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Evaluation of the Environmental Sustainability of a Stirling Cycle-Based Heat Pump Using LCA

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Abstract: Heat pumps are increasingly seen as efficient and cost-effective heating systems also in industrial applications. They can drastically reduce the carbon footprint of heating by utilizing waste heat and renewable electricity. Recent research on Stirling cycle-based very high temperature heat pumps is motivated by their promising role in addressing global environmental and energy-related challenges. Evaluating the environmental footprint of a heat pump is not easy, and the impacts of Stirling cycle-based heat pumps, with a relatively high temperature lift have received little attention. In this work, the environmental footprint of a Stirling cycle-based very high temperature heat pump is evaluated using a “cradle to grave” LCA approach. The results for 15 years of use (including manufacturing phase, operation phase, and decommissioning) of a 500-kW heat output rate system are compared with those of natural gas- and oil-fired boilers. It is found that, for the Stirling cycle-based HP, the global warming potential after of 15 years of use is nearly -5000 kg CO₂ equivalent. The Stirling cycle-based HP offers an environmental impact reduction of at least 10% up to over 40% in the categories climate change, photochemical ozone formation, and ozone depletion when compared to gas- and oil-fired boilers, respectively.

Keywords: stirling cycle-based heat pump; gas/oil-fired boilers; life cycle assessment; SimaPro; eco-indicator 99

1. Introduction

Energy is one of the sectors that pollute and harm the environment the most [1]. A key challenge is to address global environmental problems by supporting energy and environmental conditions in parallel. For sustainable development, it is important to change practices and technologies. Total energy use and efficiency are significant motivating factors for assessing the environmental effect of energy use on the environment. Therefore, it is essential to follow the principles of sustainable development strictly [2]. Aiming at a cleaner and better future, the negative impacts of energy use on the environment can be minimized by implementing the usage of renewable energy sources or by adopting environmentally friendly technologies.

Electricity and heat generation contribute to almost half of the global annual CO₂ emissions [2]. One of the major contributors to climate change is emissions of CO₂ from the energy sector, which were a major topic for discussions at the 21st Conference of Parties (COP21) in Paris from 30 November to 11 December 2015. As an outcome of this conference, initiatives have been taken to address these issues of annual emissions so that global temperature rise will be below 2 °C, and preferably below 1.5 °C. This target can be achieved by substituting fossil fuels, specifically coal, oil, and natural gas, with renewable energy sources [3].

Heat pumps offer an energy-efficient solution to heating and air conditioning as they can use renewable electricity and low value heat that can often be taken freely from surroundings. Since heat

pumps rely on transmission of heat rather than generation of heat, they do so at one-quarter of the operational cost of conventional heating or cooling technologies, depending on the efficiency of the heat pump, which is often given as the coefficient of performance (COP).

With the electricity markets introducing more and cheaper electricity from renewable sources, heat pumps are gaining market share, replacing traditional fuel-based heating. This is currently happening in the industry as well, with higher temperatures—e.g., above 120 °C—being a challenge. This is where high temperature heat pumps [4] become of interest. The Stirling-cycle based heat pump has already been shown to be efficient at high temperatures and high temperature lifts (see, for instance, the previous work by the authors [5]).

The manufacturing phase of a heat pump is a key contribution phase for determining the environmental impacts arising throughout a product life cycle [6,7]. However, the importance of the manufacturing phase in a life cycle assessment (LCA) is dependent on the heat pump, its capacity, main components, and efficiency [8]. The environmental impacts of the operational phase are sometimes less than the impacts caused by the production and assembling phase. For cases such as these, an LCA study is greatly suggested to recognize and quantify the environmental impact hotspots along the complete life cycle of process units or products.

According to Linke et al. [9,10], to make improvements in manufacturing processes and to attain environmental benefits, companies should add Environmental Impact Assessment (EIA) to their manufacturing phase of products. EIA is a necessary step for the planning of any technical structure to gain clear insight into the likely environmental impact of the structure. EIA techniques are designed to minimize or avoid the adverse effect of development, a process, or a product on the environment.

A comprehensive study was conducted by Stamford et al. [11] to investigate the life cycle environmental and economic sustainability of Stirling engine micro-CHP (combined heat and power) systems and compare it with conventional energy provision from natural gas boiler and grid electricity. Another study addressed the environmental impacts of domestic Stirling engine micro-CHP integrated with solar photovoltaics and battery storage. They concluded that relative environmental impacts can be reduced by 35–100% by replacing grid electricity and a gas boiler by such integrated system [12]. Other relevant work includes two studies that estimated the CO₂ reduction achievable by Stirling engine and internal combustion engine-based CHP systems, but they did not follow a life cycle approach [13,14].

In this paper, the environmental footprint of an industrial size Stirling cycle-based heat pump is compared to that of natural gas or oil-fired boilers. Environmental footprint as the name suggests is defined as environmental impacts associated with any entity, process, or product. It considers the resources a person/product/process utilizes and the resulting emissions to land, air, and water. The study was made using the SimaPro software [15] for LCA. The construction phase, 1, 8, or 15 years of use, and the decommissioning and recycling are considered.

LCA is increasingly becoming standard procedure environmental footprint analysis and comparison of processes or products. One novelty of this paper is to apply it to an energy technology that has very recently found application at an industrial scale. Sufficient real-time data have recently been produced to make this study possible. While hardly any work on LCA applied to Stirling cycle-based energy technology has been reported in the open literature, this paper addresses a reversed Stirling cycle-based heat pump.

2. Materials and Methods

The description of the system and a description of the LCA-methodology used in this work are given in the two next sections. The goal and scope, as well as a description of the system boundaries, are given in the third and fourth sections.

2.1. System Description

The heat pump studied for this study is a double-acting alpha configuration Stirling cycle heat pump. A Stirling engine is driven at different temperatures by periodic compression and expansion of

a working fluid (for this study, helium gas) such that the net transmission of heat energy results in mechanical work. When operated as a heat pump, the process runs in reverse: work (electricity) is used to yield high-temperature heat from low-temperature heat.

The heat pump is comprised of main components such as the heater, regenerator, cooler, and compression and expansion cylinders arranged in a Franchot configuration. The internal heat exchangers include heating, cooling, and regenerating sections in the same unit. The heat exchanger is constituted of stainless-steel tubes while the regenerator is made of a metallic mesh of stainless steel. The heat pump in this study as shown in Figure 1 is used to recover heat and use this heat along with the electrical input (250 kW) to generate steam at 10 bar at an output of 500 kW [16].

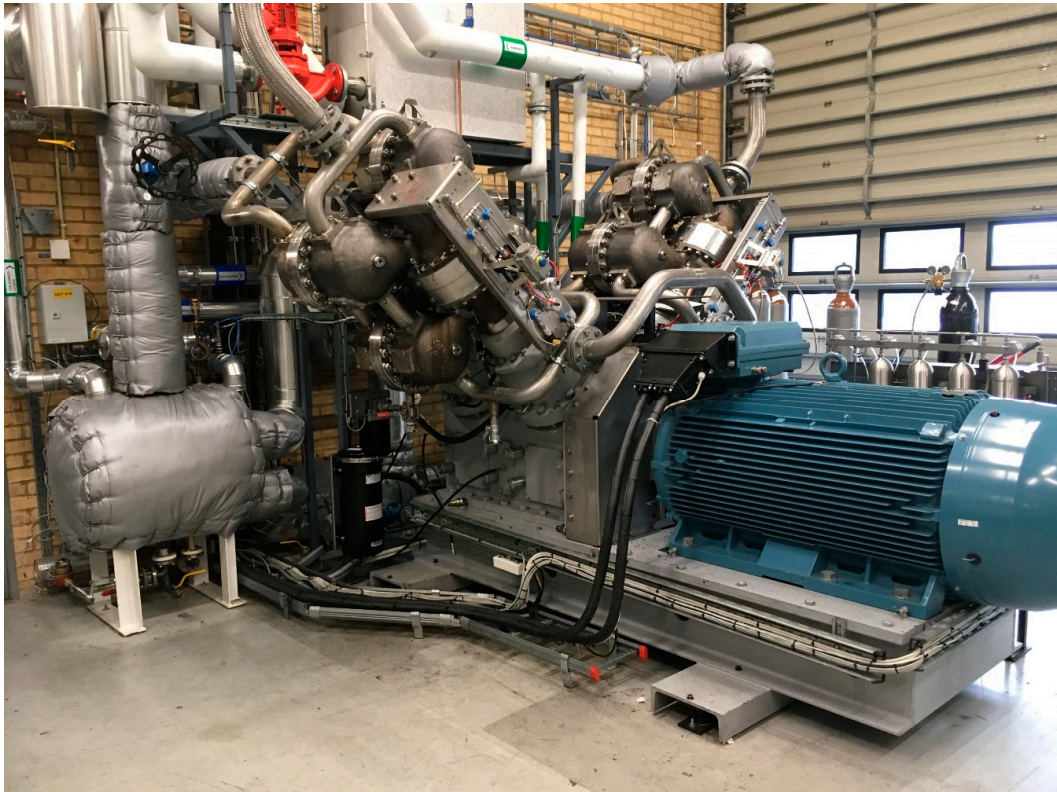


Figure 1. The HighLift HTHP from Olvondo Technology installed in the heat pump room at pharmaceutical company AstraZeneca, Gothenburg, Sweden. The nominal heat output from the heat pump is between 450 and 500 kW.

2.2. LCA Methodology

To evaluate the sustainability of heat pump and compare that to other, more conventional but potentially more polluting heaters, reliable scientific tools that consider the entire lifetime of a product are needed. LCA is an evaluation tool that assesses and quantifies environmental impacts associated with product/process throughout the life cycle of a product known as “cradle to grave” analysis. The manufacturing and use of resources (i.e., materials and energy), as well as emission to the environment (land, air, and water), are calculated for each process. The significance of impact on environmental categories such as climate change, human and ecotoxicity can then be assessed for several so-called impact categories.

For this study, the LCA methodology was applied using the commercial software SimaPro 9.0. *SimaPro* is a software tool that collects, analyzes, and monitors the sustainability performance of any product or process. Two types of data are used to model the functional systems: foreground and background data [17]. The foreground data, which include data about technology, efficiency, and installed capacity, were taken from industrial technical data sheets and literature. Background

data, which include information about raw material manufacturing and fuel use for transportation, construction, and decommissioning of functional unit, were obtained from the Ecoinvent (v.3.5) database, which is embodied in the SimaPro software. SimaPro contains many LCI (Life cycle impact) databases, besides the well-known Ecoinvent v3 database, e.g., the Agri-footprint database and the ELCD database. The Ecoinvent database is a data source for studies and assessments based on ISO 14040 and 14044. The Ecoinvent LCI data are utilized to conduct the life cycle assessment, water footprint assessment, life cycle management, carbon footprint assessment, environmental performance monitoring, product design, and eco-design or Environmental Product Declarations (EPD) [17]. The ISO standardization makes LCA scientifically well-supported while databases for it are continuously expanding. Limitations of LCA are the need for reference or comparison data in the databases used, which sometimes need to be added by the user, or, for research purposes, lack of data for a new process or product. For the current study, database as well as real-life heating system data were sufficiently available.

The heating systems studied are: (a) Stirling cycle-based heat pump (SE HP); (b) oil boiler (OB); and (c) natural gas-fired boiler (NGB). These three systems were evaluated for locations in Sweden with identical climatic conditions. The choice of the location was according to the location of the heat pump under study, which is in Gothenburg, Sweden. The results of the analysis might be different depending on the chosen location.

The LCA methodology is comprised of four main stages of analysis: (i) defining goal and scope; (ii) data collection for life cycle inventory (LCI); (iii) identifying the environmental impact of all the inputs and outputs (LCIA); and (iv) interpreting the results. Several assessment methods have developed over time to classify and characterize the environmental performance of a system: Eco-indicator 99, EDIP 2003, CML 2001, IMPACT 2002+, ReCiPe Endpoint, CML 2 baseline 2000, BEES, TRACI 2, EDIP 2, etc. [18]. The methods used for the current analysis are IMPACT 2002+ and Eco-indicator 99. IMPACT 2002+ v Q2.2 [19] combines the midpoint/damage-oriented approach to impact categories such as human toxicity, carcinogenic effects, non-carcinogenic effects, respiratory effects (due to inorganics), etc. The Eco-indicator 99 [20] method specifies the environmental impact in numbers or scores. This score is scaled in such a way that each point signifies the annual environmental load of an average [European] citizen. The impact categories to be investigated for this study are *respiratory effects*, *climate change*, *ozone layer depletion*, and *acidification* because they have been found to be the significant ones in this kind of studies.

For each phase during the manufacturing, operation, and decommissioning, inventory lists, including raw materials and fuel acquisition/manufacturing and air/water emissions, were computed and categorized into the impact categories. The data for impact categories were from information provided by Pre Consultants [21]. Through characterization, the environmental impacts were determined for each category. Lastly, it was investigated which practice has the major impact on the environment during manufacturing and decommissioning, respectively, as these phases are independent of the duration of use of a product between these two phases.

2.3. Goal and Scope

The scope of the analysis comprises:

- The quantification of resource use and emissions resulting from the manufacturing, operation, and decommissioning of the 500-kW Stirling cycle-based heat pump (SE HP) and oil and natural gas burners (OB, NGB).
- A quantitative comparison between different heat pumps to provide a more complete picture of the potential benefits of the SE HP over NGB and OB from an environmental footprint viewpoint.
- This analysis is related to Swedish conditions. The functional unit employed for this analysis is a boiler. The lifespan of the boiler is assumed to be 15 years or shorter.

2.4. System Boundary

To quantify the impacts of the analyzed unit, system boundaries must be determined. The system boundaries adopted in this study are shown in Figure 2.

Manufacturing: The first phase across the system boundaries is the manufacturing phase. It includes extraction of raw materials, the production of the parts for the unit, transportation activities, the assembly and packaging of components, and testing analysis at the unit.

Operation: The operation phase includes the transport of the HP or boiler to consumers and the processes that follow during the use phase. The processes entail fuel consumption/acquisition, electricity production and usage during boiler operations, the heating process, the hot water cycle, and combustion emissions. Besides water consumption that may occur, the HP also brings about a consumption (due to losses) of helium working fluid.

Maintenance: The transport of engineers to and from the site for maintenance of unit is included. The installation or replacement of any component needed during maintenance is excluded, as the contribution may be assumed negligible. If some of the main components are replaced, e.g., the main motor, this assumption is no longer valid. However, the heat pump is engineered to ensure long-life operation of the large critical components.

Decommissioning: Lastly, the end of life (EoL) phase is also assessed, considering the heat pump's handling activities after the estimated life span use. In the decommissioning process, disassembly, cleaning, repairing of parts, and final disassembly are considered. In principle, this makes the raw materials available for other use. (In the LCA, this typically results in negative values for environmental impact.)

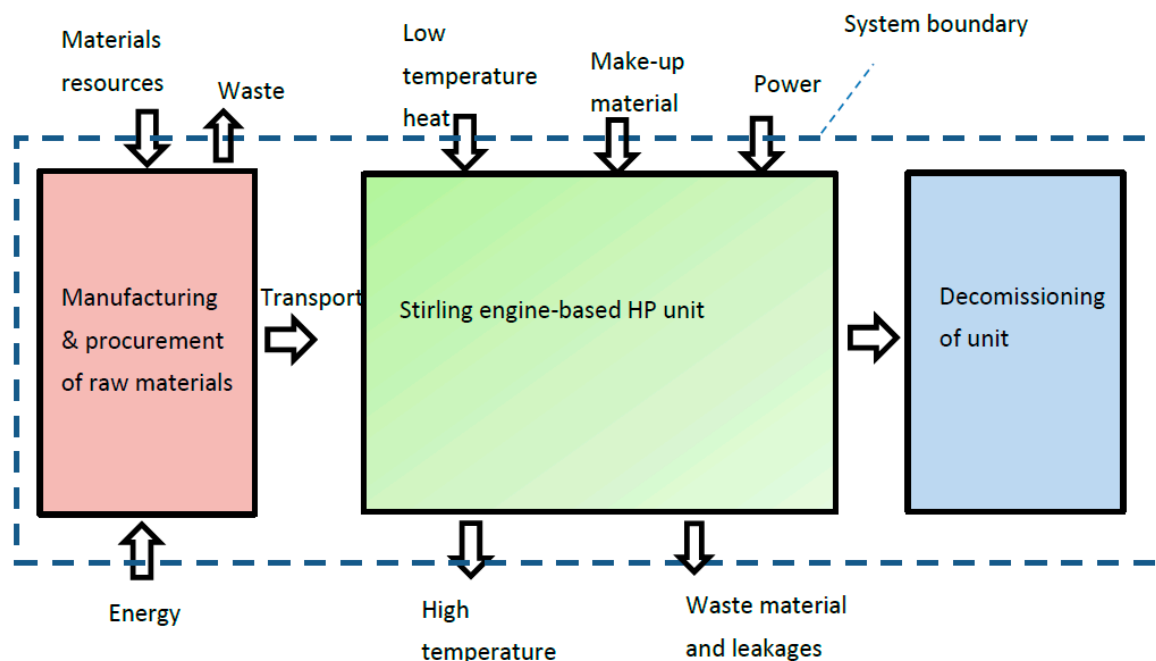


Figure 2. Schematic diagram of the system boundary for life cycle assessment of SE HP.

The system boundary for natural gas-fired boiler and oil boiler are slightly different, consisting of raw material extraction/acquisition, fuel and materials transportation, boiler unit construction, the operation (combustion of fuel), annual maintenance of boiler, and decommissioning of boiler. The production of imported fuel (natural gas) is also considered.

The inventory data sheet used for the development of an LCI network diagram for the Stirling engine-based heat pump (SE HP), natural gas-fired boiler (NGB), and oil boiler (OB) is given in Table 1.

Table 1. Inventory data for LCA analysis of Stirling engine-based HP, Natural gas-fired boiler and oil boiler.

Lifecycle Phase	Raw Materials and Resources Used		SE HP	NGB	OB
Construction	Stainless Steel	kg	7697	104	0
	Steel low-alloyed	kg	0	2396	0
	Steel	kg	0	0	2425
	Cast iron	kg	1500	0	0
	Copper	kg	700	63	125
	Brass	kg	0	1	0.25
	Aluminum	kg	0	156	75
	Lead	kg	0.1	0	0
	Chromium	kg	1	0	0
	Tungsten	kg	1	0	0
	Plastic 1 PTFE	kg	1	0	0
	HDPE	kg	0	19	7
	Silica aerogel	kg	100	0	0
	Rockwool	kg	0	167	95
	alkyd paint	kg	0	0	13
	Brazing solder	kg	0	0	30
	Corrugated board	kg	0	0	50
	Medium voltage electricity	kWh	0	6125	1660
	Natural gas	MJ	0	9833	9600
	Light fuel oil	MJ	0	5187	5100
Tap water	kg	0	0	3705	
Operation	Helium	kg/yr	20	0	0
	Water	m ³ /yr	50	0	0
	Motor oil	L/yr	200	0	0
	Land occupation industrial set- up	m ²	50	50	50
	Electricity Power	kW	250	0	0
	Heat output	kW	500	0	0
	Natural gas	MJ/m ³	0	36.8 *	0
	Oil	MJ/kg	0	0	45.2 *

* Based on Ecoinvent v2.0 database (2012).

3. Results

The following section assesses the environmental impacts associated with Stirling cycle-based heat pump, natural gas-fired boiler, and oil boiler with design capacity of 500 kW and compares them with a Stirling cycle-based heat pump. In the tables and figures, dimensionless values are given, grouping several impact categories, unless clearly indicated with a unit.

3.1. Stirling Cycle-Based Heat Pump

The contributions of the construction, operational use, and decommissioning stages of the Stirling cycle-based HP to the total impact were assessed using SimaPro software. Table 2 shows the impacts associated with the generation of 500 kW of heat using a Stirling cycle-based HP.

Table 2. Impact assessment and characterization per impact category for a 500-kW heat output Stirling cycle HP.

Impact Category	Unit	Construction + 1 Year of Use	Construction + 8 Years of Use	Construction + 15 Years of Use + Decommission
Carcinogens	DALY *	2.65×10^{-3}	2.67×10^{-3}	8.80×10^{-4}
Non-carcinogens	DALY	1.01×10^{-2}	1.01×10^{-2}	8.54×10^{-3}
Respiratory (inorganics)	DALY	2.65×10^{-2}	2.69×10^{-2}	1.28×10^{-2}
Ionizing radiation	DALY	6.56×10^{-5}	6.63×10^{-5}	6.17×10^{-5}
Ozone layer depletion	DALY	2.9×10^{-6}	3.20×10^{-6}	2.84×10^{-6}
Respiratory (organics)	DALY	1.80×10^{-5}	2.02×10^{-5}	-6.20×10^{-5}
Aquatic ecotoxicity	PDF \times m ² \times year **	4.58×10^2	4.60×10^2	3.60×10^2
Terrestrial ecotoxicity	PDF \times m ² \times year	2.52×10^4	2.54×10^4	2.17×10^4
Terrestrial acid/nutri	PDF \times m ² \times year	5.42×10^2	5.57×10^2	3.47×10^2
Land occupation	PDF \times m ² \times year	4.61×10^2	4.63×10^2	3.22×10^2
Global warming	kg CO ₂ -eq	8.11×10^3	9.61×10^3	-4.89×10^3
Non-renewable energy	MJ primary	7.68×10^5	7.98×10^5	7.00×10^5
Mineral extraction	MJ primary	6.82×10^4	6.82×10^4	6.76×10^4

* DALY, disability-adjusted life year; ** PDF, potentially disappeared fraction of species.

Figure 3 shows impact assessment for the heat pump on a relative scale. This means that the plotted values are the values in Table 2 divided by the average for the three cases. As can be seen from the graph, the main contributions to the environmental impact are during the construction and decommissioning stages.

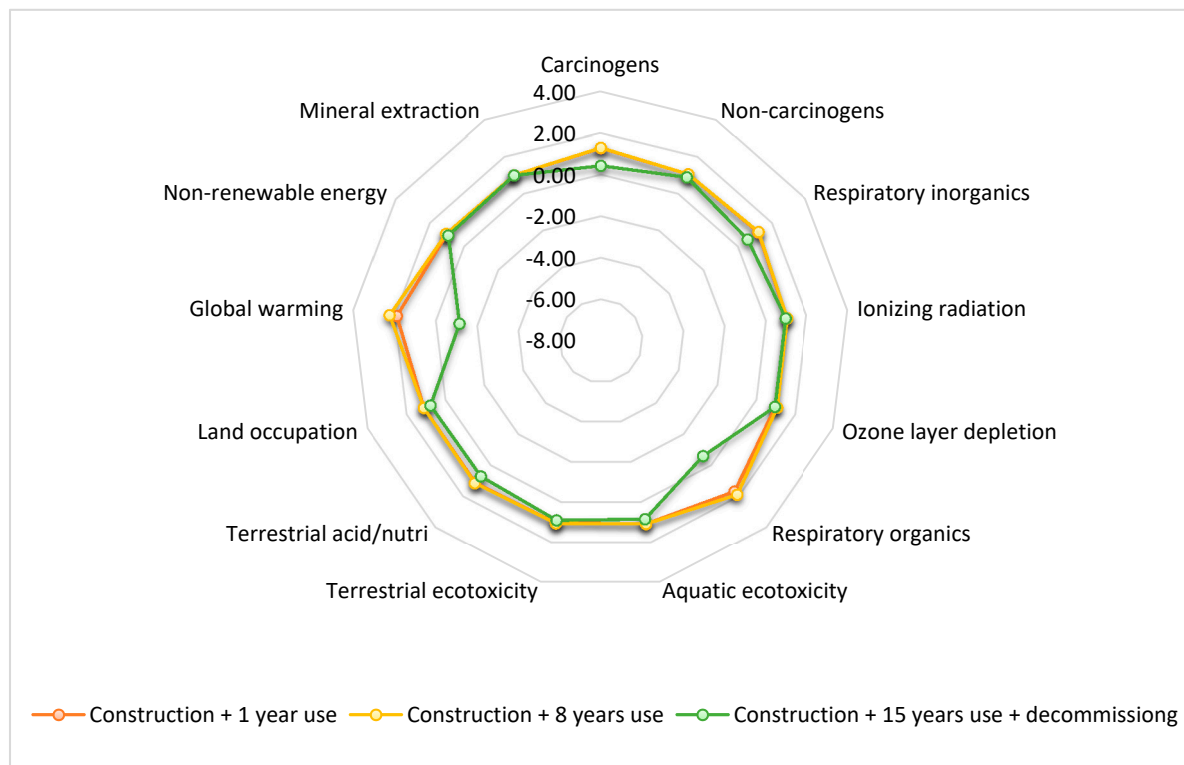


Figure 3. Relative impact assessment for the heat pump with varying use duration. The different factors are made dimensionless by dividing each value by the average value of the factors.

The analysis shows that almost 80% of the impact stems from the production of raw material for constructing the Stirling cycle HP itself, whereas the operation phase contributes less than 20%. Only a small fraction of the impact is due to the maintenance of the engine.

Figure 4 shows that among the impact categories terrestrial ecotoxicity and respiratory inorganic, the share of the processing is close to 50%. The use of water for the operational phase and maintenance phase and the production of cast iron and copper are the main contributing factors, respectively.



Figure 4. Life-cycle assessment of a 500-kW heat output Stirling cycle-based HP.

When decommissioning is included in the assessment, the impact category global warming and respiratory organic effects show negative values, which means a positive effect on the environment. This effect stems from the 90% recycling of the engine’s material.

For most categories, the score is positive, which shows that the net effect is damage to the environment. However, in categories such as respiratory organics and global warming, where a score is negative, the benefits are more significant than the burdens. This is because some substances are paired with a negative characterization factor (C.F.). These substances are known to, for example, contribute to global cooling.

For the Stirling cycle-based HP, the primary emission source leading to the impact is the emissions of zinc to air, mainly stemming from copper production. The analysis showed considerable emission of nitrogen oxides and sulfur oxides as well, which contributes to the photochemical ozone formation and acidification. One of the main contributions to the result is water used for cooling in the context of electricity production.

The resource indium also has a significant impact for the Stirling cycle-based HP. Indium appears in lead-zinc mining as a resource input from nature. In the Ecoinvent dataset, it is assumed that this indium is not used, and thus the resource is wasted. However, with rising demand, it would be possible to extract this resource in the process of lead-zinc mining. The indium accounts for about 60% of the total impact. The contributing factor for ozone depletion by a Stirling cycle-based heat pump is the emission of halons resulting from power generation.

A Stirling cycle-based heat pump has an average impact of 0.02 DALY for human health, 2.2×10^4 PDF·m²·year. for ecosystem quality, -4894 kg CO₂-eq for global warming and 765,000 MJ for

resource consumption. These values include manufacturing, use for 15 years, and decommissioning at end-of-life, as listed in Table 3.

If impacts of the Stirling cycle-based H.P are analyzed over the years, the result shows that one year (including manufacturing phase) of the daily operation of 500-kW heat output Stirling cycle HP emits 8114 kg CO_{2-eq} with 836,067 MJ energy needed for the extraction/manufacturing of materials. Daily operation of this H.P for eight years (including manufacturing phase) emits 9610 kg CO_{2-eq} requiring 865,853 MJ energy. Finally, after 15 years of operation including manufacturing and the decommissioning phase, 767,212 MJ energy is needed with overall negative emissions of −4894 kg CO_{2-eq}.

Table 3. The environmental footprint of the 500-kW heat output Stirling cycle HP for construction, use and end-of-life decommissioning.

Damage Category	Unit	Construction + 1 Year of Use	Construction + 8 Years of Use	Construction + 15 Years of Use + Decommission
Human health	DALY *	0.0393	0.0397	0.0223
Ecosystem quality	PDF × m ² × year **	2.66 × 10 ⁴	2.69 × 10 ⁴	2.27 × 10 ⁴
Climate change	kg CO _{2-eq}	0.81 × 10 ⁴	0.96 × 10 ⁴	−0.49 × 10 ⁴

* DALY, disability-adjusted life year; ** PDF, potentially disappeared fraction of species.

The ECO INDICATOR 99 method was used to analyze further the damage on human health, ecosystem quality, and climate change, as shown in Figure 5. The Pt unit (a dimensionless value) measures the impact of these damages. A value of 1 Pt refers to one-thousandth of the yearly environmental impact of one average European inhabitant.

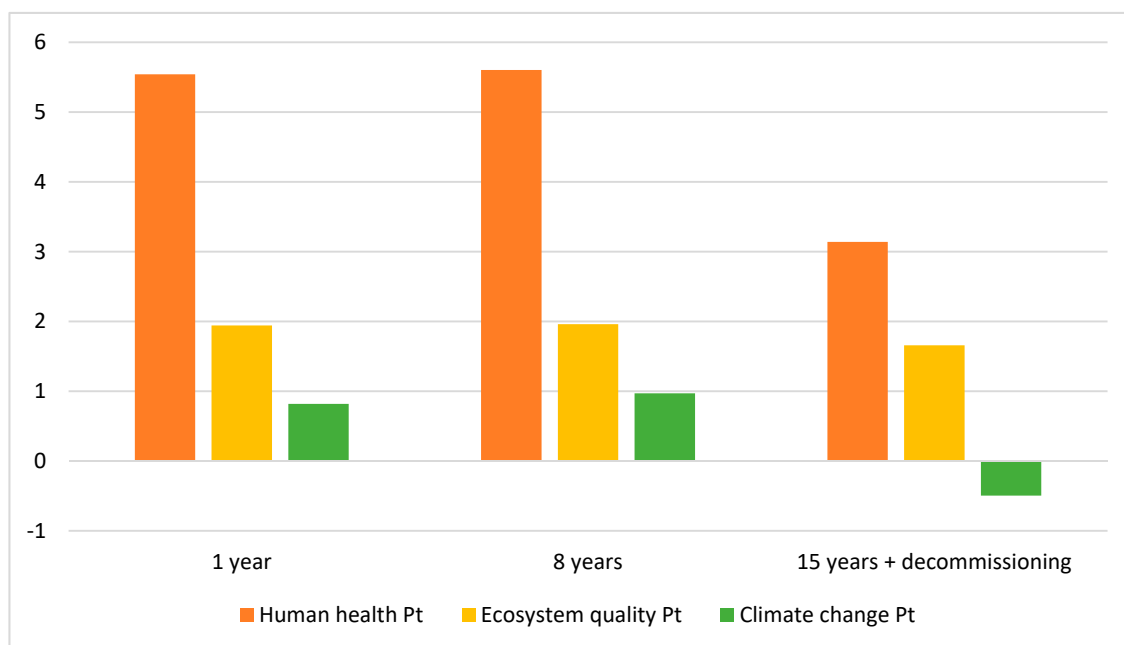


Figure 5. Damage assessment and characterization for Stirling cycle-based HP.

The figure shows that the major impact the Stirling cycle-based HP is on human health. From the analysis of the results, it seems clear that the most critical material in terms of environmental impact is copper (used in the electromotor of the Stirling cycle). The reason is that copper production, although typically 41% recycled copper is used, contributes to the emission of direct atmospheric arsenic emission.

Moreover, the environmental impact for one year of operation is almost the same as for eight years of operation. This shows that the main impact is associated with the production/extraction of raw material for the equipment. It makes clear that, over the 15 years of operation, the additional impact on human health, ecosystem, and climate change is not significant.

3.2. Natural Gas-Fired Boiler (NGB)

A natural gas-fired boiler shows a more significant environmental impact compared to a Stirling cycle HP. For all the options that supply heat by burning natural gas (or oil, as discussed below), the emissions of mercury to air are the crucial values. Table 4 shows the life cycle impacts associated with natural gas boiler for 1, 8, and 15 years of operation. A significant emission source is the emission of bromochlorodifluoromethane. This emission results from the typically long-distance transportation of natural gas in pipelines as it is used for fire suppression within natural gas pipelines infrastructure. The chromium (VI) emissions from iron production process contribute to the human toxicity and cancer effects.

The CO₂ emissions from burning natural gas have the main impact on climate change during boiler use. Some further climate change effects stem from methane emissions that mainly occur due to losses during the transport of natural gas (imported from Denmark via North Sea lines) in long-distance pipelines (methane being the main component of natural gas). The use of a natural gas boiler also results in considerable emissions of particulate matter from the combustion process. Finally, the emission of nitrogen oxides during the combustion process at the heat pump results in photochemical ozone formation, acidification, and terrestrial and marine eutrophication.

Table 4. Impact assessment and characterization for the 500-kW heat output natural gas-fired boiler (NGB).

Damage Category	Unit	Construction + 1 Year of Use	Construction + 8 Years of Use	Construction + 15 Years of Use + Decommission
Human health	DALY *	0.109	0.127	0.114
Ecosystem quality	PDF × m ² × year **	4.08 × 10 ⁴	4.08 × 10 ⁴	3.98 × 10 ⁴
Climate change	kg CO ₂ -eq	8.89 × 10 ⁵	7.16 × 10 ⁶	1.27 × 10 ⁷

* DALY, disability-adjusted life year; ** PDF, potentially disappeared fraction of species.

3.3. Oil Boiler (OB)

The analysis of the life cycle footprint of an oil boiler shows a similar split (Table 5) of the total impact as for natural gas. In addition, here, the emissions of the burning process, especially CO₂, contribute most to the impact category climate change. A prominent difference is that the emissions from the oil burning process also contribute most in the impact categories photochemical ozone formation, terrestrial eutrophication, and marine eutrophication. Electricity (needed during the equipment construction phase) contributes very little in most categories, being also, per MJ of heat produced during the use phase, smaller than for a natural gas boiler. The oil boiler has higher impacts on acidification compared to natural gas, a large extent the result of sulfur dioxide emissions. These emissions result primarily from the oil production (refining) process. For the oil boiler, emissions of copper and zinc to air both contribute to the environmental impact, stemming mainly from the burning process.

For heat from an oil boiler, the emission of bromotrifluoromethane (with a high ozone-depleting potential) from oil production is an important input. The emission stems from leakage, losses at filling, and false alarms.

Table 5. Impact assessment and characterization for oil boiler (OB).

Damage Category	Unit	Construction + 1 Year of Use	Construction + 8 Years of Use	Construction + 15 Years of Use + Decommission
Human health	DALY	0.162	0.21	0.198
Ecosystem quality	PDF × m ² × year	5.45 × 10 ⁴	5.46 × 10 ⁴	5.29 × 10 ⁴
Climate change	kg CO ₂ -eq	1.68 × 10 ⁶	8.94 × 10 ⁶	1.73 × 10 ⁷

The comparison of damage assessment and characterization of Stirling cycle-based HP, oil boiler (OB), and natural gas-fired boiler (NGB) during their life span of 15 years is given in Table 6.

Table 6. Impact assessment and characterization for construction, 15 years of use, and end-of-life decommissioning of a Stirling cycle-based HP (SE HP), an oil boiler (OB), and a natural gas-fired boiler (NGB) for 500-kW heat output.

Impact Category	Unit	NGB	OB	SE HP
Carcinogens	DALY	1.73 × 10 ⁻¹	1.59 × 10 ⁻¹	8.80 × 10 ⁻⁴
Non-carcinogens	DALY	1.05 × 10 ⁻²	1.23 × 10 ⁻²	8.54 × 10 ⁻³
Respiratory inorganics	DALY	4.89 × 10 ⁻¹	6.75 × 10 ⁻¹	1.28 × 10 ⁻²
Ionizing radiation	DALY	2.17 × 10 ⁻⁴	2.30 × 10 ⁻⁴	6.17 × 10 ⁻⁵
Ozone layer depletion	DALY	2.48 × 10 ⁻³	2.76 × 10 ⁻³	2.84 × 10 ⁻⁶
Respiratory organics	DALY	3.56 × 10 ⁻⁵	3.60 × 10 ⁻⁵	-6.20 × 10 ⁻⁶
Aquatic ecotoxicity	PDF × m ² × year	5.76 × 10 ²	6.66 × 10 ²	3.60 × 10 ²
Terrestrial ecotoxicity	PDF × m ² × year	3.76 × 10 ⁴	5.01 × 10 ⁴	2.17 × 10 ⁴
Terrestrial acid/nutri	PDF × m ² × year	9.99 × 10 ²	1.14 × 10 ³	3.47 × 10 ²
Land occupation	PDF × m ² × year	6.50 × 10 ²	1.04 × 10 ³	3.22 × 10 ²
Global warming	kg CO ₂ -eq	1.27 × 10 ⁷	1.73 × 10 ⁷	-4.89 × 10 ³
Non-renewable energy	MJ primary	9.15 × 10 ⁵	8.12 × 10 ⁵	7.00 × 10 ⁵
Mineral extraction	MJ primary	8.14 × 10 ⁴	1.02 × 10 ⁵	6.76 × 10 ⁴

Similar to Figure 3, a comparison of relative impacts (normalized around the average value) for the three technologies is given in Figure 6.

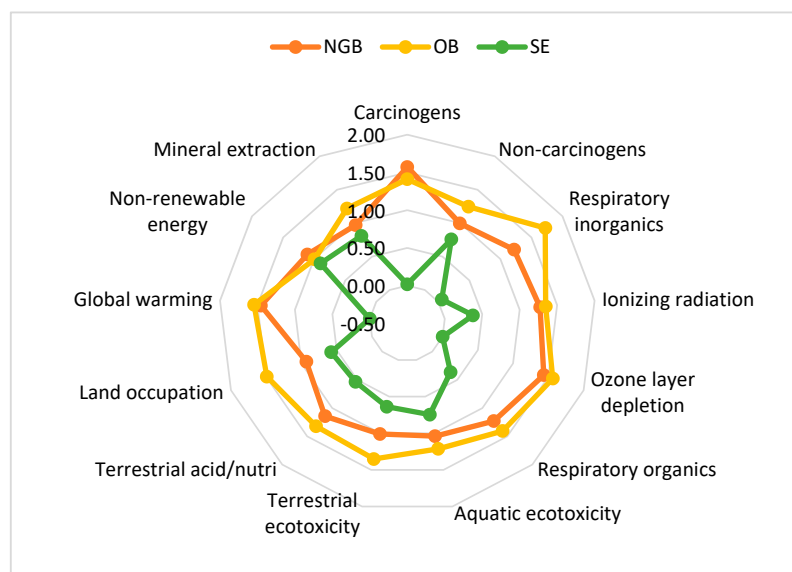


Figure 6. Comparing the relative impact assessment of the technologies. The different factors are made dimensionless by dividing each value by the average value of the factors.

4. Discussion

The Stirling cycle-based heat pump technology causes lower to non-significant environmental impacts compared to a natural gas-fired boiler or an oil-fired boiler. The toxicity originates to the largest part from chromium (VI) emissions into the water in all considered technologies. The unit process is responsible for emissions with the main impact on human toxicity, cancer effects, and global warming.

Figure 7 shows the relative distribution of impacts associated with the use of SE HP, NGB, and OB. Among all categories, human impact is the largest contributing category by these heating technologies following climate change (i.e., global warming potential).

The unit processes with the most significant direct emissions are the processes in which fuels are burned. The largest impacts then come from the oil boiler, followed by the natural gas boiler. The emissions with the highest influence in this category are, besides CO₂, sulfur dioxide and particulate emissions. For the Stirling cycle-based HP construction, nickel and lead manufacturing are the main contributors, besides copper, which is used in the electromotor.

For the impact on climate change, a substantial reduction is possible by replacing a natural gas or oil boiler with a high temperature heat pump. A reduction of up to 15% of the original impact is possible for the options that do not use natural gas. For the oil boiler, a reduction by almost one third is possible. For particulate matter, the oil-fired boiler gives a much higher environmental burden, comparatively. Many impact categories show similar results since the same emissions (see, e.g., emission of nitrogen oxides to air) is responsible for various environmental problems.

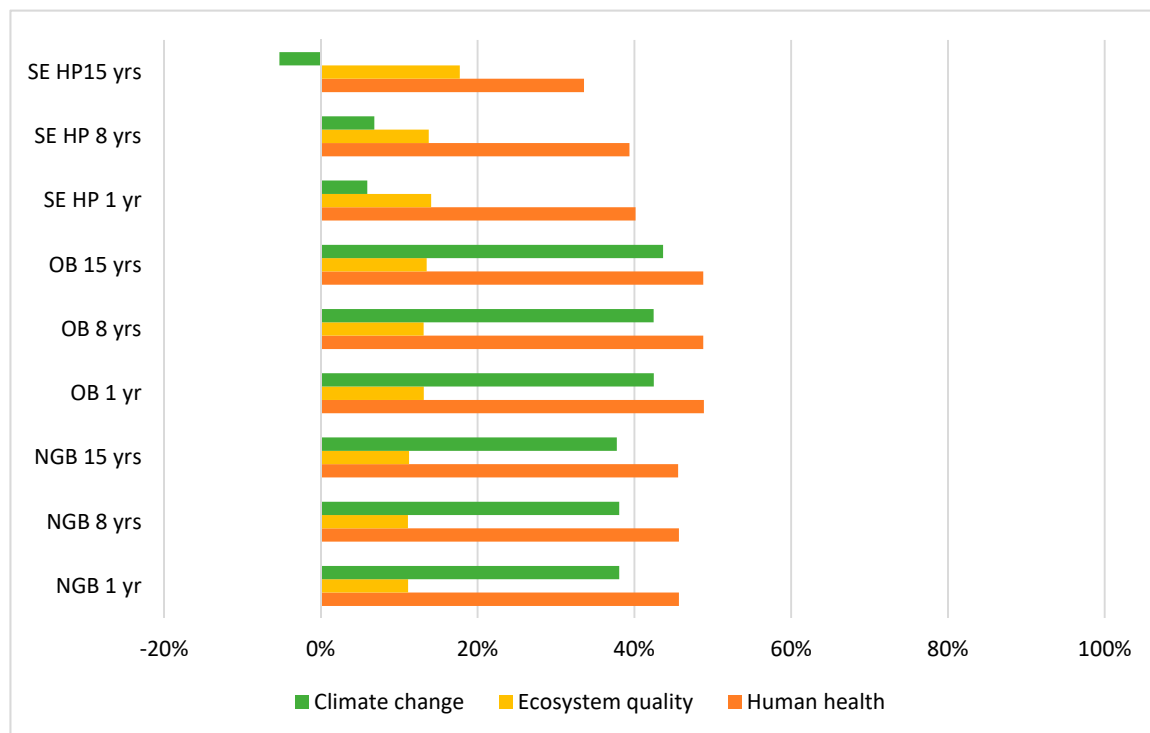


Figure 7. Comparison of damage assessment and characterization Stirling cycle-based HP (SE HP), oil boiler (OB), and natural gas-fired boiler (NGB) on a relative scale.

Figures 8–10 give a comparison of environmental impact for nine damage categories for construction + 1 year of operation (Figure 8), construction + 8 years of operation (Figure 9) and construction + 15 years of operation followed by decommissioning (Figure 10).

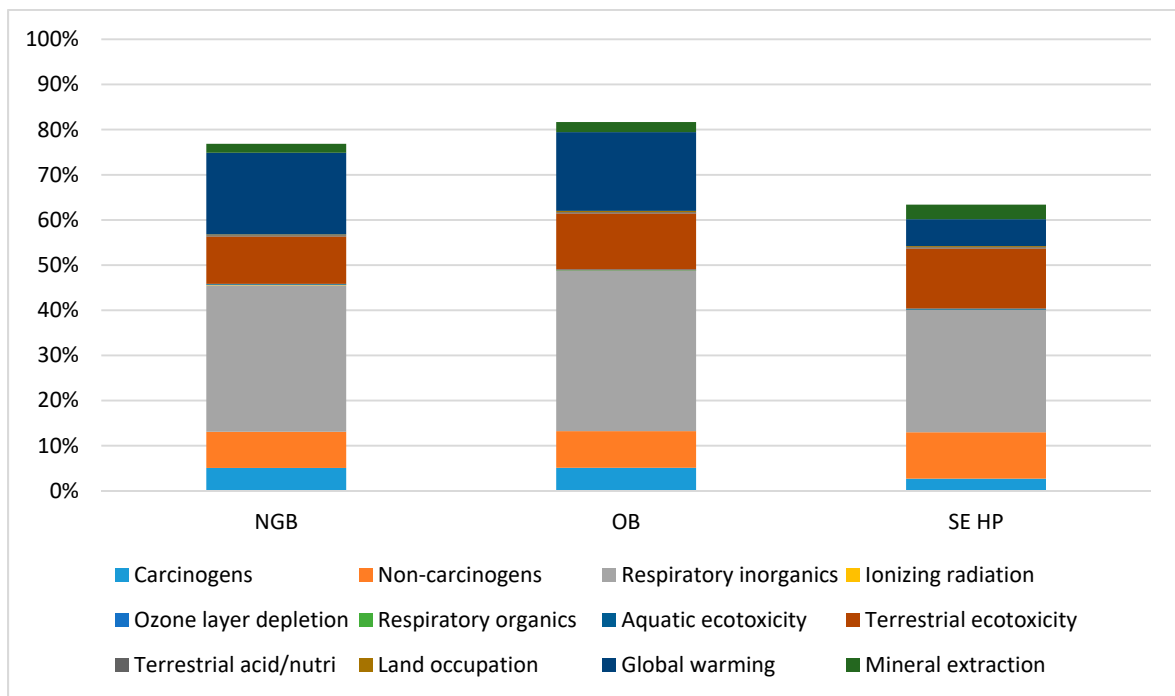


Figure 8. Comparison of damage assessment and characterization for a Stirling cycle-based HP (SE HP), an oil boiler (OB), and a natural gas boiler (NGB) on a relative scale for one year of operation (excluding decommissioning).

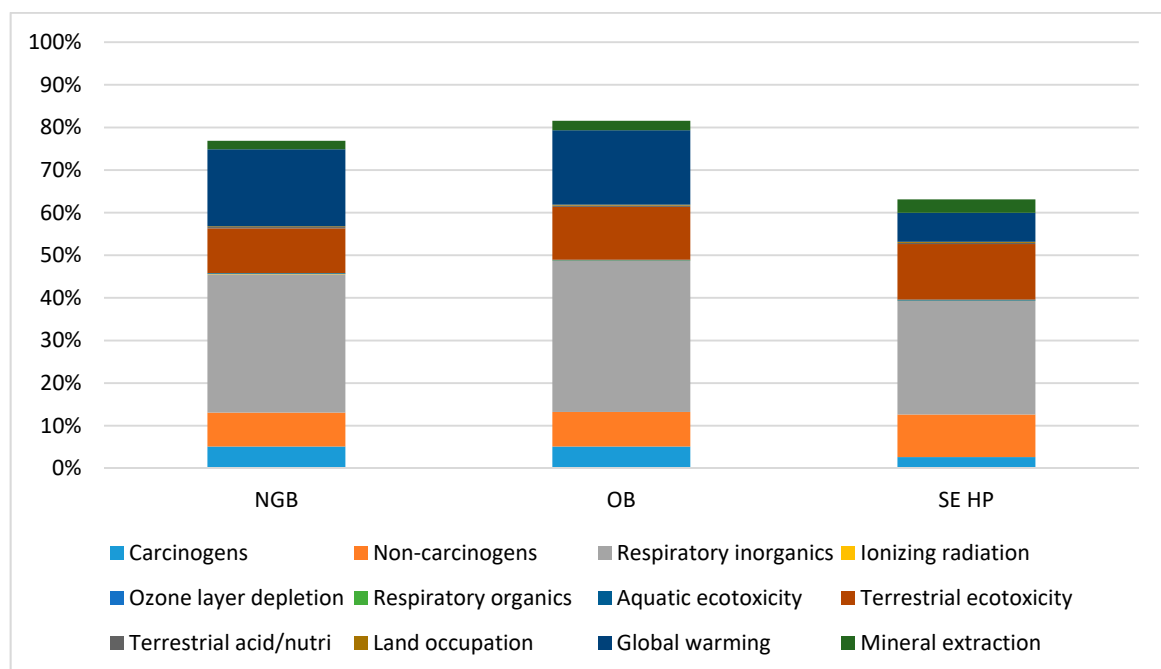


Figure 9. Comparison of damage assessment and characterization Stirling cycle-based HP (SE HP), oil boiler (OB), and natural gas boiler (NGB) on a relative scale for eight years of operation (excluding decommissioning).

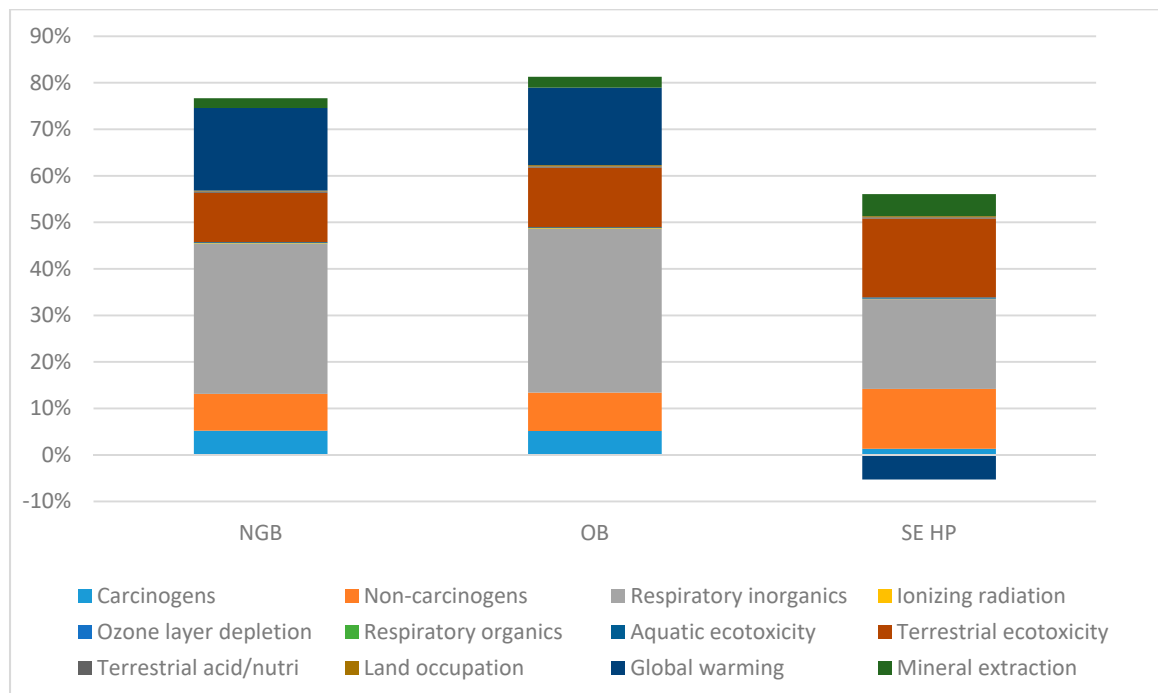


Figure 10. Comparison of damage assessment and characterization for a Stirling cycle-based HP (SE HP), an oil boiler (OB), and a natural gas-fired boiler (NGB) on a relative scale for 15 years of operation (including decommissioning).

The already mentioned paper by Stamford et al. [11] gives a similar study done for a much smaller 1-kW Stirling engine HP and compares it with a gas-fired boiler. They concluded that the S.E. micro-CHP system offers an environmental and economic advantage over the oil boiler by 30%, similar to what is found here.

5. Conclusions

The study evaluated the environmental sustainability of a Stirling cycle-based HP using the LCA approach. The analysis conducted above shows that the manufacturing phase has the most impact during the life span (15 years) of a Stirling cycle-based HP in terms of environmental impacts. The results show that, for the Stirling cycle HP to produce 4 GWh heat output (including manufacturing phase, operation phase, and decommissioning phase), the global warming potential at the end of its life span is -5000 kg CO₂ equivalent and acidification potential 202 kg SO₂ equivalent.

This study also compared the environmental impacts of a Stirling cycle-based heat pump with that of an oil boiler and a natural gas-fired boiler for 500-kW heating. The major impacts of the oil boiler and the natural gas-fired boiler are during the use phase of the engine.

For future work, the comparison should be conducted concerning the economic sustainability of the Stirling cycle-based HP and its comparison with a natural gas-fired boiler, oil boiler, and, if possible, an electric heater boiler. This would be beneficial in providing a still broader picture of how Stirling cycle-based HP technology can replace NGB, OB, and electric boilers in terms of lower environmental and economic impacts.

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