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Prediction of Stirling-cycle-based heat pump performance and environmental footprint using exergy analysis and LCA

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Abstract:

Compared to other heat pump systems, the Stirling-cycle-based heat pump has several benefits. The use of Stirling-cycle-based heat pumps in high temperature applications, *e.g.,* above 120°C, and waste heat recovery at an industrial scale is of increasing interest due to the promising role in producing thermal energy with zero CO_2 emissions. This paper analyzes one such technology as developed by Olvondo Technology and installed at the pharmaceutical company AstraZeneca in Sweden. In this application, the heat pump uses roughly equal amounts of low temperature heat and electricity and generates 500 kW of steam at 10 bar. A scale-up to 750 kW with improved energy efficiency is ongoing. To develop and widen the use of a high-performance high temperature heat pump that is both economically and environmentally viable and attractive, various analysis tools such as exergy analysis and life cycle assessment (LCA) can be combined. The benefit of exergy analysis is that it not only quantifies losses of work potential but also identifies the source and location of these losses. To evaluate the performance of the Stirling-cycle-based heat pump the Total Cumulative Exergy Loss (TCExL) method is used. The TCExL method determines total exergy losses caused throughout the life cycle of the heat pump. Moreover, an LCA study using SimaPro is conducted, which provides insight into the different emissions and overall environmental footprint resulting from the construction, operation (for example, 1, 8, 15 years), and decommissioning phases of the heat pump. The combined results are compared with the results of a fossil fuel oil boiler (OB), bio-oil boiler (BOB), natural gas-fired boiler (NGB) and biogas boiler (BGB). The findings indicate that a Stirling-cycle-based heat pump is a sustainable alternative to fossil fuel-fired boilers.

Keywords:
Stirling-cycle-based heat pump, exergy analysis, total cumulative exergy loss (TCExL), life cycle assessment (LCA), sustainability

1. Introduction

The need for sustainable energy solutions has never been more critical than today. Our current energy infrastructure and use patterns are unsustainable. The change in the climate we face today is most likely largely because of emissions of greenhouse gases. Fossil fuel combustion in the energy industry is responsible for about two-thirds of global emissions of greenhouse gas (GHG), primarily CO_2 emissions. The use of fossil fuels (which is still increasing) has an impact not only on the environment but also on human wellbeing. Changes should be introduced in the energy market to solve the climate crisis. To do so, it is essential to move towards sustainable technologies that supply energy carriers where and when needed causing minimal environmental damage. There has been a transition for decades, but this also needs to go even further, and faster too.

Heating today accounts for almost half the total consumption of heat, power and fuels by Europeans [1]. Oil, gas, and coal-fired boilers play a large role in industrial energy use and are the primary components of power generation and industrial plants. An estimated 5.6% of compound annual growth rate (CAGR) in the global Oil & Gas industry by United States, Canada, Japan, China, and Europe [2]. EEA reported that the United States boiler population consists of around 43,000 units with a gross input capability of 439 GW. Boiler capacity is concentrated in five sectors (i.e., plastics, paper, food, processing, metals), comprising 82 % of overall boiler capacity. In the cluster of regional markets, China will remain among the fastest growing. Asia-Pacific demand is expected to exceed 132.8 thousand tons of steam per hour (TSPH) by 2027 [2]. The global demand for industrial boilers, estimated at 859.8 TSPH in 2020, is expected to reach a revised size of 1.2 million TSPH by 2027 in the sense of the COVID-19 crisis, rising with a CAGR of 4.7% over the 2020-2027 analysis period [2].

A heat pump adds mechanical energy to a system that transfers heat from lower temperatures to higher temperatures [3]. The mechanism can in theory be described by an inverse Carnot cycle or refrigeration cycle although most heat pumps operate using a vapor-compression process that is in fact a reversed Rankine cycle.

Thomas Nowak, secretary-general of the European Heat Pump Association, emphasized the importance of heat pumps by saying, "Heat pump technologies are ready to decarbonize residential and commercial buildings as well as industrial processes. They complement the advantages of district heating and help stabilize the grid – all with European-based technologies" [3].

Despite the covid-19 pandemic, Finnish heat pump sales continued to rise. Heat pumps generate approximately one TWh of renewable, non-combustive heating and refrigeration energy per year. In 2020, 102,000 heat pumps were sold, an increase of 4% compared to the year before, bringing the total amount of heat pumps installed well over one million according to estimates from the Finnish Heat Pump Association [4].

1.1. Current market developments of Stirling-cycle-based heat pumps

The second-highest market for process heating is the industry sector in Europe. The industrial process heating demand is high in countries like Sweden, Finland, United Kingdom, Estonia, France and Germany [5]. The data reports that 27% of process heat demand in European countries is for temperature range 100-200°C [5]. The majority of process heating demand is for higher temperatures.

This Stirling-cycle-based heat pump technology (SC HP) [6,7] can help minimize energy consumption and increase the renewable energy use needed for the achievement of global climate objectives.

Assessment of the European market for high temperature heat pumps reveals a large market potential in the EU28+3 of more than 57,000 of these technology units, based on the likely assumption that 65% of the industries that have a demand for process heat also have sufficiently amounts of excess waste heat. This technology can potentially transform the existing potential of 175 TWh excess waste heat into industrial process heat to cover an estimated 47 TWh demand in the 100-200ºC output temperature range [5].

1.2. Life cycle assessment (LCA)

The concept of sustainability has developed over the past couple of years through various global deliberations. The principle of sustainability stresses on merging the social, economic, and environmental interests. LCA contains a tremendous promise of enhancing environmental sustainability and advancing new technologies, and it has historically been used for the measurement and retrospective appraisal of commercially advanced technology. The application of LCA to new technology at research and development levels poses many methodological problems.

For the study reported here, the LCA approach was employed using the SimaPro 8.3.3 commercial program. SimaPro is a software that records, analyzes, and monitors the sustainable performance of many goods or processes [8]. For each phase during the manufacturing, operation and decommissioning, inventory data sets were collected and combined with data from the ecoinvent (v. 3.5) database [9]. The exergy analysis and environmental impacts were calculated for each phase.

1.3. Exergy analysis

Exergy is the potential upper limit of the work rate that an energy source system can have if the inputs are brought into equilibrium with their reference environment. Or in short: the capacity of the energy to do work. For planning, refining, upgrading, and controlling energy conversion processes, exergy analysis is useful. An exergy analysis can determine positions and calculate the sums of the system's thermodynamic losses. The degradation of exergy is strictly proportional to entropy production via the simple linear relation: exergy consumption (J or W) = temperature of the surroundings (K) × entropy production (J/K or W/K) [10].

The Total Cumulative Exergy Loss (TCExL) method is developed [11] for the assessment of technological systems. It includes all exergy losses incurred during the system's life cycle. The advantage of the TCExL method is that it is based on exergy losses which are thermo-dynamically very well defined. TCExL is calculated by combining the loss of internal exergy, exergy losses due to abatement and due to land use as given in the following equation [11]:

$$TCExL = Ex_{loss,internal} + Ex_{loss,abatement} + Ex_{loss,land} \quad (1)$$

The internal exergy loss of a process or system is calculated as given in the following equations [11]. Ex_{input} equals the Cumulative Exergy Demand (CExD) as is calculated by the SimaPro software and is readily obtained from the results.

$$Ex_{loss,internal} = Ex_{input} - Ex_{product} - Ex_{emissions\&wasteflow} \quad (2)$$

Abatement exergy loss is loss of exergy due to processes that reduce waste and emissions from the technical system. For this research work, only the abatement exergy values of carbon dioxide, sulfur dioxide, nitrogen oxides, and phosphates have been considered [11].

$$Ex_{loss,abatement} = \sum(emissions * Ex_{loss}) \quad (3)$$

An exergy loss can also be allocated to the use of land. Exergy loss of 215 GJ per hectare per year has been calculated with NPP values [11,12].

$$Ex_{loss,land} = land\ use * 215\ GJ/\ (ha * yr) \quad (4)$$

1.4. Environmental impact assessment

UNEP describes environmental impact assessment (EIA) as a method to recognize the environmental impacts of a project [13]. It is targeted at predicting early environmental effects in the preparation and construction of projects. Both environmental and economic gains, such as decreased cost, project time and design expenses, avoided treatment/clean-up costs, and consequences of laws and regulations, can be evaluated using EIA [13]. Environmental impact assessment is part of a life cycle assessment.

For this study, the environmental impacts were calculated using the SimaPro software. The Eco-Indicator 99 [14] framework discloses the environmental impacts in terms of a number or scoring. Eco-Indicator 99 provides a method for assessing numerous environmental impacts and displays the final result as a single, easy-to-understand score. The key categories included in this analysis are climate change, respiratory effects, ozone layer depletion and acidification [14]. These categories were chosen because they offer an overview of key consequences on human health and the environment.

2. Case study

The Stirling-cycle-based heat pump under study – see Fig. 1 [6] – comprises the heater, regenerator, cooler, and expansion and compression cylinders arranged in a double-acting alpha Franchot configuration. The internal heat exchangers include a heating section, a regenerating section, and a cooling section, all integrated into the same unit. The heat pump is used to recover heat and use this heat and electrical energy to generate steam at 10 bar at an output of 450 to 500 kW, using equal amounts of low temperature heat and electrical energy input [6].

This corresponds to a COPh of 2, which is a rounded-up approximation of the actual COPh. With the new 750 kW heat pump a COPh in the range of 1.7-1.9 can be expected for these temperatures. More information about the actual performance was reported by the authors recently [15].

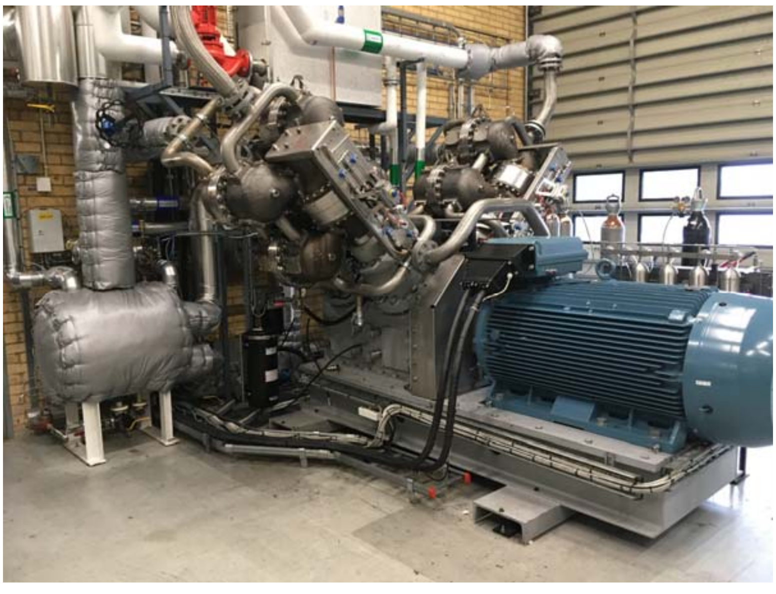

Fig. 1. The HighLift Stirling-cycle-based heat pump (SC HP) from Olvondo Technology is installed in the heat pump room at pharmaceutical company AstraZeneca, Gothenburg, Sweden. The nominal heat output from the heat pump is between 450 and 500 kW [6].

2.1 System boundary

To quantify the impacts of the analyzed unit, system boundaries must be determined. The system boundary for the Stirling-cycle-based heat pump is shown in Figure 2. Manufacturing includes raw materials extraction, parts production, and parts assembly. The end-of-life activities of the heat pump after the estimated life span are also assessed. In the decommissioning process, disassembly of parts, cleaning, repairing parts, and final disassembly is considered. In principle, this makes the raw materials available for other use. The lifespan of all the technologies is considered to be 15 years [15].

The construction phase (a), plus an operation phase for 1 year (b), 8 years (c), 15 years followed by decommissioning (d) and just the decommissioning phase with no use phase (e) are considered. The reason for considering the 1 and 8 year operating phases is to assess the impacts connected with each year as well as when the unit's (expected) half life span has elapsed. Decommissioning is only considered after 15 years of operation since the life span of all the heating technologies compared in this paper is assumed to be 15 years.

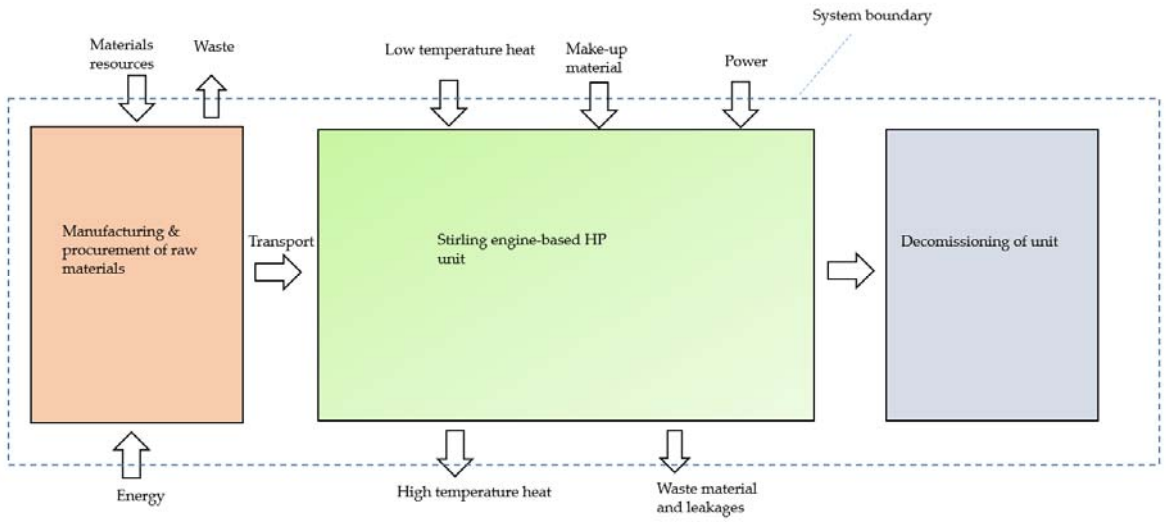

Figure 2. Schematic diagram of the system boundary for life cycle assessment of Stirling-cycle-based heat pump (SC HP) [16]

The system boundary of a system containing a natural / biogas- or fossil / bio-oil-fired boiler includes the extraction/acquisition of raw materials as well as fuel and materials delivery.

2.2. Stirling-cycle-based heat pump vs. fuel-fired boilers

The heating systems studied for this study are a Stirling-cycle-based heat pump, a fossil fuel oil boiler, a bio-oil boiler, a natural gas-fired boiler and a biogas boiler. These five systems are evaluated for locations in Sweden with identical climatic conditions. The location's choice was according to the location of a set of SC HPs under study in the EU Horizon 2020 project HighLift [7], which is in Gothenburg, Sweden. The results of the analysis might be different depending on the chosen location. It was assumed that the same boiler can be used for all four fuels.

3. Results and discussion

The section discusses and compares the total cumulative exergy losses and environmental impacts associated with Stirling-cycle-based heat pump (SC HP), fossil fuel oil boiler (OB), bio-oil boiler (BOB), natural gas-fired boiler (NGB) and biogas boiler (BGB) with a design capacity of 500 kW. For the fuel-fired boilers, 500 kW LHV fuel input is needed, for the SC heat pump 250 kW low temperature heat plus 250 kW electricity is needed to provide 500 kW of high temperature heat – see also [15].

3.1. Exergy analysis

The overall thermodynamic performance of the boilers was evaluated based on their exergy losses. Results of the total cumulative exergy loss (TCExL) calculations are summarized in Table 1.

Table 1. Summary of results of the total cumulative exergy loss (TCExL) calculations for construction + 1 year use, construction + 8 years use and construction +15 years use + decommissioning.

		Construction + 1 year operation				
	Unit	NGB	OB	BOB	BGB	SC HP
CExD	PJ	$1.99\text{x}10^{-2}$	$6.24\text{ x}10^{-2}$	$2.29\text{ x}10^{-2}$	$2.60\text{ x}10^{-2}$	$1.52\text{ x}10^{-2}$
$Ex_{product}$	PJ	$1.50\text{ x}10^{-2}$	$1.50\text{ x}10^{-2}$	$1.50\text{ x}10^{-2}$	$1.50\text{ x}10^{-2}$	$1.50\text{ x}10^{-2}$
$Ex_{emissions\&wasteflow}$	PJ	$3.60\text{ x}10^{-6}$	$3.70\text{ x}10^{-6}$	$5.67\text{ x}10^{-7}$	$9.96\text{ x}10^{-7}$	$2.81\text{ x}10^{-7}$
$Ex_{loss,\ internal}$	PJ	$4.90\text{ x}10^{-3}$	$7.90\text{ x}10^{-3}$	$4.74\text{ x}10^{-2}$	$1.10\text{ x}10^{-2}$	$2.20\text{ x}10^{-4}$
$Ex_{loss,abatement}$	PJ	$1.44\text{ x}10^{-2}$	$2.48\text{ x}10^{-1}$	$1.79\text{ x}10^{0}$	$7.84\text{ x}10^{-3}$	$7.85\text{ x}10^{-5}$
$Ex_{loss,land}$	PJ	$8.04\text{ x}10^{-5}$	$2.76\text{ x}10^{-4}$	$6.31\text{ x}10^{-4}$	$2.76\text{ x}10^{-4}$	$1.60\text{ x}10^{-5}$
TCExL	PJ	$1.93\text{ x}10^{-2}$	$2.95\text{ x}10^{-1}$	$1.79\text{ x}10^{0}$	$1.91\text{ x}10^{-2}$	$3.14\text{ x}10^{-4}$
		Construction + 8 years operation				
	Unit	NGB	OB	BOB	BGB	SC HP
CExD	PJ	$1.47\text{ x}10^{-1}$	$2.90\text{ x}10^{-1}$	$1.78\text{ x}10^{-1}$	$1.36\text{ x}10^{-1}$	$1.28\text{ x}10^{-1}$
$Ex_{product}$	PJ	$1.26\text{ x}10^{-1}$	$1.26\text{ x}10^{-1}$	$1.26\text{ x}10^{-1}$	$1.26\text{ x}10^{-1}$	$1.26\text{ x}10^{-1}$
$Ex_{emissions\&wasteflow}$	PJ	$3.35\text{ x}10^{-5}$	$3.39\text{ x}10^{-5}$	$1.30\text{ x}10^{-6}$	$4.30\text{ x}10^{-6}$	$8.85\text{ x}10^{-7}$
$Ex_{loss,\ internal}$	PJ	$2.10\text{ x}10^{-2}$	$5.20\text{ x}10^{-2}$	$1.64\text{ x}10^{-1}$	$1.01\text{ x}10^{-2}$	$2.00\text{ x}10^{-3}$
$Ex_{loss,abatement}$	PJ	$1.15\text{ x}10^{-1}$	$1.98\text{ x}10^{0}$	$1.43\text{ x}10^{1}$	$6.27\text{ x}10^{-2}$	$1.74\text{ x}10^{-4}$
$Ex_{loss,land}$	PJ	$6.43\text{ x}10^{-4}$	$2.21\text{ x}10^{-3}$	$5.05\text{ x}10^{-3}$	$2.21\text{ x}10^{-3}$	$6.50\text{ x}10^{-5}$
TCExL	PJ	$1.36\text{ x}10^{-1}$	$2.148\text{ x}10^{0}$	$1.43\text{ x}10^{1}$	$7.50\text{ x}10^{-2}$	$2.24\text{ x}10^{-3}$
		Construction + 15 years operation + decommissioning				
	Unit	NGB	OB	BOB	BGB	SC HP
CExD	PJ	$4.09\text{ x}10^{-1}$	1.95 x10	$9.18\text{ x}10^{-1}$	$2.54\text{ x}10^{-1}$	$2.40\text{ x}10^{-1}$
$Ex_{product}$	PJ	$2.37\text{ x}10^{-1}$	$2.37\text{ x}10^{-1}$	$2.37\text{ x}10^{-1}$	$2.37\text{ x}10^{-1}$	$2.37\text{ x}10^{-1}$
$Ex_{emissions\&wasteflow}$	PJ	$3.31\text{ x}10^{-4}$	$3.31\text{ x}10^{-3}$	$2.10\text{ x}10^{-6}$	$7.65\text{ x}10^{-6}$	$1.50\text{ x}10^{-6}$
$Ex_{loss,\ internal}$	PJ	$1.72\text{ x}10^{-1}$	$1.71\text{ x}10^{0}$	$6.81\text{ x}10^{-1}$	$1.75\text{ x}10^{-2}$	$3.48\text{ x}10^{-3}$
$Ex_{loss,abatement}$	PJ	$2.15\text{ x}10^{-1}$	$3.71\text{ x}10^{0}$	2.68 x10	$1.18\text{ x}10^{-1}$	$2.48\text{ x}10^{-4}$
$Ex_{loss,land}$	PJ	$1.21\text{ x}10^{-3}$	$9.46\text{ x}10^{-3}$	$3.55\text{ x}10^{0}$	3.55 x10	$1.20\text{ x}10^{-4}$
TCExL	PJ	$3.89\text{ x}10^{-1}$	$8.97\text{ x}10^{0}$	$6.989\text{ x}10^{0}$	$3.68\text{ x}10^{0}$	$3.85\text{ x}10^{-3}$

Figure 3 shows the comparison of the CExD among different technologies. From the results it can be seen that the fossil oil boiler (OB) has the highest cumulative exergy demand followed by a bio-oil fueled boiler (BOB), natural gas-fired boiler (NGB), and biogas-fueled boiler (BGB). It should be noted that CExD includes material (minerals, metals, and water) resources as well as energy resources. The large contribution of exergy demand is associated with fuel production and its use for operation. The combustion contributes the most immense amount of exergy destruction. The transport of biogas (as also for natural gas) is highly energy demanding.

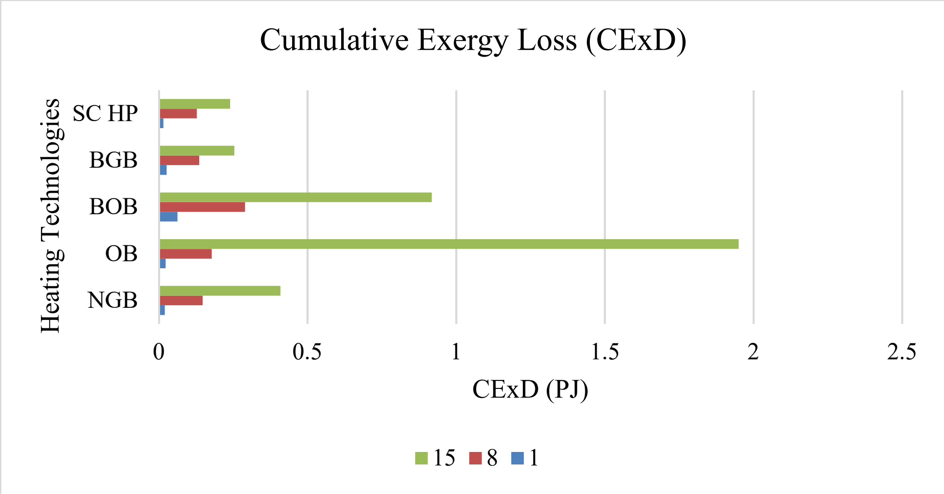

Figure 3. Cumulative exergy demand for different heating technologies for construction + 1 year use (1), construction + 8 years use (8) and construction +15 years use + decommissioning (15)

For the bio-oil fueled boiler (BOB), the internal exergy losses are comparatively higher for 1 and 8 years of operation as shown in Figure 4. The source of input for bio-oil is wood from Sweden, and the impact associated with the land to grow that wood is included for exergy loss calculations. The reduced heating value of the wood chip fuel is the primary cause of reduced efficiency compared to natural gas.

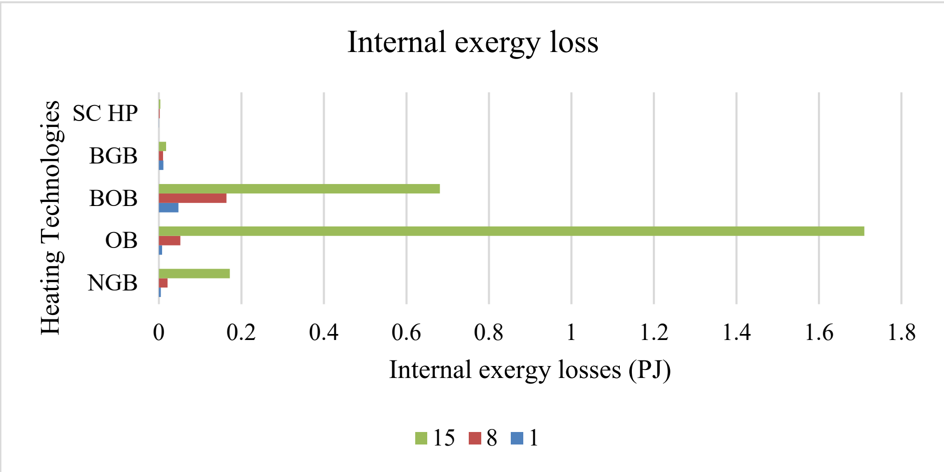

Figure 4. Internal exergy loses for different heating technologies for construction + 1 year use (1), construction + 8years use (8) and construction +15 years use + decommissioning (15)

A low TCExL is found for the Stirling-cycle-based heat pump as can be seen in Figure 5. This is because it has lower emissions and thus lower abatement exergy losses. The higher TCExL for the natural gas and fossil oil boilers is because of the contribution that arises from the life cycle footprint of natural gas and oil i.e., extraction, processing, distribution, and combustion. If the biofuel cannot be sourced locally, transportation costs, both economically and environmentally, could be higher than for natural gas.

For further analysis, only construction and decommissioning of the SC HP and boiler was also considered. Table 2 shows that for the HP most of the impacts stems from construction of the SC HP and only a small fraction is contributed by operation of the SC HP.

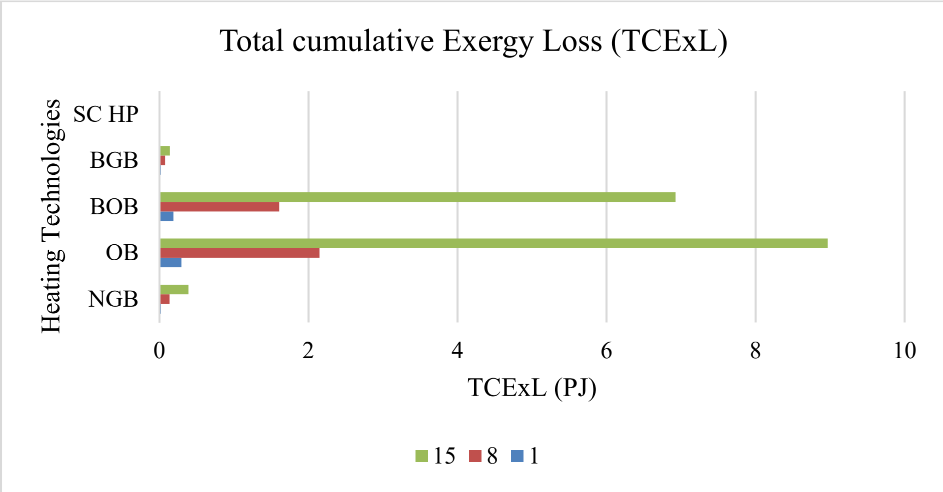

Figure 5. Total cumulative exergy loss for different heating technologies for construction + 1 year use (1), construction + 8 years use (8) and construction +15 years use + decommissioning (15)

The negative numbers in the table for decommissioning are the result of more pure (recovered) materials compared to the materials entering the decommissioning phase (incl. metal ores).

Table 2. Summary of results for total cumulative exergy loss (TCExL) calculation for construction, decommissioning of the boiler and construction, decommissioning of the SC heat pump

	Units	Boiler construction	Boiler decommissioning	HP construction	HP decommissioning
CExD	PJ	1.32×10^{-3}	-5.72×10^{-5}	2.81×10^{-5}	-1.59×10^{-4}
$Ex_{emissions\&wasteflow}$	PJ	5.01×10^{-6}	-1.75×10^{-8}	1.61×10^{-9}	-3.13×10^{-8}
$Ex_{loss, internal}$	PJ	1.31×10^{-3}	-5.72×10^{-5}	2.81×10^{-5}	-1.59×10^{-4}
$Ex_{loss,abatement}$	PJ	3.22×10^{-4}	-3.08×10^{-5}	6.10×10^{-7}	-9.15×10^{-5}
$Ex_{loss,land}$	PJ	2.17×10^{-5}	-1.01×10^{-6}	1.09×10^{-7}	-2.84×10^{-6}
TCExL	PJ	1.39×10^{-3}	-8.90×10^{-5}	3.50×10^{-4}	-2.54×10^{-4}

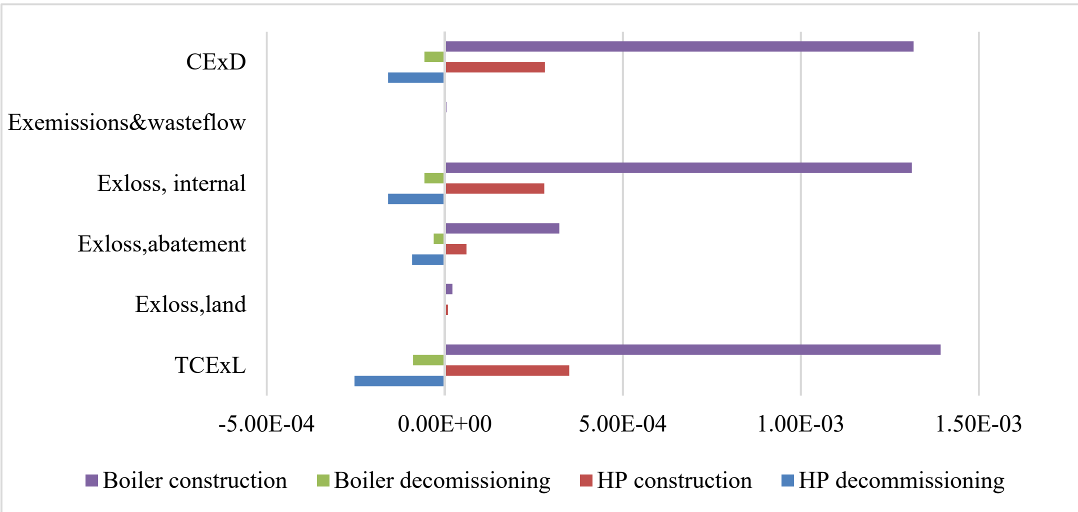

Figure 6. Exergy demand and losses for different heating technologies for construction, decommissioning of the boiler and construction decommissioning of the heat pump. Unit: PJ

Figure 6 shows the relative cumulative exergy demand and losses associated with the manufacturing and decommissioning of the boiler and the heat pump. It can be seen from the results that the total cumulative exergy loss for the manufacturing phase is lower for the heat pump than for the boiler. The negative values for exergy demand and losses during decommissioning of the boiler and HP unit are caused by 90% recycling of materials.

3.2. Environmental analysis

The following figure assesses the environmental impacts associated with all the heating technologies (NGB, OB, BGB, BOB) with a design capacity of 500 kW and compares them with the Stirling-cycle-based heat pump (SC HP). The Eco-Indicator 99 method was used to analyze the damage categories climate change, human health and ecosystem quality as shown in Figures 7 through 9, respectively. The values are given in kPt. Figure 7 indicates that fossil fuel systems have a three to five times higher negative environmental effect than SC HP, which is in line with the assessment technique of IMPACT 2002+.

Biogas plays a major role in reducing emissions of greenhouse gases. However, unwanted emissions of methane and nitrous oxides (N_2O) must be taken into account. Of all the gaseous emissions considered for direct emission from biogas combustion, the amount of nitrogen oxides (NOx) was of interest. The NOx pollution problem is due to low ozone synthesis, which is a harmful compound. One of the main issues is the ozone at the ground level (smog), which arises due to NOx and volatile organic compound (VOC's) reaction in sunlight. This occurrence is detrimental both to humans, animals, and to plants. Methane losses at the biogas processing plant and natural gas heat generation add much to global warming potential.

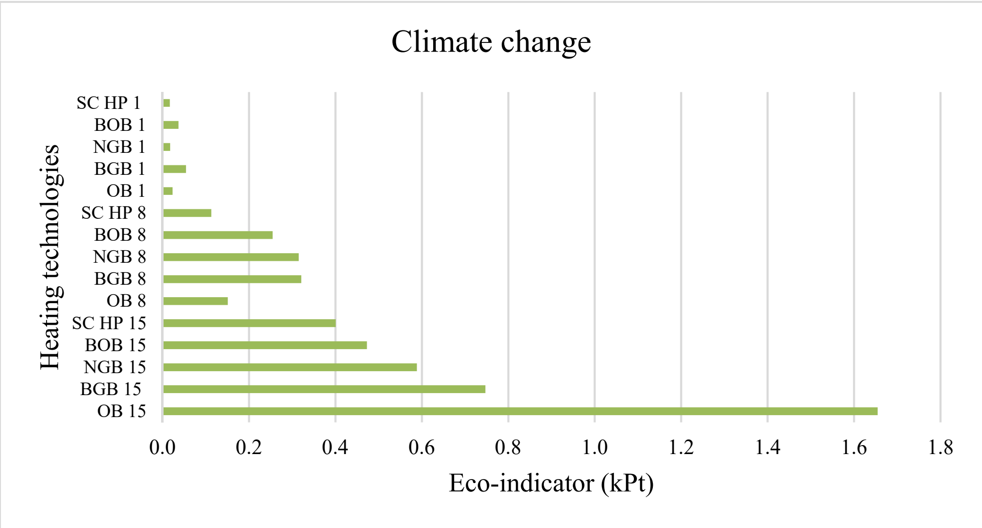

Figure 7. Characterization of damage via climate change for construction + 1 year use (1), construction + 8 years use (8) and construction +15 years use + decommissioning (15)

It can be seen from Figure 8 how fossil fuel boilers have a higher negative effect on human health. This is because of the air emissions and toxicity associated with the fuel combustion.

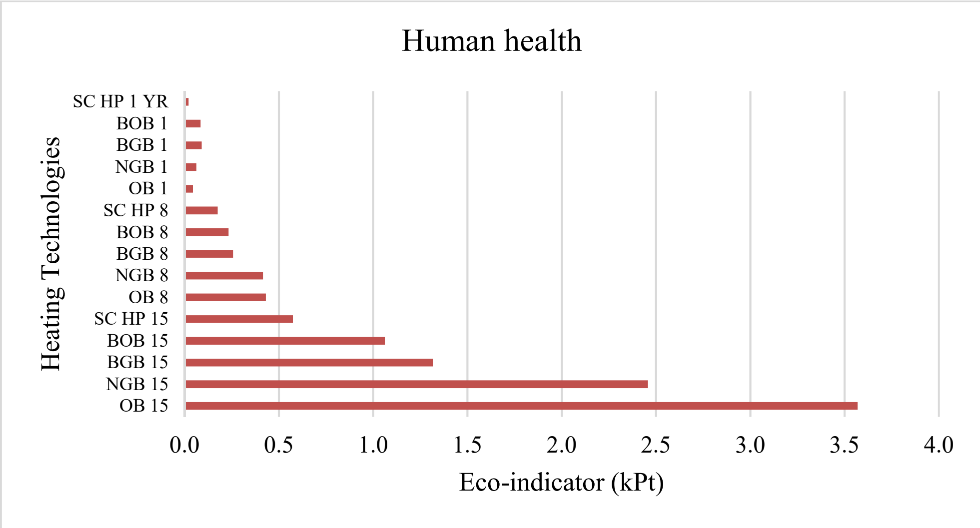

Figure 8. Characterization of damage on human health for construction + 1 year use (1), construction + 8 years use (8) and construction +15 years use + decommissioning (15)

Figure 9 shows the contribution of heating technologies towards ecosystem quality. It can be seen from the figure that the bio-oil-based boiler has a higher impact on ecosystem quality. A quite important consideration is the amount of area necessary for the wood from which bio-oil is made. The use of land is known to have the highest environmental effects for the BOB. The negative contribution of biogas in the effect group for eutrophication is due to the decrease, as a nutrient, of nitrogen leaching, in ammonium nitrate production.

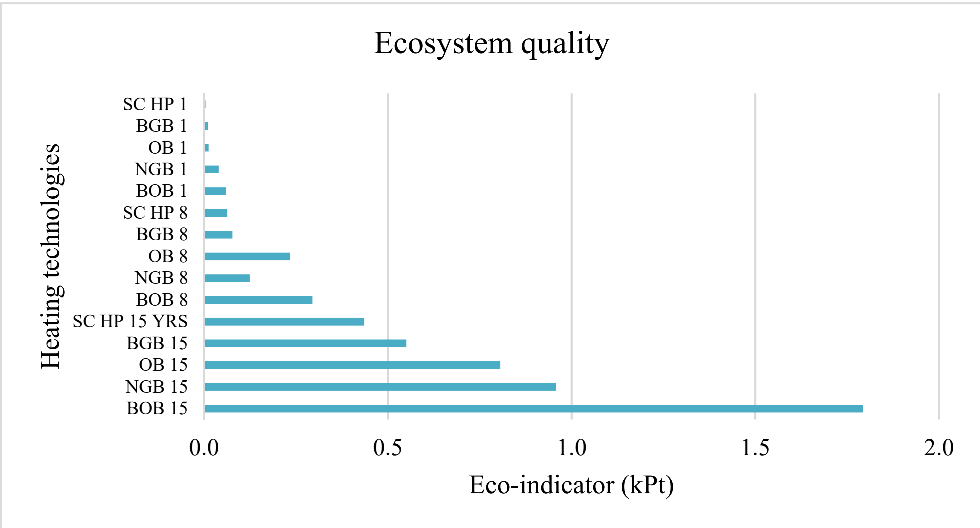

Figure 9. Characterization of damage on ecosystem quality for construction + 1 year use (1), construction + 8 years use (8) and construction +15 years use + decommissioning (15)

During the life cycle of ethanol extracted from wood, low impacts on eutrophication can be seen. Transportation, combustion, gas, and sawdust give significant contributions (all of them releasing NOx emissions). The CO_2 emissions from natural gas combustion have the most significant effect of the boiler use on climate change. Methane emissions occur mainly because of losses in long-distance pipelines while transporting natural gas. The emissions of chromium (VI) from iron manufacture are toxic for humans and may cause cancer. Nitrogen oxides result in photochemical ozone production, acidification, terrestrial and aquatic eutrophication during the combustion phase.

An analysis of the footprint of an oil boiler's life cycle indicates that the overall effect is similar to that of natural gas. For the oil boiler, copper and zinc pollutants affect the atmosphere and hence air quality, primarily via combustion. The 'Non-renewable energy' group has a greater influence on natural gas systems than OB. Oil-based heating systems with environmental impacts between three and four times greater than the SC HP are the most environmentally unfriendly option. There are significant variations between biofuel and fossil fuel systems in the 'Emission into air' and 'Energy Supplies' categories.

Figure 10 shows the comparison of the manufacturing and decommissioning phases of the heat pump and boiler on the scale of Eco-indicator. It can be seen from the graph that the impact categories show negative values during the decommissioning phase. This is because of 90% of boiler and heat pump material is being recycled and hence contributes positively toward the environment.

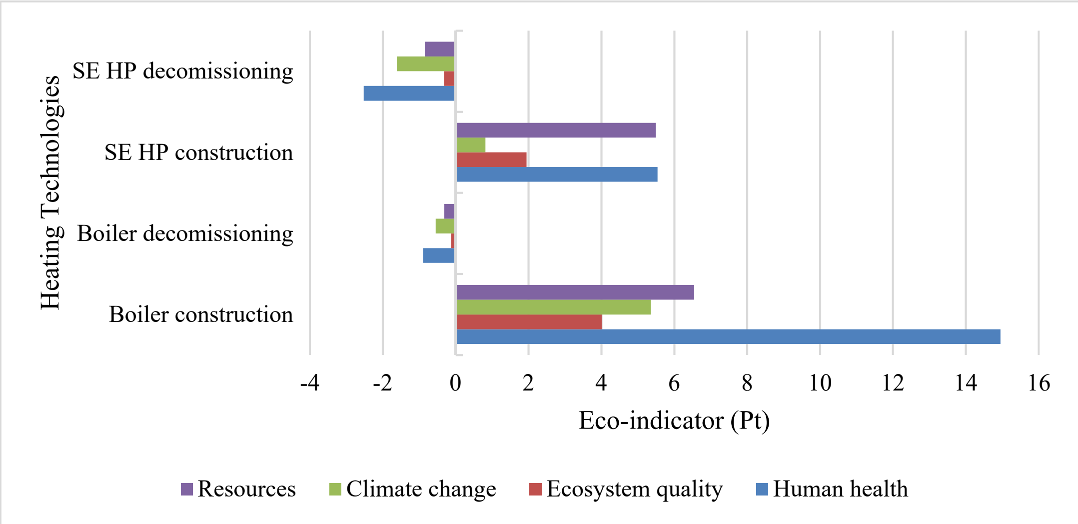

Figure 10. Characterization of damage from construction or decommissioning of the boiler and of construction or decommissioning of the SC HP.

Note that for the new and larger, 750 kW, heat pump a COP_h of 1.7-1.9 is expected which will, however, not affect the comparison between the heating technologies as given above very much. The actual differences with the fossil fuel boilers will be somewhat smaller.§

4. Conclusion

The aim of the study is to compare a Stirling-cycle-based heat pump (SC HP) with heating technologies based on various fuels (oil, natural gas, biomass, bio-oil), and to identify which heat pump is best for the environment provided its life cycle from development through to final use is considered. The assessment of the models' life cycles showed that the SC HP is more eco-friendly and causes less exergy loss over its lifetime than the other technologies. SC HPs can be a part of the solution to today's most important environmental issue - global warming.

For future work, a comparison on economic sustainability should be made (as is scheduled as the next step of the research). This can be useful in presenting a broader image of how the SC HP system performs compared to the natural gas, fossil fuel oil and biofuel boilers in terms of environmental and economic impacts. Also the effect of a somewhat different COP_h may be considered, based on future data obtained from the 750 kW SC HP.

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