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DOI
10.1016/j.cesys.2022.100105

Publication date
2023

Document Version
Final published version

Published in
Cleaner Environmental Systems

Cleaner Environmental Systems 8 (2023) 100105

Contents lists available at ScienceDirect

Cleaner Environmental Systems

journal homepage: www.journals.elsevier.com/cleaner-environmental-systems

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ARTICLE INFO

Keywords:
Stirling-cycle-based heat pump (SC-HP)
Life cycle cost analysis (LCCA)
Levelized cost of energy (LCOE)
Net present value (NPV)

ABSTRACT

Heat pumps (HPs) which use low temperature (waste) heat and renewable energy sources to provide high temperature heat are widely regarded as a critical technology for reducing carbon dioxide emissions in the industrial sector. The HighLift technology considered here can provide high temperature output heat up to around 200 °C. This article focuses on the Life Cycle Cost Analysis (LCCA) method and its use for the economic evaluation of different industrial-scale heating methods i.e., a Stirling-cycle-based heat pump, a fossil fuel oil-fired boiler (OB), a bio oil-fired boiler (BOB), a natural gas-fired boiler (NGB) and a biogas-fired boiler (BGB). Many input parameters and boundary conditions apply to Sweden, where the considered heat pump is located. Findings from this study suggest that when comparing the life cycle costs of all these technologies Stirling-cycle-based heat pumps give more economic benefits than fossil fuel or biofuel-fired conventional boilers. For a typical 15-year lifespan, its total life cycle cost decreases in following order OB > BOB > NGB > BGB > SC-HP. The study indicates that replacing conventional boilers with a Stirling-cycle-based heat pump, despite an increased initial cost, would still be a cost-effective heating option due to lower operating and maintenance costs.

1. Introduction

The use of energy-efficient and cost-effective heating systems is essential for achieving global sustainability when using energy and other resources. In Europe (EU), after a brief rise from 2014 to 2017, oil consumption began to fall in 2019. There has been an increase in the use of renewable energy sources especially since 2018 (European Union International Energy Agency Report, 2020). The present climate change makes it urgent to identify and take into use ways to reduce carbon dioxide emissions. Heat pumps are an eco-friendly alternative to gas- or oil-fired boilers when it comes to CO_2 emissions. Heat pumps may in the near future replace many boilers, with one example being the UK government initiative to phase out fossil fuel-fired boilers by 2025 (British Gas UK, 2022). A heat pump operates by transferring heat from a lower temperature to a higher temperature. Use of waste heat from other operations as a low-temperature heat source together with electricity, which increasingly becomes available from a renewable source, offers an apparent alternative to using fuel combustion as a heat source (US Department of Energy, 2022), drastically reducing CO_2 emissions.

Heat pumps are widely used in Northern Europe, especially for private households with ground heat or ambient air as the low temperature heat resource, and often using solar electricity in a so-called assisted heat pump (Finnish heat pump association, 2022). Norwegian authorities have been successfully implementing a heat pump adoption program (Patronen et al., 2017).

As stated by the International Energy Agency (IEA), heat of a modest temperature (100 °C) is the most widely used in industrial settings (International Energy Agency Report, 2021). Industrial heating and cooling systems have developed over the last several decades and heat pumps may offer a heat output that is up to 5 times the input electricity (International Energy Agency Report, 2021). (This ratio defines the coefficient of performance, COP.) In contrast, when producing heat in a fuel-fired boiler, the temperature of the heat that is needed is often significantly lower than the temperatures of flames and flue gases of combustion systems, which gives a significant energy efficiency penalty (International Energy Agency Report, 2020). To properly evaluate the choice between a fuel-fired boiler and a heat pump, or when considering adding a heat pump (HP) to an existing boiler system, a detailed economic study is required taking into account life cycle cost (LCC).

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https://doi.org/10.1016/j.cesys.2022.100105
Received 14 October 2022; Received in revised form 9 December 2022; Accepted 27 December 2022
Available online 31 December 2022

1.1. Current market potential for heat pumps

Despite the recent COVID-19 outbreak, sales of heat pumps have continued to climb, demonstrating that the heat pump industry in Europe is seeing an ongoing strong market growth (European Heat Pump Association, 2021). Ten countries alone accounted for 87% of the overall volume of the European market. The market potential and deployment of heat pump systems strongly correlates with the relative cost of electricity compared to fuel, which in most cases implies natural gas. Sales of heat pumps in German reached 140,390 units in 2020, representing a 37.2% increase. Swedish sales: 107,723 units, a 4.4% increase over the previous year; Italian sales: 232,834 units, a 12.2% increase; French sales: 394,129 units, a 0.7% increase. Germany, Italy, Poland, the Netherlands, and Denmark were among the nations with the largest absolute gains regarding heat output capacity installed (Nowak, 2021). Thus, over the last 20 years, nearly 15 million heat pump units have been taken into use in Europe. This means that 128.7 GW of thermal capacity has been installed. In 2020, heating and cooling gave a reduction of 4.31 million tons of CO_2-equivalent emissions by using 14.24 GW installed heat pumps in Europe, corresponding to about 27.11 TWh useable heat (Nowak, 2021).

1.2. Life cycle cost analysis (LCCA)

LCCA is a technique for analyzing the economic performance throughout the course of the full life cycle of a process, product or service (or a part of that). While the more widely used environmental life cycle assessment (LCA) quantifies the environmental footprint and effect on human health via the use of resources and emissions to the environment (Pré Sustainability Enterprise, 2022), the LCCA method is based on initial costs, operating costs, and maintenance costs, as well as potentially varying life cycles (Stanford University, 2005).

The authors concluded before that Stirling-cycle-based heat pumps offer significant environmental advantages when compared with traditional boilers (Khan et al., 2021). In another study (to be presented at the 14th IEA Heat pump conference in 2023) several countries are compared from an environmental footprint LCA and system pay-back time point of view (Högnabba et al., 2023). The environmental impact of operating a very high temperature heat pump is highly dependent on the source of electricity used. The authors studied the impacts associated when technology was operated in Finland, France and Poland. Finland's electricity is a mix of nuclear, hydro, wind, and biomass power, which has a relatively low environmental impact, whereas Poland's electricity is primarily based on fossil fuels, which has a higher environmental impact. Sweden is one of the leading countries in decarbonization, with more than 90 percent of the country's electricity coming from renewable sources such as hydropower, nuclear, wind, and solar (Distribution of elecricity generation in Sweden, 2021).

When comparing future return flows to a project's initial investment costs, LCCA is a comprehensive economic analysis method since it is based on more information than assessments based on startup costs or short-term concerns only. It can quantify the relative economic benefits of – in the case of this paper – several energy efficiency options. It considers the timing of costs and benefits, as well as the time value of money, producing a single figure representing the total life cycle cost of the energy system project. LCCA is particularly effective for comparing technologies that meet the same performance criteria but vary in terms of initial costs and operating expenses, enabling the choice for one that optimizes net savings.

One recent study compared the life cycle environmental and economic consequences of a typical Stirling engine micro-CHP system for household energy supply with those of traditional sources of heat (a natural gas boiler) and electricity (grid electricity) (Stamford et al., 2018). The LCCA method used for that study was compatible with ISO14040/44. The study concluded that the Stirling engine (SE) unit was economically feasible at a high efficiency. Capital and operating expenditures were the key contributors to life cycle costs; consequently, a decrease in capital costs might substantially improve the economics of the SE system. Nonetheless, assuming a lower energy efficiency (77%), the system will be more costly than conventional solutions.

Another study gave a consumer cost-benefit analysis of integrating solar PV, SE CHP and battery storage (Pail et al., 2015). The analysis showed that the SE unit paired with solar photovoltaics will be an economically viable option when compared to a conventional system. In circumstances with greater-than-average heat demand, cost savings would be more likely. However, when the SE unit was paired with battery storage it would not be financially viable any longer, as a result of the higher capital and replacement costs of the battery cells. A performance study comparing the μ-CHP unit with a condensing gas boiler in (Gerry et al., 2016). The results demonstrated that a μ-CHP unit with payback time of 13.8 years may give yearly cost savings of €180 when compared to a condensing gas boiler.

Life cycle cost evaluation of Stirling cycle-based heat pumps is not well covered in the literature. Altogether, a Web of Science search reveals around forty publications addressing "heat pump" and "LCA", mostly dealing with temperatures too low to be relevant for this work. This drops to a number of two publications, by the authors of this work, when adding the search term "Stirling".

This study aims to offer insight into the comparative life cycle cost assessment of Stirling cycle-based heat pumps and conventional heating technologies.More specifically, it analyses the total life-cycle costs (LCCA) of Stirling-cycle-based heat pumps and compares the result for to that for alternative heating technologies. This information enables decision-makers to choose the most cost-efficient heating technology.

2. Method

Life cycle costing was employed as a research approach in this study. The assessments are based on ISO standardization ISO 14040 and 14044. Addressed will be the total life cycle cost analysis (LCCA) with and without carbon pricing, Net Present Value (NPV), payback period, fuel prices, and levelised cost of energy (LCOE), largely following Reddy and Kurian (2015).

The utility rate i.e., electricity, and natural gas, biogas, fossil or bio-based fuel oil and maintenance expenses of each technology were monitored for a use phase of up to fifteen years followed by decommissioning. The average Swedish electricity and fuel costs were utilized as the heat pump under investigation is situated in Sweden. Because the environmental impact strongly depends on the use and operation phase compared to the phases of construction and end-of-life handling, the LCCA employs a variety of temporal perspectives i.e., 1, 8 and 15 years, including the construction and end-of-life decommissioning after 15 years. The operational lifetime of the heat pump is expected to be around 15 years; the shorter periods of 8 and 1 year were considered as well in order to see the effect of OPEX versus CAPEX and the possible benefit of resale when using the heat pump less than 15 years.

2.1. Case study

Highlift (Stirling cycle-based heat pump) technology developed by Olvondo Technology (see the reference) in Norway forms the basis for this case study. A Stirling cycle-based heat pump converts low temperature heat into high temperature heat using electricity, operating with the Stirling cycle in reverse. Usually the cycle is operated as a power generating system. The Stirling cycle is a thermodynamic cycle that comes close to the reversible Carnot cycle: besides compression and expansion stages it features isothermal heat addition and rejection, using a so-called regenerator in which heat can be stored at constant volume. This technology allows for reaching higher heat output temperature than the maximum approx. 120 °C that can today be achieved using (cascaded) vapor-compression process cycles. (For the latter, Dai et al. (2022) very recently gave an LCC analysis.).

A heater, cooler and regenerator are all part of the Stirling-cycle-based heat pump under investigation (with several units in use at AstraZeneca in Gothenburg, Sweden) as shown in Fig. 1 (Khan et al., 2021). Internal heat exchangers combine a heating component, a regeneration component, and a cooling component into a single unit.

Using waste heat and electrical energy, the heat pump as shown in Fig. 2 generates steam with a 450–500 kW output at 10 bar. This can realistically yield a COPh (coefficient of performance for heating) value of approximately 2 (Tveit et al., 2020). Today's performance of the heat pump corresponds to a lower COPh, but current development shall increase the heat pump efficiency from 45 to 50% towards 53–56%, or a COPh closer to 2. For the calculations given here, a COPh of 2 is assumed. (LCA results are linear with operation cost: a 10% higher COP implies a 10% smaller electricity input per unit output heat, scaling the LCA accordingly.)

2.2. System boundary and functional unit

Establishing the system boundaries is a pre-requisite for doing a system assessment. Fig. 3 depicts the boundary of the Stirling-cycle-based heat pump system considered here. The system may leak a few liters of He gas each day during operation, compensated for by a make-up feed for it.

The system boundaries include the manufacturing/production and operating phases over a period of one year, eight years (the unit's anticipated half-life), or fifteen years (the full life span of the heat pump), when quantifying the total costs associated with technologies. Both the first year and eighth year of operation were analyzed as well in order to determine the unit's (estimated) half-life duration and the consequences of each year of operation.

A similar system boundary was used for a boiler firing either natural gas, biogas, or fossil fuel oil or bio-oil as shown in Fig. 4. Raw material extraction/acquisition as well as distribution/transport is included in the system boundaries of a boiler, similar to the SC-HP.

For all heating systems, the heat output (needed at ~ 200 °C) was 500 kW, which is the functional unit for this study.

Table 1 gives a listing of inventory data that was utilized in the creation of life cycle inventory (LCI) network diagram for the construction of a Stirling-cycle-based heat pump and boiler unit.

For a desired output of 500 kW, Table 2 lists the necessary input of electricity or fuel apart from, for the SC-HP, consumable helium and low temperature (waste) heat. For the boilers, 90% fuel to useful heat efficiency is assumed.

2.3. Life cycle cost (LCC)

The life cycle costs of a project are estimated by adding all the costs that occur throughout the project's lifespan. The following equation demonstrates how to compute the total life-cycle cost.

$$LCC = C_I + C_{OMR} - C_{res} \quad (1)$$

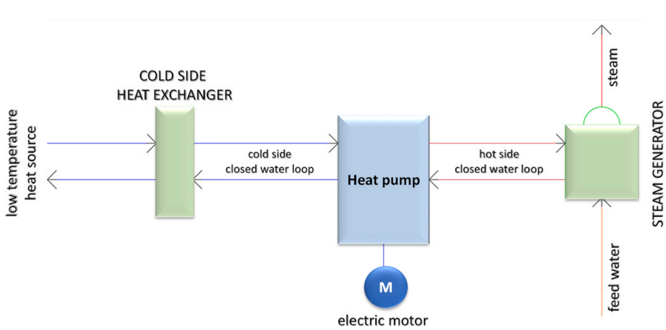

Fig. 1. Simplified flowsheet of the heat pump installation (Khan et al., 2021).

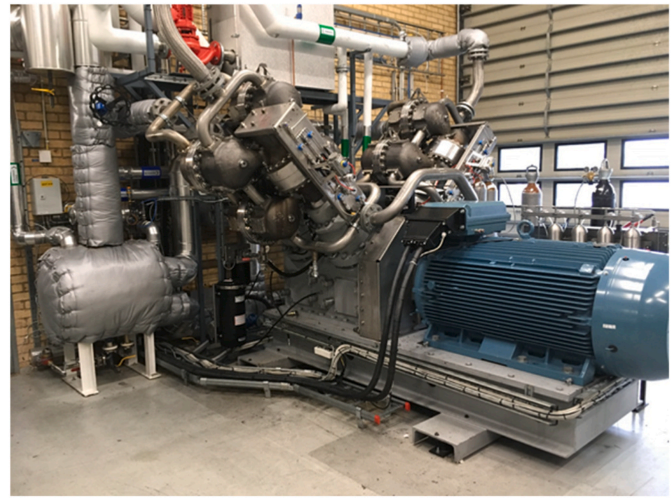

Fig. 2. The Stirling-cycle-based heat pump technology (SC-HP) installed at AstraZeneca, Sweden (Khan et al., 2021).

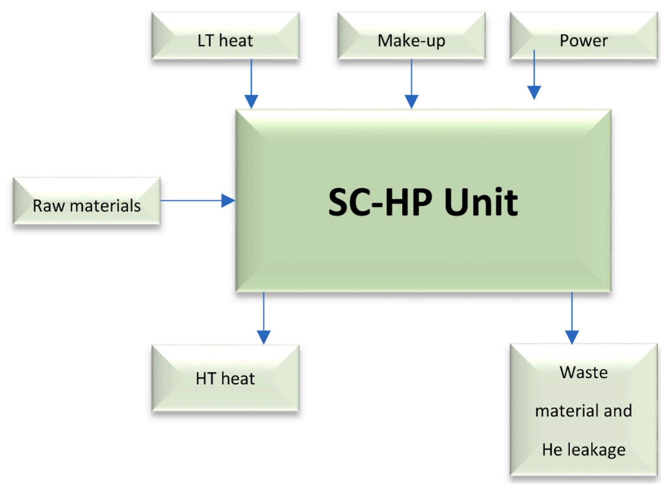

Fig. 3. System boundary for the LCCA of a Stirling-cycle-based heat pump (SC-HP).

where C_I = investment costs, C_{OMR} = operation, maintenance and repair costs and C_{res} = resale costs, respectively.

Resale costs are the residual value of the system based on its present value. For example, the residual value of a 15-year-use scheduled system after operating 8 years would be the original investment costs multiplied by the ratio of the remaining years from the life span, i.e. 7 years in this case, and the total life span years, i.e. 15 years in this case. Table 3 displays the various costs that were determined for each heating technology. The extra project management costs including expediting, stakeholder communication and management, approval-related costs, equipment installation costs, pipe costs, etc., are also included in operation, maintenance, and repair costs.

2.4. Levelised cost of energy (LCOE)

The levelised cost of energy (LCOE) is used to assess various heating technologies in terms of their total costs and the amount of heat they produce during their lifespan. The LCOE is calculated as (Reddy and Kurian, 2015):

$$LCOE = \frac{LCC}{LEP} \quad (2)$$

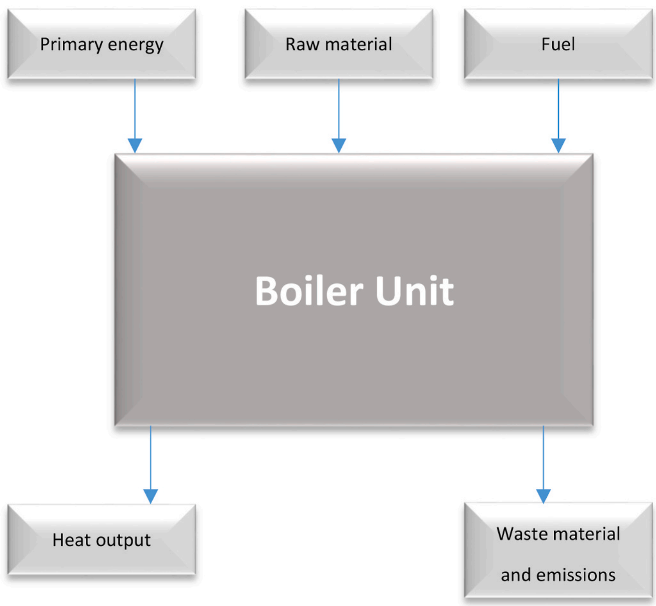

Fig. 4. System boundary for the LCCA of a boiler powered by either natural gas, biogas, or fossil fuel oil or bio-oil.

Table 1
Life Cycle Inventory (LCI) for boiler and Stirling-cycle-based heat pump construction.

Boiler unit			SC-HP unit		
Light fuel oil	5100	MJ	Water	12	m^3
Tap water	12	m^3	Stainless steel	7697	kg
Alkyd paint	12.5	kg	Cast iron	1500	kg
Aluminum	75	kg	Copper	700	kg
Brass	0.25	kg	Lead	0.1	kg
Brazing solder	30	kg	Chrome	1	kg
Copper	125	kg	Tungsten	1	kg
HDPE	7	kg	Plastic 1 PTFE	2	kg
Rockwool	95	kg	Silica aerogel	100	kg
Corrugated board	50	kg			
Steel	2425	kg			
Transport	100	km	Transport	100	km
Electricity medium voltage	1660	kWh	Electricity medium voltage	1660	kWh
Electricity low voltage	74.5	MJ	Electricity low voltage	74.5	MJ
Occupation, industrial area	50	m^2	Occupation, industrial area	10	m^2
Natural gas burned in industrial furnace	9600	MJ			

where levelised estimated output (LEP) is the amount of heat (GJ or MWh, for example) produced during the lifespan of the technology.

2.5. Net present value (NPV)

Net Present Value (NPV) is used to estimate the profitability of an investment. It is a method for determining the present value of future cash flows. The equation below was used to calculate the net present value of a project (Reddy and Kurian, 2015):

$$NPV = \sum_{n}^{N} \frac{Cash\ flow\ at\ year\ n}{(1 + rate\ of\ return)^n} \tag{3}$$

where

$n = Time\ period$

$N = Total\ number\ of\ years$

A depreciation rate of 8% per annum, varying from 6 to 10%, is assumed for the calculations given below.

2.6. Payback time

Payback time corresponds to the number of years after which an investment will start having positive cash flow, quantifying the number of years needed to recoup the initial investment. For various technologies, it is calculated using the following equation (Reddy and Kurian, 2015):

$$PB = \frac{Initial\ investment}{Cash\ inflows} \tag{4}$$

3. Results and discussion

This section discusses the results of the analyses, i.e. the total life cycle cost analysis (LCCA) with and without carbon pricing, Net Present Value (NPV), payback period, fuel prices, and levelised cost of energy (LCOE). This allows the source of high-cost contributions to be identified. Furthermore, comparing alternatives can help to establish which options are the best.

3.1. Life cycle cost analysis (LCCA)

Installation and energy costs are the key drivers of a strictly economic decision for a heating system from a life cycle cost standpoint. This part of the results will present the LCCA for each heating technology. The operational costs were calculated by multiplying the amount of electricity or fuel used per year with the corresponding electricity or fuel price for each respective year. The cash flows were then summed up for

Table 2
Energy and helium input for SC-HP or fuel boilers.

	SC-HP	Fossil fuel oil	Natural gas	Bio-oil	Biogas
Input consumable	Electricity 250 kW + waste heat 250 kW + Helium (600 kg/year)	500 kW 45 MJ/kg	500 kW 46 MJ/kg	500 kW 45 MJ/kg	500 kW 50 MJ/kg

Table 3
Various costs for each type of heating technology (15 years of operation).

	SC-HP	Oil boiler	Natural gas boiler	Bio-oil boiler	Biogas boiler
C_I (M€)	4	3.5	3.5	3.5	3.5
C_{OMR} (M€)	27.39	35.44	29.32	27.99	32.58
C_{res} (M€)	0	0	0	0	0

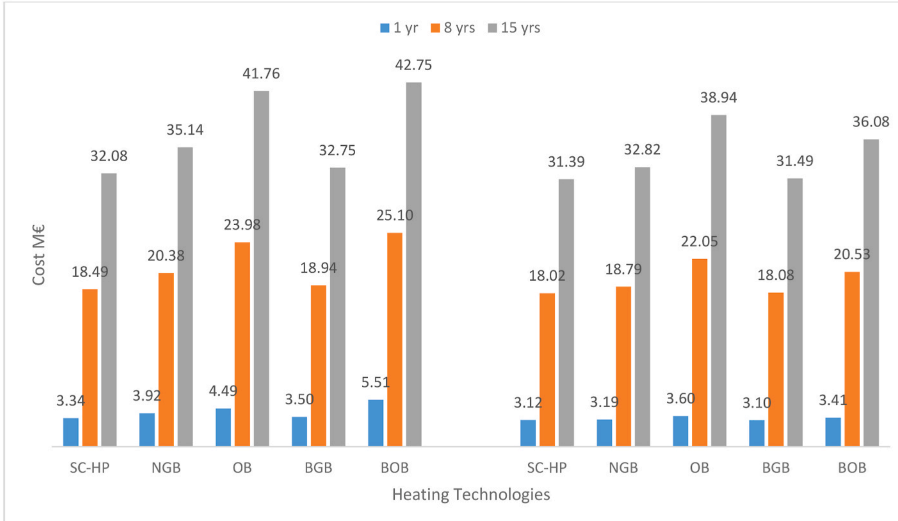

Fig. 5. Life cycle costs of the various heating technologies over an operation period of 1, 8 and 15 years with ETS carbon costs (left) and without ETS carbon costs (right).

each technology. Overall life cycle cost for 15 years, as shown in Fig. 5 (right-hand side), will be higher for the boilers (be it only slightly for a biogas boiler). Reasons behind this are for example: more components, higher complexity, higher installation costs and fuel costs.

When comparing the manufacturing/construction cost of a Stirling-cycle-based heat pump and a fuel-fired boiler, it becomes evident that the heat pump is more expensive. The reason for this is that heat pumps are more complex mechanical units, made of a larger amount of construction materials (in this case stainless steel, copper and cast iron) and they often demand a larger footprint surface.

When the operational costs of all the technologies are compared, the cheapest to operate is a Stirling-cycle-based heat pump (31.4 M€), while the most expensive is a fossil fuel oil-based boiler (38.9 M€) when excluding CO_2 emissions pricing. The costs of operating a heat pump are then 44% lower than those of a fossil fuel oil-based boiler for Swedish energy price assumptions. The reason of the high operational costs for fossil fuel oil-based boiler (OB) is the high fuel oil cost (1.258 € per liter). Another factor for the Stirling-cycle-based heat pumps' lower operating costs is its high efficiency resulting from the (reversed) Stirling process cycle. While the Stirling-cycle-based heat pump in the analysis has a COP of around 2, producing 2 kW of heat for every kW of electricity required, the boilers, in this case 90% efficient, give 0.9 kW of useful heat per kW of fuel input energy.

Moreover, the Stirling-cycle-based heat pump utilizes waste heat as a significant part of the energy input, which reduces the operation costs for the heat pump compared to the other technologies. The longer the heat pump stays in operation after the estimated lifetime and the higher future fuel prices are, the higher the savings will be. The comparison of the costs of construction and operation is given in Table 4. The operating costs account for 72% of a Stirling-cycle-based heat pump's entire life cycle cost, while the construction costs account for 28%, for construction and fifteen years of 500 kW heat output operation.

Table 4
Relative costs of construction and fifteen years operation for the heating technologies studied.

	Construction costs %	Operating costs %
Stirling-cycle-based heat pump	28	72
Natural gas-fired boiler	5	95
Biogas-fired boiler	9	91
Fossil fuel oil-fired boiler	2	98
Bio-oil-fired boiler	3	97

Thus, the overall life cycle cost of all technologies, i.e. for 15 years life span, increases in the following ascending order SC-HP < BGB < NGB < BOB < OB as shown in Fig. 5. Although the Stirling-cycle-based heat pump has the highest construction costs of any technology, the reduced operating costs decrease the entire life cycle cost of the system.

Earlier work by the authors gives a detailed picture of the environmental life cycle assessment of a Stirling-cycle-based heat pump (Khan et al., 2020). When calculating the economic feasibility of any heating system, CO_2 emissions are a major environmental cost and must be taken into account. Because of the combustion process, boilers that use traditional fuel (oil and natural gas) unavoidably emit more (fossil) CO_2 during operation. When considering the transport of biogas from production site to the operational unit, carbon dioxide emissions are higher for a biogas-based boiler compared to the other fuels. Land occupancy to grow the required wood must be addressed for bio-oil based boilers. Stirling-cycle-based heat pumps use comparatively clean energy.

The price of EU Carbon Permits has risen by 0.53 percentage point since the beginning of 2022, according to trading on a contract for difference (CFD). The price projection for EU carbon permits in tons from 2020 to 2035 is shown in Fig. 6. Carbon costs are expected to rise in a linear fashion across Europe. As a result, the use of carbon-friendly technology will be cost effective.

All heating technologies' total life cycle costs calculations were repeated with also the European carbon price taken into account as shown in Fig. 5 as well (left-hand side). Average carbon pricing for the

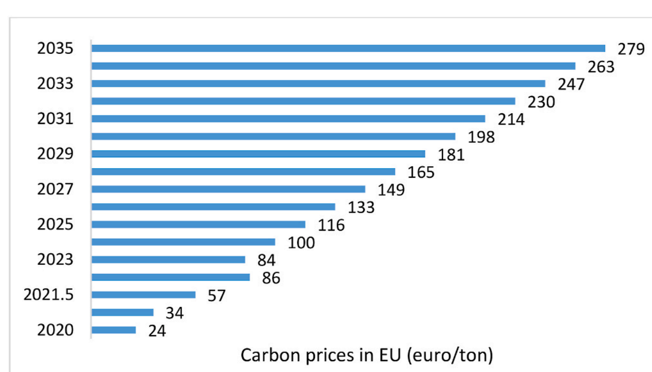

Fig. 6. Carbon dioxide emission prices (ETS) in EU until today and forecasted until 2035 (Carbon dioxide emission allowance Sandbag, 2022).

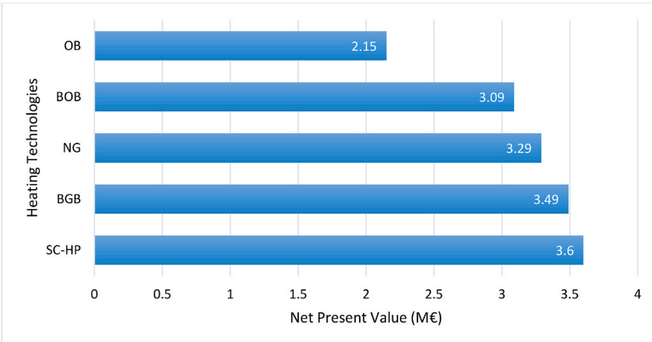

Fig. 7. Net Present Value (M€) of various technologies over operation period of 15 years.

years until 2021, until 2028 and until 2035 was taken to be 55, 120 and 175 euro per ton in Europe, respectively. Since oil boilers create the largest amount of carbon dioxide during combustion, their total life-cycle costs will be higher. When carbon pricing is accounted for, the total life cycle costs of all heating methods have grown by a factor of one-fourth.

3.2. Net present value (NPV) and payback period

The NPV is the potential value of technology at present. Having a positive net present value means here that a project promises a rate of return that is higher than 8% (= the depreciation rate used here as mentioned in section 2.5). All the technologies considered give a positive NPV suggesting that investment on either technology will give a profit. When comparing all technologies it can be seen that the Stirling-cycle-based heat pump resulted in a higher NPV, suggesting that the investment on this technology will have a higher yield – see Fig. 7.

To investigate the effect of the discount rate on the NPV of the considered technologies, a sensitivity analysis was made with discount rates of 6%, 8% and 10%. The NPV is inversely related to discount rate, which means that with a lower discount rate (6%), all technologies offer a larger NPV. This is understandable because the discount rate decreases the future cash flow by a factor to present value, and thus a lower discount rate means a smaller drop in future cashflow, resulting in a higher NPV. The trend for increasing NPV remains the same order i.e. SC-HP > BGB > NGB > BOB > OB regardless of discount rate.

The Stirling-cycle-based heat pump would have a four-year payback period. The payback period for traditional boilers would be 5 years. The payback period is determined by a variety of factors including construction and installation expenses as well as operating and maintenance costs. Even though Stirling-cycle-based heat pumps have greater construction and installation costs, the payback period for this technology is shorter when considering annual operating expenses.

3.3. Fuel prices and levelised cost of energy (LCOE)

The LCOE for a Stirling-cycle-based heat pump depends on a number of factors such as operational materials consumed, which in this case is helium gas because of a small leakage, besides the size of the heat pump and maintenance costs. The maintenance costs are assumed to be the same for a boiler and a SC heat pump. On comparing the LCOE costs of all the heating technologies, the Stirling-cycle-based heat pump has the lowest LCOE costs while the fossil fuel oil boiler gives the highest. A low LCOE indicates that in order to produce a certain amount of output heat, the technology would cost less. The main factor affecting the LCOE is clearly what type of fuel (versus electricity and waste heat input) is used.

The worldwide helium market is expected to increase at a moderate rate over the forecast period. The reason for this is that some COVID vaccines that have been approved or are awaiting approval require

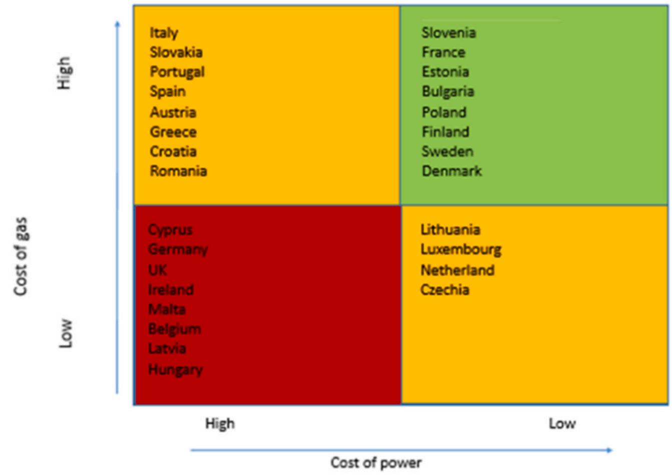

Fig. 8. Country rankings for Europe based on natural gas and electricity costs (Johansson et al., 2021).

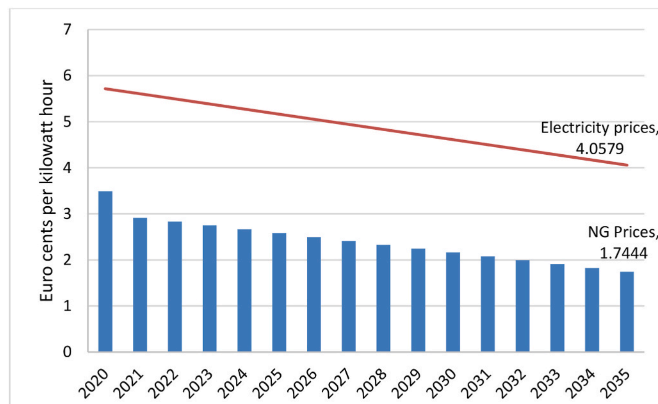

Fig. 9. Industry electricity and NG prices in Sweden in 2020 and forecasted until 2035 (Prices of electricity for industry, 2021; Prices of natural gas for industry, 2020).

shipping and storage at extremely low temperatures, and here helium is used as the working medium. In 2022, helium gas prices are predicted to average 21.77 €/liter STP and then will drop by 8% in 2024 (Digital Coin Price Report, 2022).

As a Stirling cycle-based heat pump utilizes both waste heat and electrical energy, it is a useful starting point to take into consideration the price difference between gas and electricity. In an interim report for

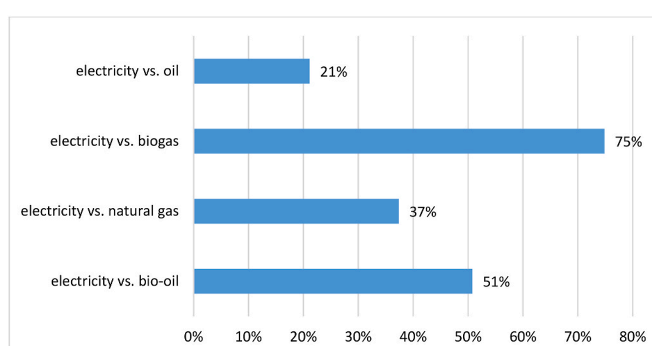

Fig. 10. Saving on energy costs when switching from a fuel to electricity, i.e. percentage decrease in energy costs (Prices of electricity for industry, 2021; Prices of natural gas for industry, 2020; Commodity Prices, 2021; Bioenergy news, 2022).

the EU H2020 HighLift project, an investigation of the market for the HighLift heat pump was given (Johansson et al., 2021). The study assessed which EU nations had the largest price gap between the two types of input energy. Fig. 8 ranks countries by their average annual cost of electricity and natural gas. From among the countries that were studied, the price ratios in Finland, Sweden, Denmark, Poland, France, the Czech Republic, Bulgaria and Estonia are the most attractive for SC-HP implementation.

Fig. 9 shows the projected costs of natural gas and electricity in Europe (end of summer 2022). This data does not account for recent natural gas and electricity price changes in Europe due to the ongoing Russia-Ukraine conflict. Altogether, projections like this are very hard to give in today's world.

The current conflict has resulted in an unprecedented rise in electricity prices, particularly in Europe. The current Russia-Ukraine crisis might result either in a reduction of supply of gas or in a total shutdown from Russia, most likely resulting in a surge in gas in the future. Dutch TTF (Title transfer facility, a virtual trading point of natural gas in the Netherlands) estimated that by January 2023 gas delivery would be quadrupled from 72 €/MWh to 150 €/MWh in the Netherlands because of the conflict.

The electricity price is compared with different fuel prices for the year 2022 and the result is shown in terms of a percentage difference when switching from a boiler to an SC heat pump in Fig. 10.

According to Fig. 10, switching from oil fuel, for example, to electricity will result in a cost decrease of around 21.2%. A comparison for 8 or 15 years has not been conducted due to the limited availability of biofuel pricing and the continuously and dramatically changing fuel and electricity costs.

4. Conclusions

This study aims to offer insight into the economic sustainability of Stirling-cycle-based heat pumps and how this could be an economically viable heating solution compared to traditional heating technologies for producing heat at 150–200 °C in industrial-scale applications. The LCCA study can assist determining whether replacing a conventional boiler with a Stirling-cycle-based heat pump is economically advantageous. To determine the most cost-effective technology, the entire life cycle costs footprint, including construction, raw material procurement, raw material transportation/fuel and unit operation costs is considered. It is necessary to look at the results from a long-term economic viewpoint when considering sustainability. Results show that the Stirling-cycle-based heat pump gives a comparatively lower operational cost and a higher Net Present Value (NPV). The overall life cycle cost of all technologies escalates in the following order SC-HP < BGB < NGB < BOB < OB. LCOE of the heating system is the lowest for the Stirling-cycle-based heat pump. Construction costs for a Stirling-cycle-based heat pump are higher than those for a fuel-fired boiler. At 31.4 M€, a Stirling-cycle-based heat pump had the lowest life cycle costs for 15 years of use, with oil-based boilers costing 38.9 M€, excluding CO_2 emissions pricing. Assuming energy costs in Sweden, a heat pump will save 44% annually compared to an oil-fired boiler. Total life cycle cost including carbon pricing was also calculated for each technology, and it was found that when carbon pricing was factored in, the total life cycle cost of the conventional boiler increased by one-fourth. When CO_2 pricing is included the values increase to 32.1 M€ for the SC-HP and the highest value becomes 42.8 M€, for the bio-oil boiler. Thus, it can be concluded that when conventional boilers are replaced with a Stirling-cycle-based heat pump, the initial cost may rise, but operating and maintenance expenses are drastically lowered, making it a cost-effective alternative for heating purposes.

Funding

The work described in this paper is partly financed by the European Commission under the Horizon 2020 Fast Track to Innovation programme, grant agreement number 831062 (2019–2022).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgments

The authors thank the project co-workers at Olvondo Technology, Norway and AstraZeneca, Sweden for input data and other support. Kim Högnabba at ÅAU is acknowledged for commenting and checking.

Nomenclature

BGB	Biogas-fired boiler
BOB	Bio oil-fired boiler
CO_2	Carbon dioxide
CHP	Combined heat and power
CI	Investment costs
COP	Coefficient of performance
C_{OMR}	Operation, maintenance, and repair costs
C_{res}	Resale costs
ETS	Emission trading system
He	Helium
HT	High temperature
LCA	Life cycle assessment
LCCA	Life cycle cost assessment
LCOE	Levelised cost of energy
LEP	Levelised estimated output
NGB	Natural gas-fired boiler
NPV	Net present value
OB	Fossil fuel oil-fired boiler
OMR	Operation, maintenance and repair
PB	Payback time
SC-HP	Stirling-cycle-based heat pump
SE	Stirling engine
μ-CHP	Micro combined heat and power system

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