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Life Cycle Assessment of a Stirling Cycle-Based High-Temperature Heat Pump for Industrial Decarbonization

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Abstract

High-temperature heat pumps (HTHPs) that utilize industrial waste heat as a low-temperature source in combination with renewable electricity offer a promising alternative to fossil fuel-based heat generation and can significantly reduce CO_2 emissions in the industrial sector. This study presents a detailed life cycle assessment (LCA) of a stirling cycle-based high-temperature heat pump (SC-HTHP). Experimental testing of the SC-HTHP system was conducted at the SUSHEAT end-user site at the IVAR biogas facility in Stavanger, Norway. The analysis uses the ReCiPe 2016 Endpoint (H) impact assessment method and the IPCC 2021 GWP20 climate change indicator, taking a "cradle-to-partial-grave" approach. Life cycle inventory (LCI) data were obtained from the Ecoinvent database (via SimaPro), along with manufacturer-specific data from Enerin. The functional unit is defined as a 400 kW SC-HTHP, and the assessment includes the construction/manufacturing, distribution, and use/operational stages over a projected 25-year lifetime. The results demonstrate that the environmental impact is primarily driven by the use/operational phase of the SC-HTHP, whereas the construction/manufacturing and distribution phases contribute significantly less. The total category impact for the use/operational phase, the construction/manufacturing phase, and the distribution phase was found to be 90.13%, 9.86%, and 0.0001%, respectively. Furthermore, the total CO_2 emissions (2.42×10^6 kg CO_2-eq) associated with the operational phase exceeded those associated with the construction and distribution phases over 25 years of use.

Keywords: Stirling cycle-based high-temperature heat pump; Life cycle analysis; Manufacturing and use phases; Environmental impacts; Emissions

1. Introduction

The industrial sector is a major global emitter of greenhouse gases and a significant obstacle to achieving a decarbonized society in the future [1]. In 2022, the industrial sector accounted for over 25.1% of the EU27's final energy consumption and over 19.6% of its total greenhouse gas (GHG) emissions [2]. Through the Green Deal, the European Union (EU) has set ambitious targets to reduce greenhouse gas emissions and achieve climate neutrality by 2050 [3]. Intensive industrial activity demands high energy use and significantly contributes to GHG emissions, negatively affecting resource conservation and the environment through global warming [4]. The updated Renewable Energy Directive [5], which came into effect in November 2023, aims to increase the share of renewable energy to 45% by 2030. Reducing the use of fossil fuels and the resulting carbon dioxide emissions, which are a primary cause of global warming, nowadays requires the use of renewable energy [6]. The decarbonization of Europe's industry and heating sectors relies heavily on heating, ventilation, and air conditioning (HVAC) systems [3]. In this context, heat pump technologies play a crucial role by using decarbonized energy sources, such as renewable electricity, and applying renewable or waste heat across various industrial, district heating, and civil applications. Furthermore, heat pumps are a significant contributor to improving energy efficiency in buildings and construction, as they utilize renewable energy

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sources [7]. Recovering waste heat presents a promising strategy for reducing GHG emissions in the industrial sector. According to [8], heat pumps use external energy to transfer heat from low-temperature sources to high-temperature sources. In other words, Heat pumps can be used efficiently when high-temperature heat demand aligns with the availability of nearby low-temperature waste heat [9]. Stirling cycle-based High Temperature Heat Pump (SC-HTHP) systems provide a low-carbon, extremely energy-efficient solution that lowers energy consumption, encourages the use of renewable energy sources, and helps achieve global climate targets [10, 11, 12]. However, the development of high-temperature heat pumps (HTHPs) with sink temperatures above 150°C is a key area of research and development (R&D) focus. Several lab-scale and pilot systems are under development and testing [1].

Effective methods are needed to identify and address the weakest elements in each process to reduce risks and environmental impacts. According to the European Commission, life cycle assessment (LCA) is among the most sophisticated techniques for evaluating the environmental impact of technology, products and systems from the extraction of raw materials to recycling or final disposal [3, 13]. When applied to heat pumps, LCA provides valuable insights that help consumers and policymakers evaluate the environmental performance of new systems and choose more environmentally friendly solutions [13]. Koroneos and Nanaki [14] conducted an LCA of a ground source heat pump at Pylaia Town Hall in Greece. They identified acidification (74%) as the dominant impact, mainly due to SO_2 and NOx emissions from raw material production and system operation. In another study, Shamoushaki and Koh [15] performed a comparative LCA of four heat pump systems: ground-source heat pump (GSHP), water-source heat pump (WSHP), air-source heat pump (ASHP) and a novel hydrogen-source heat pump (HSHP), from an environmental perspective. The main impact contributors, based on the results of this study, are the manufacturing and use phases. While HSHP depicted noticeably lower carbon emissions, ASHP showed the highest environmental burden. Evaluation of the environmental impacts of an ASHP was done by [16] throughout their entire life cycle, including manufacturing, operation and end-of-life phases. The operational phase dominated environmental impacts by about 95%. For ASHP (based on Irish data), its global warming potential (GWP) reached 35.8 t CO_2-eq., with operation as the main contributor.

While numerous studies have examined the environmental impacts of heat pumps and their effects on human health, ecosystems, and the natural environment [17, 3, 4], the current research landscape seeks to address this critical gap by conducting LCA and environmental impact assessments of an industrial Stirling cycle-based high-temperature heat pump, a core component of the novel technology developed under the SUSHEAT project to support industrial decarbonization. The LCA of the Stirling cycle HTHP follows a cradle-to-partial-grave approach, covering construction/ manufacturing, distribution phase and 25 years of use/operational phase. It is worth mentioning that the impacts of end-of-life (EoL) are excluded from this study.

The paper is structured as follows: Section 2 describes the LCA methodology, covering the system description, life cycle inventory and environmental assessment method. Section 3 presents and discusses the LCA results. Section 4 concludes the paper by summarizing the key findings.

2. Methodology

This study employs the Life Cycle Assessment (LCA) methodology, following the principles outlined in the ISO 14040 [18] and 14044 [19] standards established by the International Organization for Standardization, to quantify the environmental impacts of the SC-HTHP used in the SUSHEAT system. LCA quantifies resource use and environmental impacts across a product's entire life cycle, from production and use to transportation and end of life (cradle to grave). This approach supports improvement plans and helps identify potential environmental issues.

2.1. System description

In the EU-funded SUSHEAT system, Enerin offers a new industrial HTHP unit (HoegTemp) that uses helium (R-704) as refrigerant. Figure 1 presents the schematic of the SUSHEAT system and the heat pump installation. It is worth noting that, beyond the Stirling cycle-based HTHP, the SUSHEAT system also includes a bio-inspired phase change material (PCM) thermal energy storage (TES) system, a solar Fresnel collector, and a control and integration twin (CIT) system, as shown in Figure 1a [9]. The SUSHEAT system is designed to support industrial processes requiring high temperatures, typically between 150°C and 250°C, while aligning with the capabilities of current Stirling cycle high-temperature heat pumps (SC-HTHPs). The high-temperature heat pump (HTHP) testing of the SUSHEAT system is conducted at the end-user sites at the IVAR biogas facility in Stavanger, Norway. The HoegTemp is a four-circuit, double-acting gamma-type piston compressor heat pump (see figure 1b). This enables flexible operation, a high lifting capacity, and temperatures above 200 °C [20]. Internal heat exchangers integrate heating, cooling, and regeneration functions into one unit (see Figure 1c). The LCA uses an SC-HTHP to produce steam with an output of 400 kW from waste heat and electricity. At the IVAR biogas facility, recovered waste heat at approximately 30 °C serves as the heat source for the heat pump system. Heat output is measured in a closed water circuit that acts as the heat sink, transferring heat from the heat pump to a steam generator for the plant's CO_2 capture system, where it is upgraded to produce steam at 140–200 °C for reuse in the CO_2 capture process. The heat source is provided by the plant cooling water circuit, which operates in parallel with a cooling tower.

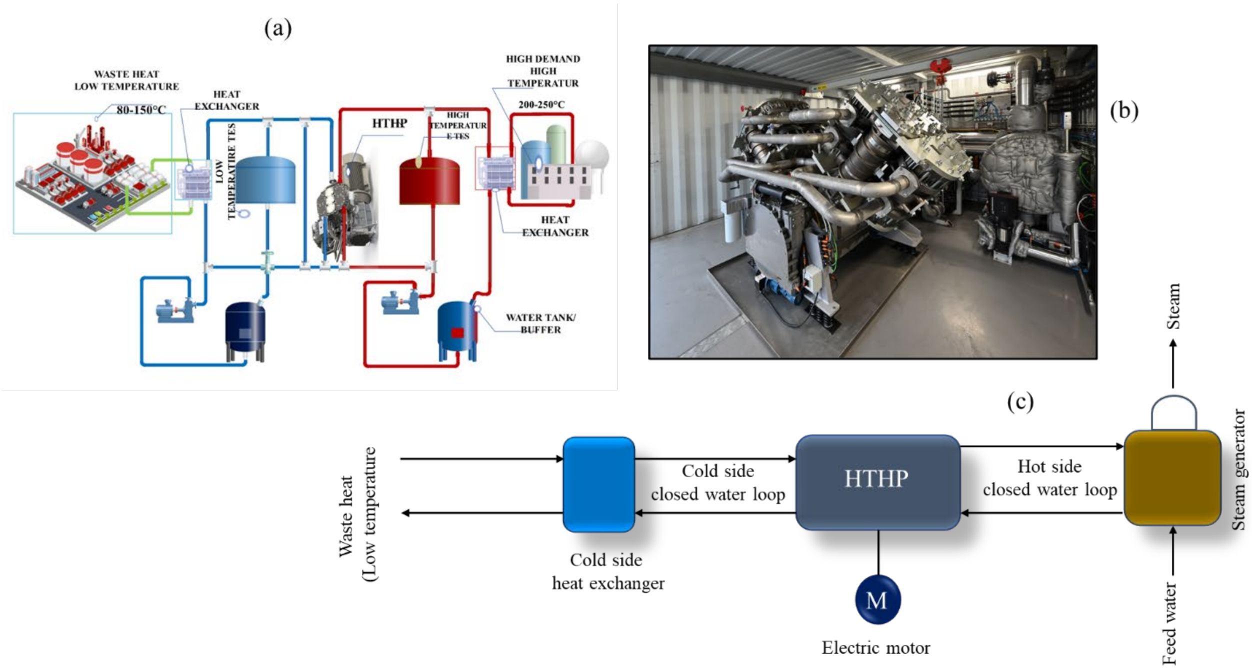

Figure 1. Schematic (a) SUSHEAT system, (b) SC-HTHP and (c) basic flowsheet of the heat pump configuration.

2.2. LCA framework

2.2.1. Goal and scope definition, functional unit and system boundary

LCA is a four-phase method for analyzing environmental aspects and potential impacts, according to ISO: (1) defining the goal and scope; (2) analyzing the inventory; (3) assessing the impact; and (4) interpreting the results [21], as shown in Figure 2.

The primary objective of this work is to quantify the environmental impacts of the SC-HTHP system across its full life cycle and to identify the emissions generated during each phase. The SC-HTHP is manufactured by the Norwegian company Enerin. To ensure the comparability of LCA findings in different technologies, key parameters must be clearly defined and standardized. Most importantly, the system boundaries must be harmonized and define the product system. However, the LCA conducted in this study focuses solely on the SC-HTHP installed at the IVAR biogas facility, where a 400 kW HTHP is integrated into the SUSHEAT system. The life cycle analysis conducted in this study followed a "from cradle to partial grave approach" and focuses on three main phases as system boundary: construction/manufacturing, distribution and use/operational phase (25 years of use), while the stage of end of life is excluded in this study (see Figure 2). In this study, as mentioned previously, the end-of-life phase was excluded due to a lack of reliable, system-specific data; however, it will be addressed in future work through a life cycle assessment of the complete SUSHEAT system. Additionally, data related to maintenance activities are included in the use/operational phase. Transport of materials from the supplier to the SC-HTHP assembly site was also accounted for in the construction/manufacturing phase. As a functional unit, a 400 kW SC-HTHP is used in this study. The next key factor in standardizing LCA setups is selecting the life cycle impact assessment (LCIA) method. This topic is discussed in the following sections. The chosen system model is considered cut-off. The term "cut-off" denotes the cut-off allocation system model used in the life cycle inventory (ecoinvent database) in Simapro software. The operational lifetime of the heat pump is 20 years, although the SUSHEAT system's life cycle analysis assumes 25 years. Anyway, in this study, a 25-year lifetime was considered for the SC-HTHP; all parameter values were scaled accordingly, and the results were evaluated. The following section (Life Cycle Inventory Analysis) provides further details on the required data for the LCA of the SC-HTHP. Due to limited data availability, control system components (e.g., probes and flow meters) were excluded from this LCA, consistent with previous studies [22]. Nonetheless, this analysis gap is addressed in the project and subsequently incorporated during a later phase.

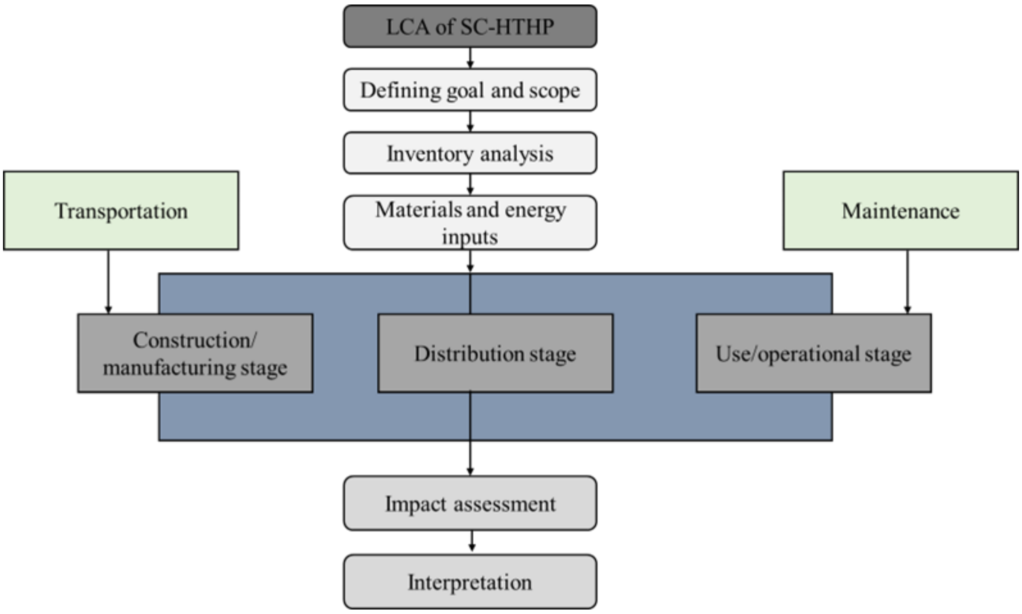

Figure 2. Schematic of the LCA method, including the system boundary.

2.2.2. Life Cycle Inventory (LCI) Analysis

LCI is the most resource-intensive stage of an LCA. It involves mapping the production process in detail, including all material and energy inputs, as well as waste and emission outputs. Various sources are available for compiling LCIs. This study relies on data sourced from the Ecoinvent database (version 3.5) and detailed data for the construction/manufacturing and transportation phase of the heat pump supplied by Enerin Company. The construction/manufacturing, distribution, and use/operational phases of the SC-HTHP unit under consideration were all covered by the calculations. The construction/manufacturing phase of the SC-HTHP system under evaluation supplies relevant information, such as production data, raw material extraction inputs, transportation and energy consumption. Table 1 displays the inventory list of all the materials utilized in the SC-HTHP system's production and distribution and operation. According to Enerin Company's transportation data, SC-HTHP materials and components are shipped via air, land, and sea. The weight of each component multiplied by the distance from suppliers to Enerin for the SC-HTHP manufacturing stage yields the total transportation impact. Furthermore, the system's transportation from Enerin Company to the installation location is covered by the distribution data. During the operational phase of the LCA study, the HTHP system consumes 1.6×10^6 kWh of electricity annually. With a Coefficient of performance (COP) of about 2, this corresponds to a heat output of 3.2×10^6 kWh. Additionally, 1.6×10^6 kWh of waste heat is utilized during operation.

Table 1. Inventory data used for the LCA of the Stirling Cycle-based HTHP unit.

Life cycle Phase	List of Raw Materials and Resource Inputs	Total amount (kg)
Manufacturing	Non-alloy steel	3403.520
	Stainless Steel	4135.833
	Low-alloy steel	111.502
	Cast iron	1041.58
	Aluminium	348.19
	Bronze	21.075
	Brass	0.069
	PTFE	17.21
	Graphite	1.26
	Elastomer	9.066
	Rubber	38.84
	Copper	973.5
	Epoxies	63
	Transport	117586 km
	Medium-voltage electricity	1328 kWh
	Helium	2 kg
	Lubricating oil	70 litres
Distribution	Transport	180 km
Operation	Lubricating oil	2 liters/year
	Water	2 m^3/year
	Helium	12 kg/year
	Land occupation industrial setup	30 m^2
	Electricity power input	1.6×10^6 kWh/year
	Waste heat	1.6×10^6 kWh/year

2.2.3. Impact assessment methodology

SimaPro software (Version 9.6.0.1) is used in this study to evaluate environmental impacts using data from the background Ecoinvent v3.5 database. The foreground data is sourced from Enerin. Among the various available impact assessment methods, this study specifically employs the ReCiPe 2016 Endpoint (H) method and the IPCC 2021 GWP20 (Global Warming Potential) approach. The ReCiPe indicator, a method used to assess environmental impact by applying three units: DALY (Disability-Adjusted Life Years), USD 2013, and species·yr (species loss per year), is based on an updated integration of the CML and Eco-Indicator 99 methodologies [23]. The Global Warming Potential (GWP) is an index that measures the relative impact of producing one kilogram of a greenhouse gas compared to producing one kilogram of CO_2. It is the foundation of the IPCC's method for assessing the effects of climate change [24].

3. Results and discussion

The following section evaluates and discusses the environmental impacts and emissions associated with the 400 kW Stirling-cycle–based heat pump throughout its life cycle.

3.1. Environmental impacts of SC-HTHP

The environmental impact results in this section are presented across three categories: human health, ecosystems and resources. Table 2 provides a comparison of the characterization and damage assessment at the midpoint level for these three endpoints, summarizing the life cycle impacts associated with the construction/manufacturing, distribution and use/operational phases of the SC-HTHP. The table reports LCA results across 22 impact categories and identifies which phases contribute most significantly to potential environmental consequences. The results clearly show that the operational phase had the highest impact in all 22 categories compared with the distribution and construction/manufacturing phases.

The obtained results in Table 2 demonstrate that the use/operational phase had a higher impact than the construction/manufacturing phase across all 22 impact categories, following the distribution phase. Based on the results obtained, the SC-HTHP system had the greatest environmental impact during the use/operational stage, primarily due to the scarcity of fossil resources (5.72×10^4 USD 2013), followed by the scarcity of mineral resources (2.89×10^3 USD 2013). These two categories also make a notable contribution during the construction/manufacturing phase, with the former being ranked at 2.40 × 10^3 USD 2013, and the latter at 7.15 × 10^2 USD 2013 (see Table 2).

Table 2. Environmental impacts and characterization for a 400 kW Stirling cycle high temperature heat pump.

Impact category	Construction/ manufacturing phase	Distribution phase	Use/operational phase, 25 years
Global warming, Human health (DALY)	4.62 × 10^{-2}	2.32 × 10^{-4}	1.75
Global warming, Terrestrial ecosystems (species.yr)	1.39 × 10^{-4}	7.01 × 10^{-7}	5.29 × 10^{-3}
Global warming, Freshwater ecosystems (species.yr)	3.81 × 10^{-9}	1.91 × 10^{-11}	1.45 × 10^{-7}
Stratospheric ozone depletion (DALY)	5.00 × 10^{-5}	5.82 × 10^{-8}	2.78 × 10^{-3}
Ionizing radiation (DALY)	1.61 × 10^{-5}	3.32 × 10^{-8}	2.29 × 10^{-3}
Ozone formation, Human health (DALY)	1.08 × 10^{-4}	4.36 × 10^{-7}	3.15 × 10^{-3}
Fine particulate matter formation (DALY)	8.37 × 10^{-2}	1.26 × 10^{-4}	1.74
Ozone formation, Terrestrial ecosystems (species.yr)	1.58 × 10^{-5}	7.01 × 10^{-8}	4.63 × 10^{-4}
Terrestrial acidification (species.yr)	4.07 × 10^{-5}	7.69 × 10^{-8}	1.59 × 10^{-3}
Freshwater eutrophication (species.yr)	1.85 × 10^{-5}	1.52 × 10^{-8}	4.19 × 10^{-4}
Marine eutrophication (species.yr)	2.56 × 10^{-9}	5.99 × 10^{-12}	6.99 × 10^{-8}
Terrestrial ecotoxicity (species.yr)	5.49 × 10^{-5}	8.46 × 10^{-8}	3.60 × 10^{-4}
Freshwater ecotoxicity (species.yr)	6.72 × 10^{-6}	4.41 × 10^{-9}	1.57 × 10^{-4}
Marine ecotoxicity (species.yr)	1.87 × 10^{-6}	1.51 × 10^{-9}	3.23 × 10^{-5}
Human carcinogenic toxicity (DALY)	6.71 × 10^{-1}	1.48 × 10^{-4}	2.15
Human non-carcinogenic toxicity (DALY)	2.74 × 10^{-2}	4.48 × 10^{-5}	5.91 × 10^{-1}
Land use (species.yr)	1.53 × 10^{-5}	1.69 × 10^{-7}	1.45 × 10^{-3}
Mineral resource scarcity (USD 2013)	7.15 × 10^{2}	1.46 × 10^{-1}	2.89 × 10^{3}
Fossil resource scarcity (USD 2013)	2.40 × 10^{3}	3.53 × 10^{1}	5.72 × 10^{4}
Water consumption, Human health (DALY)	5.54 × 10^{-4}	7.78 × 10^{-7}	1.20
Water consumption, Terrestrial ecosystem (species.yr)	3.38 × 10^{-6}	4.98 × 10^{-9}	8.00 × 10^{-4}
Water consumption, Aquatic ecosystems (species.yr)	3.65 × 10^{-10}	4.63 × 10^{-13}	5.58 × 10^{-9}

Table 3 shows the life cycle footprint of the SC-HTHP system during the construction/manufacturing, distribution and use/operational phases. This was evaluated using the ReCiPe 2016 Endpoint (H) environmental impact assessment method. The results show that the operational phase had the greatest average impact, at 7.44 DALY for human health, 0.0106 species per year for ecosystems and 6.01 × 10^4 USD 2013 for resources. Of the construction/manufacturing and distribution phases, the construction/manufacturing phase exhibits the highest average impacts across all three endpoint categories: 0.83 DALY for human health, 0.000297 species·year for ecosystems and 3.11 × 10^3 USD 2013 for resources. Moreover, as shown in Table 3, the distribution phase contributes relatively minor impacts, amounting to 5.52 × 10^{-4} DALY, 1.13 × 10^{-6} species·year, and 35.5 USD 2013 in the human health, ecosystems, and resources categories, respectively.

Table 3. Results of the impact assessment and characterization of the SC-HTHP.

Damage category	Unit	Construction/ manufacturing stage	Distribution stage	Use/operational stage
Human health	DALY	0.83	0.000552	7.44
Ecosystems	Species.yr	0.000297	1.13× 10^{-6}	0.0106
Resources	USD2013	3.11 × 10^3	35.5	6.01× 10^4

The ReCiPe 2016 Endpoint (H) environmental impact assessment method was used to analyze the impact on human health, ecosystems and resources across the three phases of the SC-HTHP: construction/manufacturing, distribution and use/operation. This is illustrated in Figures 3a, 3b and 3c. Impacts are expressed in kpt units (dimensionless), where 1 Pt represents one-thousandth of the annual environmental impact of the average European resident. The results indicate that the use (operational) phase has the highest total environmental impact (1.27 × 10^2 kPt, 90.1%), followed by the construction (manufacturing) phase (13.9 kPt, 9.86%). The distribution phase contributes negligibly (9.76 × 10^{-3} kPt, <0.01%). Among the three endpoint categories, human health exhibits the highest contribution in all phases, accounting for 1.24 × 10^2 kPt (90.0%) during the use phase, 13.8 kPt (10.0%) during construction, and 9.21 × 10^{-3} kPt (0.007%) during distribution (see Figure 3a). Ecosystems and resources represent the next most affected categories. In the use phase, impacts on ecosystems and resources amount to 2.85 kPt (97.3%) and 0.429 kPt (95.0%), respectively. The lowest impacts occur during the distribution phase, with 3.04×10^{-4} kPt for ecosystems and 2.53×10^{-4} kPt for resources, as shown in Figures 3b and 3c. Stamford et al. [26] assessed the life cycle impacts of a 1 kW Stirling engine micro-CHP system and found that, per unit of heat, it has an average 30% lower environmental footprint than a gas-fired boiler. The Tveit et al [27] study showed that the annual operational environmental impact of the HighLift HTHP is minimal and nearly insignificant compared to oil and natural gas boilers, making the HTHP the more environmentally favorable option.

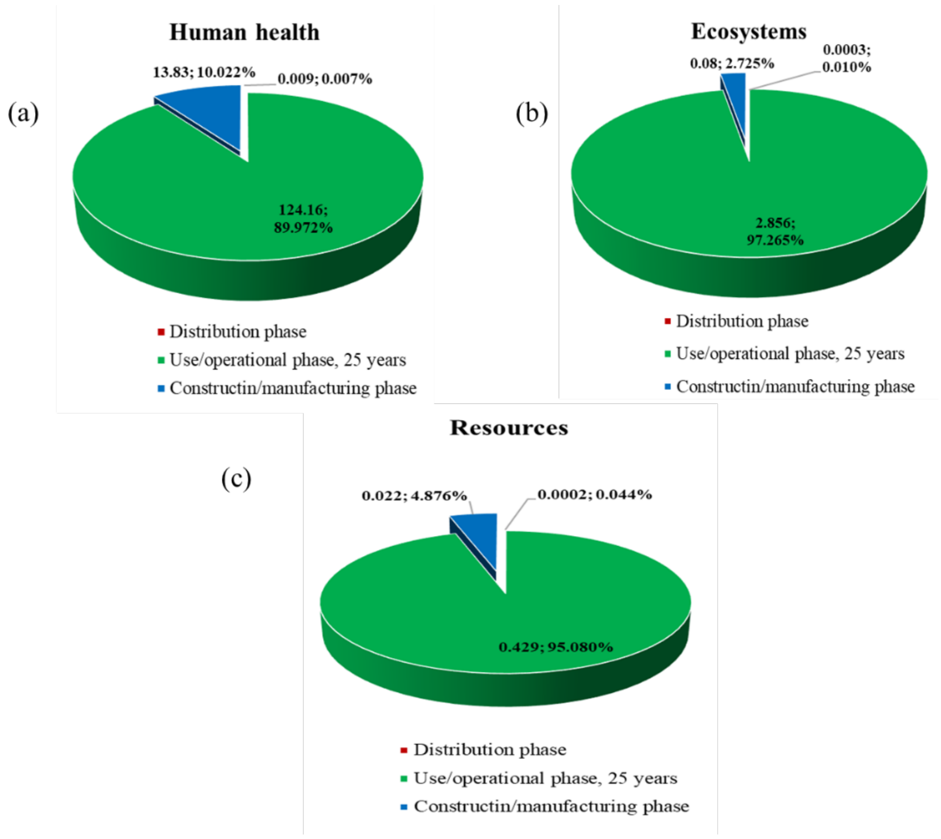

Figure 3. Contribution of the three main impact categories, (a) human health, (b) ecosystems, and (c) resources, across the construction/manufacturing, distribution, and use/operational phases, expressed as ReCiPe endpoint single score (kPt).

3.2. Emissions (kg CO_2-eq) associated with the SC-HTHP system

The IPCC 2021 GWP20 method was applied in SimaPro v9.6.0.1, using Ecoinvent v3.5, to estimate emissions (kg CO_2-eq) for the three life-cycle phases: construction/manufacturing, distribution, and use/operation. The results in Table 4 show that the operational phase has the greatest impact (2.42×10^6 kg CO_2-eq), which is considerably higher than the manufacturing phase (5.79×10^4 kg CO_2-eq) and the distribution phase (294 kg CO_2-eq) for the SC-HTHP system (see Table 4). Thus, the distribution phase contributes fewer emissions than the construction/manufacturing phase. The high environmental impact of SC-HTHP during operation is primarily due to electricity consumption, as reported by [25]. In addition to electricity consumption, waste heat utilization also significantly contributes to emissions and the overall environmental impact of this phase.

Table 4. Total emissions (kg CO_2-eq) calculated with IPCC 2021 GWP20.

Damage category	Unit	Use/operational stage	Construction/ manufacturing stage	Distribution stage
GWP20	Kg CO2-eq	2.42×10^6	5.79×10^4	294

In future work, the life cycle assessment should be extended to include plant dismantling at the end of its service life, with recyclable materials reintroduced into production cycles to enable a cradle-to-cradle LCA.

This approach would contribute to natural resource conservation and reduce environmental impacts across all heat production systems considered.

4. Conclusions

This study evaluates the environmental sustainability of a 400 kW Stirling cycle-based high-temperature heat pump through LCA. In this study, the ReCiPe 2016 Endpoint (H) and the IPCC 2021 GWP20 methods were applied to assess the environmental impacts and global warming of the considered SC-HTHP, respectively. The analysis shows that the use/operational phase had the greatest environmental impact of all the phases of a Stirling cycle-based heat pump's 25-year lifespan, compared with the construction and distribution phases. Comparison of global warming potential (kg CO_2-eq) for the three phases of the 400 kW Stirling cycle-based high-temperature heat pump shows the use/operational phase has the highest value (2.42× 106 kg CO2-eq). These findings highlight the potential of Stirling cycle-based heat pumps to reduce environmental impacts in industrial applications.

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Nomenclature

GHG	greenhouse gas	GWP	global warming potential
EU	European Union	LCI	life cycle inventory
HVAC	heating, ventilation, and air conditioning	DALY	disability-Adjusted Life Years
LCA	life cycle assessment	USD 2013	U.S. dollars standardized to the value of the year 2013
SC-HTHP	stirling cycle high-temperature heat pump	species·yr	species loss per year
GSHP	ground-source heat pump	kg CO_2-eq	kilograms of carbon dioxide equivalent.
HSHP	hydrogen-source heat pump	kpt	kilo-points
WSHP	water-source heat pump	PCM	phase change material
ASHP	air-source heat pump	TES	thermal energy storage
COP	coefficient of performance	CIT	control and integration twin
EoL	end-of-life	LCIA	life cycle impact assessment

References

[1] Trevisan S, Buchbjerg B, Höeg A, Guedez R. Techno-economic comparative assessment of high-temperature heat pump architectures for industrial pumped thermal energy storage. J *Eng Gas Turbines* Power 2025;**147**(6):061020.
[2] Marcos JD, Golpour I, Barbero R, Rovira A. Decarbonizing European industry: a novel technology to heat supply using waste and renewable energy. *Appl Sci* 2024;**14**(19):8994.
[3] Famiglietti J, Acconito L, Arpagaus C, Toppi T. Environmental life cycle assessment of industrial high-temperature to residential small-size heat pumps: a critical review. *Energy Convers Manag X* 2025;100947.
[4] Miralles JAL, García RL, Carnicero JMP, Martínez FJR. Comparative study of heat pump system and biomass boiler system to a tertiary building using the Life Cycle Assessment (LCA). *Renew Energy* 2020;**152**:1439–1450.
[5] European Parliament and the Council of the European Union. Directive (EU) 2023/2413… energy from renewable sources. Official Journal of the European Union; 2023.
[6] Alves-Filho O. *Heat pump dryers: Theory, design and industrial applications*. Boca Raton: CRC Press; 2015.
[7] European Union. Official Journal of the European Union. 2009; L 140.
[8] Lund JW, Tóth AN. Direct utilization of geothermal energy 2020 worldwide review. *Geothermics* 2021;**90**:101915.
[9] Marcos, JD., Golpour, I., Barbero, R., Butean, A., Höeg, A., Rovira, A., 2025." Environmental sustainability assessment of a Stirling cycle high-temperature heat pump (SC-HTHP): a preliminary LCA perspective". In: 38th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems; June 29–July 4; Paris, France.
[10] Diaz N, Ninomiya K, Noble J, Dornfeld D. Environmental impact characterization of milling and implications for potential energy savings in industry. Procedia CIRP 2012;**1**:518–523.

[11] Tveit TM, Khan U, Zevenhoven CA. Environmental impact of high temperature industrial heat pumps – from a global warming potential (GWP) perspective. In: Industrial Efficiency 2020: Decarbonise Industry! European Council for an Energy Efficient Economy; 2020. p. 4–001.
[12] Palacios-Lorenzo, ME., Golpour, I., Marcos, JD., 2023. "Influence of the energy mix on the life cycle assessment of a Stirling cycle-based heat pump". In: Proceedings of the 13th National and 4th International Conference in Engineering Thermodynamics (13CNIT); Castellón de la Plana (Spain); Nov 29–Dec 1.

[13] Aridi M, Pannier ML, Aridi R, Lemenand T. A comprehensive review of life cycle assessments for domestic heat pumps: environmental footprint and future directions. *Energy Build* 2025;**336**:115605.
[14] Koroneos C, Nanaki E. Environmental impact assessment of a ground source heat pump system in Greece. Geothermics 2017;**65**:1–9.
[15] Shamoushaki M, Koh SL. Net-zero life cycle supply chain assessment of heat pump technologies. Energy 2024;**309**:133124.
[16] Khan SA, Richard OH, Finn D, Kinnane O. Environmental footprint analysis of domestic air source heat pumps. Resour Conserv Recycl Adv 2024;**22**:200217.
[17] Fleuchaus P, Blum P. Damage event analysis of vertical ground source heat pump systems in Germany. Geotherm Energy 2017;**5**(1):10.
[18] ISO 14040:2006. Environmental management – Life cycle assessment: principles and framework. 2016.
[19] ISO 14044:2006. Environmental management – Life cycle assessment: requirements and guidelines. 2016.
[20] Høeg, A., Løver, K., Vartdal, G., 2024. "Performance of a high-temperature industrial heat pump using helium as refrigerant". In: High-Temperature Heat Pump Symposium; Copenhagen; January.
[21] Dzikuć M. Applying the life cycle assessment method to an analysis of the environmental impact of heat generation. Int J Appl Mech Eng 2013;**18**(4):1275–1281.
[22] Souliotis M, Arnaoutakis N, Panaras G, Kavga A, Papaefthimiou S. Experimental study and life cycle assessment (LCA) of hybrid photovoltaic/thermal (PV/T) solar systems for domestic applications. Renew Energy 2018;**126**:708–723.
[23] Llantoy N, Chàfer M, Cabeza LF. A comparative life cycle assessment (LCA) of different insulation materials for buildings in the continental Mediterranean climate. Energy Build 2020;**225**:110323.
[24] Hischier R, Weidema B, Althaus H-J, Bauer C, Doka G, Dones R. Implementation of life cycle impact assessment methods. Ecoinvent Report 3; 2010.
[25] Zsembinszki G, Llantoy N, Palomba V, Frazzica A, Dallapiccola M, Trentin F, Cabeza LF. Life cycle assessment (LCA) of an innovative compact hybrid electrical-thermal storage system for residential buildings in Mediterranean climate. Sustainability 2021;**13**(9):5322.
[26] Stamford L, Greening B, Azapagic A. Life cycle environmental and economic sustainability of stirling engine micro-CHP system. Energy technology 2018; **6**; 1119–1138 (open source).
[27] Tveit T.M, Khan U, Zevenhoven R. Environmental impact of high temperature industrial heat pumps– from a global warming potential (GWP) perspective. Industrial Efficiency 2020: Decarbonise industry!. European council for an energy efficient economy, 2020.