, natural gas-fired and oi-fired boiler, respectively.

In practice, all of the above mentioned techniques for analysing the heat pump installation fails to give a broader picture of the environmental impact of a heat pump. In order to try to extend the one-dimensional analysis of the environmental impact a life cycle analysis (LCA) of the heat pump could be made.

LCA of VHTHP vs. natural gas-fired boiler and oil-fired boiler

For the application of new technologies, evaluating their overall environmental impacts is necessary. LCA as one of the important environmental tools has been applied to evaluate the environmental impacts. The assessment addresses the environmental impacts associated with an HTHP and compared to the impacts of same amount of heat generated from boiler with natural gas and oil using SimaPro 9.3 [8]. SimaPro is the software tool used for life cycle impact assessment (LCIA) of any product or processes. It evaluates the environmental performance of product/process by considering the complete life cycle, starting from the production of raw materials to the final disposal of the products, including material recycling if needed.

This study involved a cradle-to-grave LCA of HTHP: environmental impacts from manufacturing of raw materials to an operation phase of one year is considered. The phase beyond the operation gate could be important but was not included here (e.g. decommissioning was not considered). The study

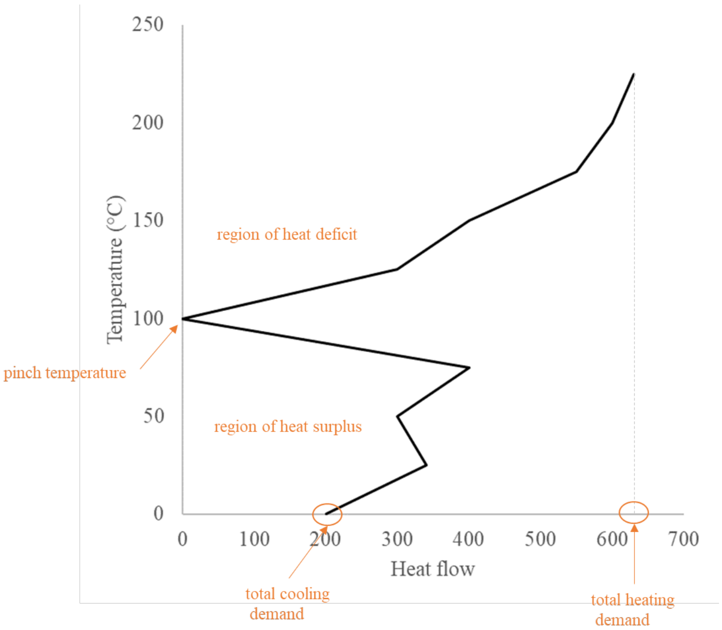


Figure 5. An example of a Grand Composite Curve. From the graph the total heating and cooling demand for the process and temperature regions of heat surplus and deficit. The temperature dividing the regions is called the 'pinch temperature'.

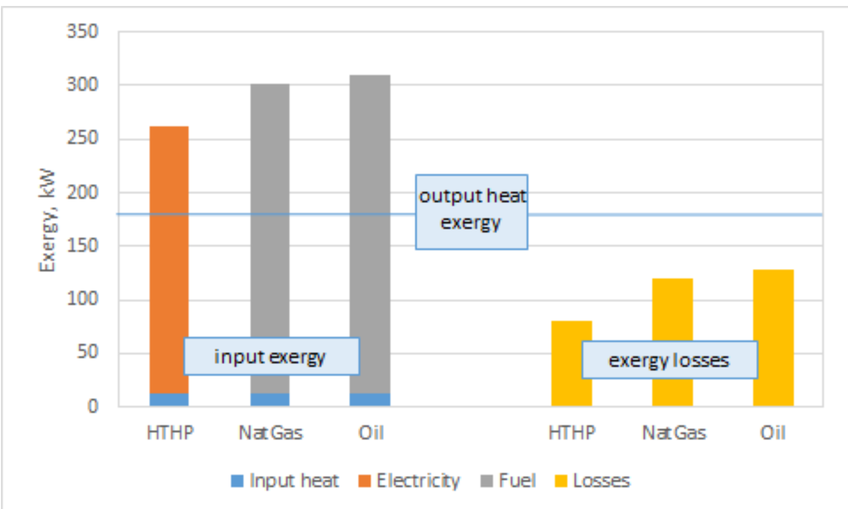


Figure 6. Exergy inputs, output and losses for a 250 kW 180 °C heat output system using a heat pump, natural gas-fired boiler or oil-fired boiler.

also compares results from life cycle assessment of the HTHP to conventional natural gas- and oil-fired boilers again with one year of operation after the construction phase. (In fact, 1 year = 8,000 h of operation at 500 kW implies 4 GWh heat output; operating 2,000 h/a during 4 years at this heat output gives the same LCA result.)

The design capacity of HTHP unit is to deliver 500 kW of useful heat. The geographical border of the study is limited to using the equipment in Sweden, with energy-related data for 2018. The Ecoinvent database (version 3.5) contains data for various economic sectors: energy, transport, agriculture, chemicals, materials, etc., and is the most complete and reliable database for the European context.

The HTHP used in the LCA is installed at the pharmaceutical company AstraZeneca's R&D facility in Gothenburg Sweden. Figure 7 shows one of three heat pumps at the site.

The heat pump is used to recover heat from the chillers and use this heat in addition to the necessary electrical input to generate steam at 10 bar. Heat pump output used in the LCA is 500 kW of 10 bar steam. The heat pump, as described above, operates with helium as the working fluid. The LCA system boundary for the HTHP is shown in Figure 8.

Figure 7. The HighLift HTHP from Olvondo Technology installed in the heat pump room at AstraZeneca, Gothenburg, Sweden. The nominal heat output from the heat pump is between 450 and 500 kW.

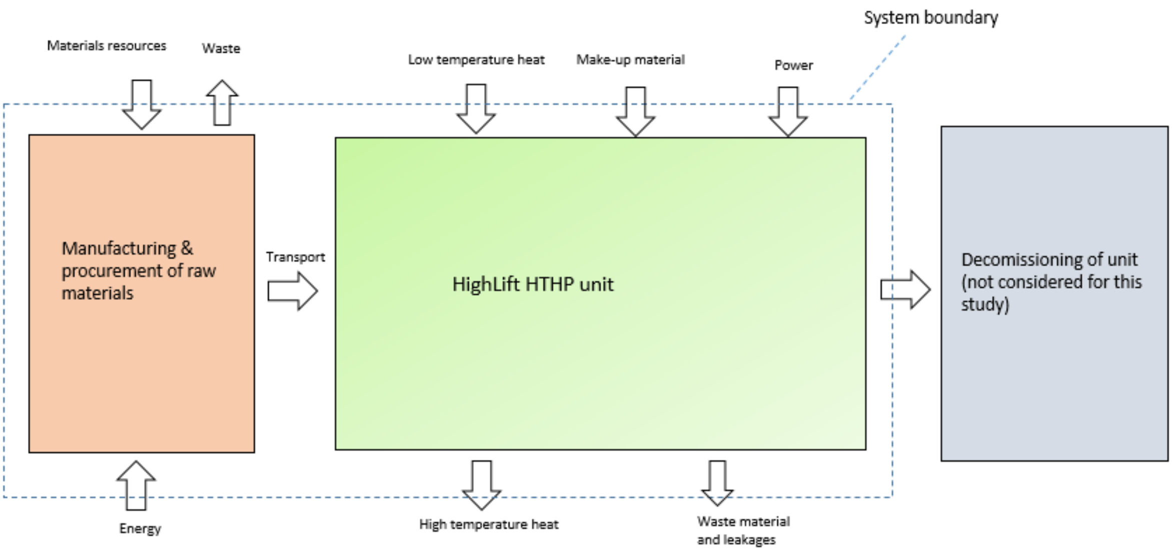


Figure 8. Schematic diagram of the system boundary for life cycle assessment of HTHP.

Table 1's list of inventory data is used for the development of an LCI network diagram for the HighLift HTHP.

The impact of the system is characterized by IMPACT 2002+ vQ2.2, which proposes a feasible implementation of the combined midpoint/damage-oriented approach. The IMPACT 2002+ vQ2.2 framework connects all types of LCI results via several midpoint categories human toxicity, carcinogenic effects, non-carcinogenic effects, respiratory effects (due to inorganics), etc. Unit "DALY" ("Disability-Adjusted Life Years") characterizes the disease severity, accounting for both mortality (years of life lost due to premature death) and morbidity (the time of life with lower quality due to an illness, e.g., at a hospital). Unit "PDF·m²·y" ("Potentially Disappeared Fraction of species over a certain amount of m² during a certain number of years") quantifies the impacts on ecosystems.

Table 2 lists the characterization of environmental impacts caused by all the raw materials for HighLift HTHP. The table shows that for daily operation of a 500 kW heat output HTHP unit, a 229 MWh amount of energy is needed for the extraction and manufacturing of the materials resulting in emissions of 7.79×10^3 kg $CO_{2,eq}$.

The results obtained show a human health score of 0.039 DALYs which implies the loss of 0.039 lives over the overall population. An ecosystem quality score of 2.7×10^4 PDF·m²·y which implies the loss of 27 % of species on 1 mm² of earth surface for one (including manufacturing) year. From the analysis of the results, it seems clear that the most critical material in terms of environmental impact is copper. The reason being, for copper production, usually 41 % copper is recycled, and it contributes to the emission of direct atmospheric arsenic emission.

The ECO INDICATOR 99 is used for further analysis and has four main impact categories: *human health*, *ecosystem quality, climate change* and *resources*. SimaPro uses the Pt unit to show these impacts. The Pt unit used in the eco indicator method is defined as a dimensionless value. The value of 1 Pt means one-thousandth of the yearly environmental load of one average European inhabitant. The results from this research show that for HighLift HTHP, to produce 500 kW × 8,000 h = 4 GWh heat (here assumed during 1 year), the *global warming* potential is 7,790 kg CO_2-equivalent: *acidification potential* 253 kg SO_2-equivalent.

According to the assessment, most damage occurs in the *human health* category with 5.5 Pt units. From the manufacturing of raw material until the operation phase (one year) the most released emissions to the air are carbon dioxide, dinitrogen monoxide, methane, nickel and sulphur hexafluoride which all have adverse effects on *human health* category. In the *respiratory inorganic* subcategory, the production of cast iron has the most negative impact on the environment, as it produces nitrogen and carbon oxides to the air.

Table 3 compares the environmental impacts associated with the generation of 500 kW of heat from HTHP, versus using a natural gas boiler and an oil boiler for this. The life cycle assessment is carried out for a year of its operational phase (4 GWh heat output as mentioned above).

The choice of working fluids and fuels is important for system performance since they influence the system efficiency, operation, and environmental impact. With the characterization factor of CO_2 equivalency ($CO_{2,eq}$), the oil boiler (OB) gives a quite substantial CO_2 equivalent emissions amount larger than the natural gas boiler (NGB) and a HighLift HTHP, the relative value compared with HighLift HTPT being about 10 times higher. In terms of airborne emissions, the oil boiler contributes most because of emissions of CO_2 and sulphur hexafluoride. For a natural gas boiler, the manufacturing of resources requires more energy, (i.e. 1.02×10^6 MJ) than for the oil boiler and the HTHP. The Ecoinvent model for the European natural gas supply was used for the natural gas boiler.

Table 1. Life cycle inventory data for HighLift HTHP.

Stainless steel	7,696.9	kg
Cast iron	1,500	kg
Copper	700	kg
Lead	0.1	kg
Chromium	1	kg
Tungsten	1	kg
Plastic PTFE	1	kg
Silica aerogel	100	kg
Total engine weight	10,000	kg
Helium	50	kg
Water	20	kg
Motor oil (lubrication)	200	litres
Electricity power input	250	kW
Heat output	500	kW

The results presented above show that the overall environmental impact arising from (for an operational phase of 1 year) HighLift HTHP is quite small and almost insignificant compared to the impact resulting from an oil boiler or natural gas boiler. Thus, the HTHP is more environmentally favourable than the oil and natural gas boiler. Figure 10 represents the graphical comparison of HighLift HTHP, NGB and OB on the scale of eco-indicator (Pt).

Stamford et al. [9] recently reported on a study on the life cycle impact of a Stirling engine micro CHP system. They compared the environmental and economic life cycle of a 1 kW Stirling engine with a gas boiler. They concluded that per unit of heat Stirling engine on average has a 30 % smaller environmental footprint than a gas-fired boiler.

For our future work, the life cycle assessment study should be extended to include that the plant would be dismantled at the end of its life and material that can be recycled will be reintroduced into production cycles (giving a cradle-to-cradle LCA). This would be beneficial in terms of natural resources saved and lower environmental impact for all heat production systems addressed here. Also, a varying operational life (in years or GWh output) is still to be addressed.

Conclusions

The analysis of the environmental impact of a heat pump is not trivial, and there is a trade-off between the quality of the results, amount of data necessary to complete a proper analysis and the possibility of interpreting the results of the analysis and make correct conclusions. A full LCA analysis gives a better picture of

Table 2. Characterization of environmental impacts for HighLift HTHP.

Impact category	Unit	Lubricating oil	Steel, stainless	Cast iron	Copper	Lead	Chromium	PTFE	Electricity	Helium	Tap water
Carcinogens	kg C_2H_3Cl eq	6.41	0.02	450.63	483.76	0.01	0.60	1.27	0.11	1.66	0
Non-carcinogens	kg C_2H_3Cl eq	4.09	0.47	207.33	3,385.17	0.12	0.92	0.02	0.54	0.12	0
Respiratory inorganics	kg PM2.5 eq	0.27	0.01	2.46	34.69	0	0.04	0	0.03	0.02	0
Ionizing radiation	Bq C-14 eq	7,275.79	4,315.23	42,330	155,993	3.03	351.58	54.30	16,245	135.93	0.18
Ozone layer depletion	kg CFC-11 eq	0	0	0	0	0	0	0	0	0	0
Respiratory organics	kg C_2H_4 eq	2.74	0.11	0.52	4.87	0	0	0	0	0.03	0
Aquatic ecotoxicity	kg TEG water	37,520	200,311	286,058	8,525,009	43.97	4,528.51	104.21	7,069.64	1,741.24	1.55
Terrestrial ecotoxicity	kg TEG soil	9,511.48	42.28	91,500	3,062,453	11.86	1,163.14	28.10	1,269.43	434.22	0.40
Terrestrial acid/nutri	kg SO_2 eq	4.91	0.27	34.04	476.48	0	0.43	0.03	0.25	0.53	0
Land occupation	m2org. arable	3.24	0	21.42	394.33	0	0.31	0.01	0.42	0.10	0
Aquatic acidification	kg SO_2 eq	1.58	0.97	8.88	241.04	0	0.12	0.01	0.05	0.13	0
Aquatic eutrophication	kg PO_4 P-lim	0.10	0	0.48	67.88	0	0	0	0	0	0
Global warming	kg CO_2 eq	234.65	0.01	2,166.32	5,312.06	0.10	25.81	2.52	9.52	39.91	0.01
Non-renewable energy	MJ primary	13,739.35	583,231	36,610	116,897	1.52	382.87	77.19	1,710	3,368.60	0.16
Mineral extraction	MJ surplus	14.62	34,579.12	89.37	33,477.95	0.20	2.46	0.13	0.66	0.36	0

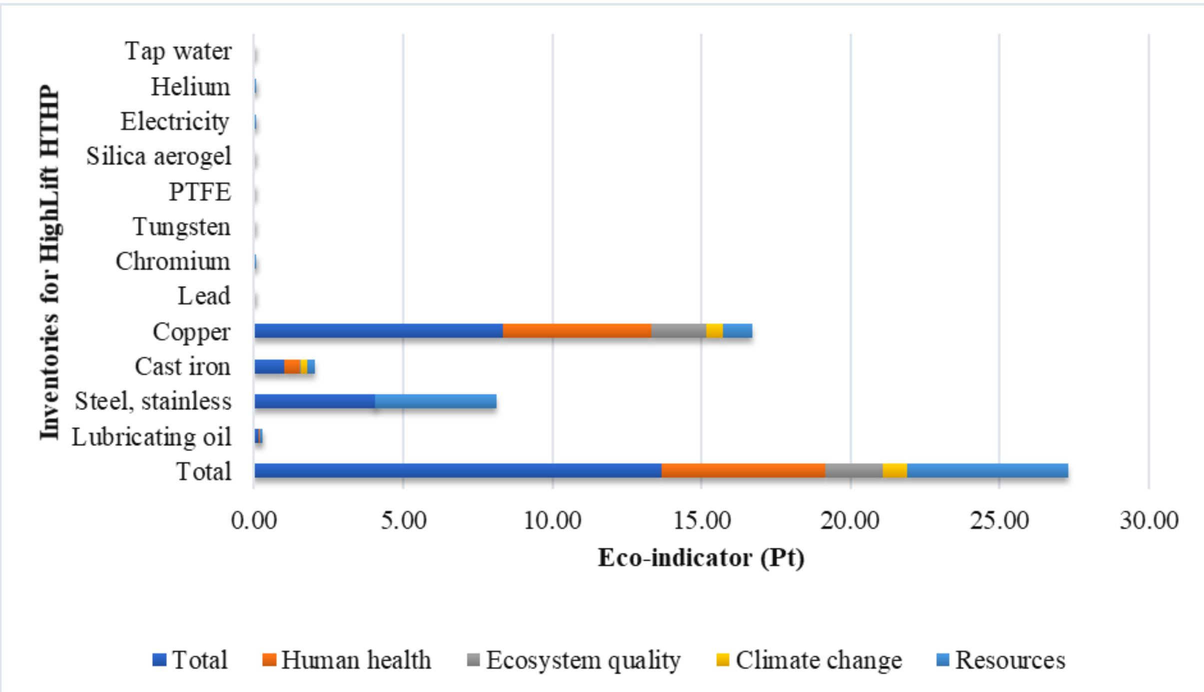


Figure 9. Life cycle assessment of HighLift HTHP based on impact categories.

Table 3. Damage assessment and characterization for HighLift HTHP.

Impact category	Unit	Nat. gas	Oil	HighLift HTHP
Carcinogens	kg C_2H_3Cl eq	3.44×10^3	3.94×10^3	9.44×10^2
Non-carcinogens	kg C_2H_3Cl eq	5.414×10^3	6.24×10^3	3.60×10^3
Respiratory inorganics	kg $PM_{2.5}$ eq	8.79×10^1	1.09×10^2	3.75×10^1
Ionizing radiation	Bq C-14 eq	1.04×10^6	1.10×10^6	2.27×10^5
Ozone layer depletion	kg CFC-11 eq	2.43×10^{-3}	2.70×10^{-3}	2.72×10^{-3}
Respiratory organics	kg C_2H_4 eq	1.688×10^1	2.03×10^1	8.28×10^1
Aquatic ecotoxicity	kg TEG water	1.20×10^7	1.41×10^7	9.06×10^6
Terrestrial ecotoxicity	kg TEG soil	4.86×10^6	6.51×10^6	3.17×10^6
Terrestrial acid/nutri	kg SO_2 eq	1.00×10^3	1.17×10^3	5.17×10^2
Land occupation	m^2org.arable	6.21×10^2	9.97×10^2	4.20×10^2
Aquatic acidification	kg SO_2 eq	3.44×10^2	3.94×10^2	2.53×10^2
Aquatic eutrophication	kg PO_4 P-lim	8.95×10^1	1.03×10^2	6.85×10^1
Global warming	kg CO_2 eq	4.78×10^4	5.24×10^4	7.79×10^3
Non-renewable energy	MJ primary	9.40×10^5	8.44×10^5	7.56×10^5
Mineral extraction	MJ surplus	8.17×10^4	1.03×10^5	6.82×10^4

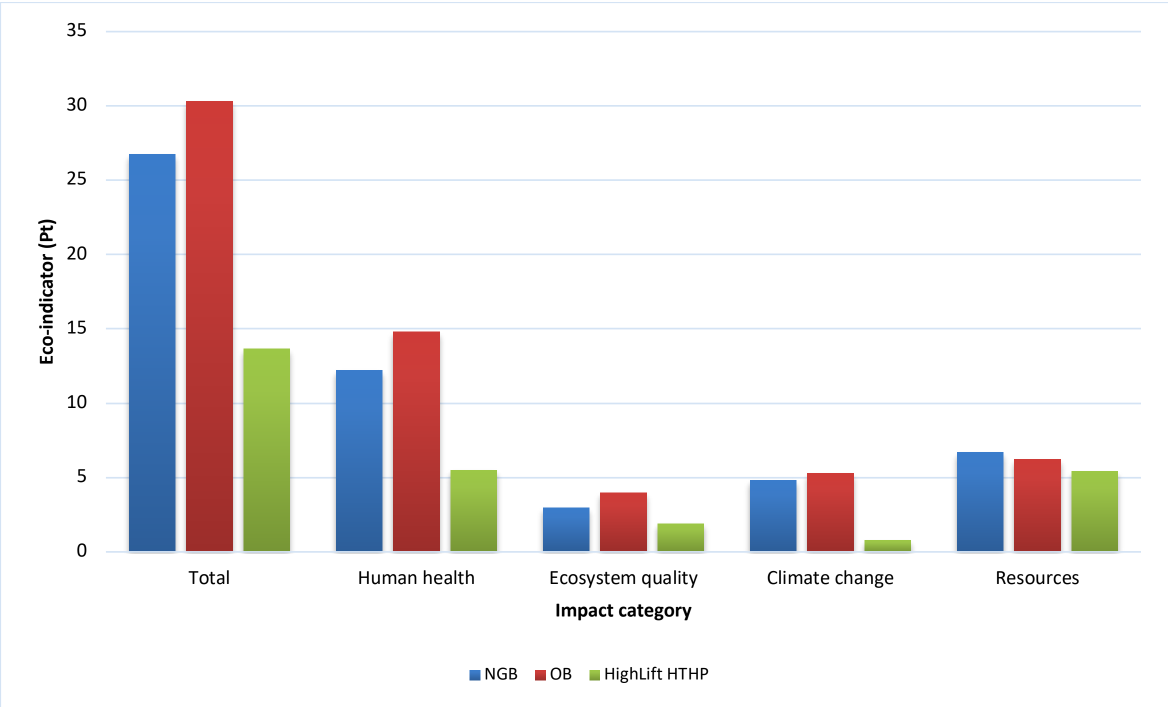


Figure 10. Comparison of life cycle assessment of HighLift HTHP, natural gas boiler and oil boiler based on impact categories.

the environmental impact of the heat pump compared to alternatives for the heat generation, but it is data intensive and it can be difficult to interpret the results. For more one-dimensional analysis, e.g. pinch or exergy, the advantage is that the results are easy to interpret. The disadvantage is that the nuances are lost in the simplifications.

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