LIFE CYCLE ASSESSMENT (LCA) OF AN AIR-COOLED ORC SYSTEM FOR WASTE HEAT RECOVERY

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ABSTRACT

Organic Rankine Cycle (ORC) systems enable locally emission-free power generation. Nevertheless, they cause emissions and resource consumption during their life cycle. Life cycle assessment (LCA) according to ISO 14044 allows identification of key environmental impacts caused by a product. An LCA was carried out for a direct air-cooled ORC system applied to recover waste heat. As working fluid R-245fa was considered and the nominal generator output was set to 100 kW_{el}. A volumetric expander with a fixed volume ratio was assumed. The simplified thermodynamic cycle was modelled for a source temperature of 130 °C. On this basis, commercially available components were selected according to publicly available data. The inventory analysis was carried out with simple mass fraction inventory of the mainly used materials. Subsequently, the reduced manufacturing processes were implemented using the integrated database of the LCA software *GaBi Education*. Scenarios were defined for the lifetime of the system and full load operation hours per year, which resulted in different amounts of electricity provided by the system. The life cycle impact assessment was carried out using the *ReCiPe 2016* method, including 18 impact categories. Results for each scenario were calculated for the entire system and all results were standardized related to the functional unit of kWh_{el}. Three substantial results were derived. First, the greenhouse gas emissions of the ORC system were significantly increased due to the unavoidable losses of R-245fa during the life cycle. These emissions of the working fluid significantly exceeded those from manufacturing of the system. Second, environmental impacts such as climate change, ionizing radiation, terrestrial acidification, water usage, and fine particulate matter formation were found to be higher compared to electricity generation by wind power if the full load operation hours remain low. Third, a reduction of environmental impacts could be achieved if low global warming potential fluids are used, resource-saving production processes are chosen, a hermetic design is implemented, and full-load operation hours are increased.

1 INTRODUCTION

The implementation of Organic Rankine Cycle (ORC) systems is often explained with its locally emission free power generation and therefore reduced amounts of carbon dioxide emissions. However, the goal must be to contribute to a climate neutral economy to comply with the Paris Agreement. The focus needs to be on minimum greenhouse gas emissions and the most resource effective technologies for electricity supply, regardless of whether the source is waste heat, solar radiation, wind or water flows. All technological systems cause environmental impacts during production, transportation, service, and deconstruction processes. For fuel-free power plants like ORC systems, life cycle assessments (LCA) are an effective strategy to relate their environmental impacts to the generated power. This allows for the comparison of electricity provided by ORC systems with electricity from other renewable resources like wind power. In a low-emission society, the specific total emissions and resource requirements of generation technologies should be a key driver in investment decisions surrounding technology implementation. Structured LCAs based on ISO 14044 can be implemented for any product system. A LCA for large geothermal ORC plants in Germany by Heberle *et al.* (2016) identified a high reduction potential in global warming impact by using low global warming potential

(GWP) fluids. Kythavone *et al.* (2019) found in their LCA of an existing 25 kW_{el} ORC system that the highest environmental impacts were caused by raw materials needed for the steel and copper consumption. So far, LCAs for the recently-growing market of ORC systems with standardized industrial components, such as those adopted from the refrigeration and heat pump technology, sector have been lacking. This study provides a theoretical approach based on readily available components, reflecting the state-of-the-art.

2 METHODOLOGY

2.1 The principles of Life Cycle Assessment

The method of LCA is a tool to identify the environmental effects of products at various points of their life cycle. It allows decision-makers to plan and design processes strategically as well as to redesign environmentally unfriendly products if necessary. The principles of LCA are described in EN ISO 14040 while the requirements are provided in EN ISO 14044. LCA considers the entire life cycle of a product and consists of four phases. The definition of goal and scope is followed by an inventory analysis, which leads to the impact assessment and interpretation. The life cycle inventory analysis (LCI) involves data collection such as energy and raw material inputs, products, waste, and emissions. Further it relates the data to the reference flow of a defined functional unit of the product or process. The third phase of life cycle impact assessment (LCIA) evaluates the significance of caused environmental impacts. There are different LCIA methods to quantify the impacts of different functional principles. The findings of LCI and LCIA are considered together in the phase of interpretation. Results according to the goal and scope of the LCA are presented, recommendations are provided, and limitations of the process are described transparently. The concluding findings intend to provide consistent information to improve the processes according to their environmental impacts.

2.2 Life Cycle Impact Assessment (LCIA) method: ReCiPe 2016

To quantify the different environmental effects caused during the life cycle stages of a product, LCIA provides a consistent model by scoring the impacts in categories. The national Institute for Public Health and the Environment of the Netherlands presented the *ReCiPe 2016* method, which is popular in Europe. It consists of 18 midpoint impact categories such as global warming. These categories are related along their damage pathways and are cumulated in three endpoint areas of protection, which are damage to human health, damage to ecosystems and damage to resource availability. The chosen "hierarchist" perspective, considers a time horizon of 100 years in a baseline scenario.

2.3 Goals and Scope of the LCA

The goal of this LCA is to analyze the environmental impacts of a theoretical air-cooled ORC system using the working fluid R-245fa and having a fixed nominal generator power of 100 kW_{el} to convert the waste heat of a source of 130 °C into electricity. The plant consists of a pump, an evaporator, a volumetric expansion machine with a fixed volume ratio, and a direct air-cooled condenser (Fig. 1).

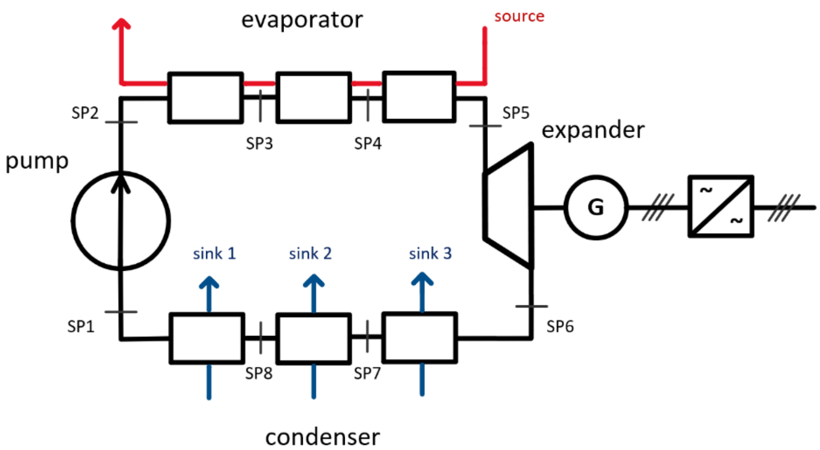

Figure 1: Structure of the assessed ORC system

The LCA aims to point out the potentials to reduce negative environmental impacts of ORC systems and evaluate the long-term perspective as a regenerative energy source by comparing the impacts with those of wind power. The LCI of the examined ORC system is based on the modeling of a simplified thermodynamic cycle and commercially available components according to publicly accessible information. The modelling of simplified production processes was carried out using the LCA software *GaBi Education*. The LCIA is based on few basic materials and processes for the main system components. Due to a lack of data, recycling could not be taken into account. The *ReCiPe 2016* method was chosen to conduct the LCIA. With different scenarios for equivalent operation hours at full load the impacts are related to the functional unit of the system, which is the electrical output in kWh_{el}. It is presumed that the required heat input is provided as waste heat without impacts inside the system boundaries.

3 CALCULATION AND MODELLING

3.1 Thermodynamic Calculation

For the thermodynamic calculation of the ORC system the optimization model of Bederna *et al.* (2021) was used. With the set generator power of 100 kW_{el}, a screw expansion machine was selected because of its robustness and flexibility. A maximum volume flow rate of 0.06 m^3/s and a volume ratio of 3 were determined as input parameters for the optimization model based on the values of an existing screw compressor model. Data from an actual industrial expansion machine used in the field were not publicly available. All input variables and key assumptions are summarized in Table 1.

Table 1: Input parameter for thermodynamic calculations

Parameter	Value
Working fluid	R-245fa
Generator power	100 kW
Heat source (pressurized water) temperature	130 °C
Heat sink (air) temperature	15 °C
Expander isentropic efficiency	0.7
Expander volume ratio	3
Maximum expander inlet volume flow rate	0.06 m^3/s
Generator and power electronics efficiency	0.85
Pump isentropic efficiency	0.7
Motor and power electronics pump efficiency	0.9
Isochoric fan efficiency	0.7
Motor and power electronics fan efficiency	0.9

The thermodynamic cycle was optimized for an unknown heat source by varying the pressure levels to maximize the exergetic efficiency, which was determined with the exergy flow at the heat source inlet and the module net power output. In addition to the pump power, the fan power of the condenser must also be subtracted from the generator power (Eq. 1). The source inlet exergy flow is determined, using the enthalpy and entropy at the inlet as well as the enthalpy and entropy of the source flow at ambient conditions (Eq. 2).

$$\eta_{exergetic} = \frac{P_{el,net}}{\dot{E}_{sou,in}} = \frac{P_{el,gen} - P_{el,pump} - P_{el,fan}}{\dot{E}_{sou,in}} \tag{1}$$

$$\dot{E}_{sou,in} = \dot{m}_{sou} \cdot \left(h_{sou,in} - h_{sou,amb} - T_{amb}\left(s_{sou,in} - s_{sou,amb}\right)\right) \tag{2}$$

First, a simplified thermodynamic cycle was calculated with an analytical calculation setup to allow for the collection of information about suitable components available in industry. Pressure drops were neglected, and a minimal temperature difference of 5 K was assumed to determine the transferred heat flows in the heat exchangers. For the fix generator power of 100 kW_{el} the results of the optimization were the evaporation and condensation pressure levels as well as the mass flows of the source, cycle, and sink. Based on the corresponding heat flows and volume flows heat exchangers and a pump model were chosen. For the condenser a state-of-the-art cross-flow heat exchanger was selected. Assumptions could then be made for the pressure losses at fluid and air side. In some cases, it was possible to take data from the data sheets. Further, the number of transfer units (NTU) could be estimated according to Eq. 3. This was necessary because a calculation of the cross-flow condenser by using the mean logarithmic temperature difference is not target-oriented. The assumptions are summarized in Table 2.

$$NTU = \frac{k \cdot A}{c_p \cdot \dot{m}} = \frac{k \cdot A}{\dot{Q}/(T_{out} - T_{in})} \tag{3}$$

Table 2: Chosen input parameters for the numeric calculations based on selected heat exchangers

Heat exchanger	Pressure drop external side	Pressure drop cycle side	NTU external side
Preheater	19 kPa	5 kPa	0.7
Evaporator	2 kPa	7 kPa	2
Superheater	1 kPa	4 kPa	0.4
Precooler	100 Pa	30 kPa	0.7
Condenser	100 Pa	40 kPa	0.7
Subcooler	100 Pa	10 kPa	0.7

Subsequently, a second numerical calculation was carried out in which the pressure losses and the NTU values were considered. The optimization was again based on the exergetic efficiency and served to determine a realistic net power output. Table 3 compares the results of both calculations. A $T - \dot{H}$ diagram of the final ORC process with a net power output of 77.3 kW at an exergetic efficiency of 10.1 % is shown in Fig. 2. The average temperature curves of the condenser are also indicated.

Table 3: Results of the cycle calculation for the component selection

Parameter	Initial analytic calculation for component selection	Numerical calculation (incl. pressure drops)
Heat source mass flow	8.7 kg/s	9.9 kg/s
Heat sink mass flow	122.3 kg/s	112.0 kg/s
R-245fa mass flow	4.48 kg/s	4.91 kg/s
Expander inlet pressure	1.458 MPa	1.582 MPa
Pump inlet pressure	0.167 MPa	0.178 MPa
Fan electric power consumption	14.3 kW	14.5 kW
Net power	79.0 kW	77.3 kW
Exergetic efficiency	11.76 %	10.07 %

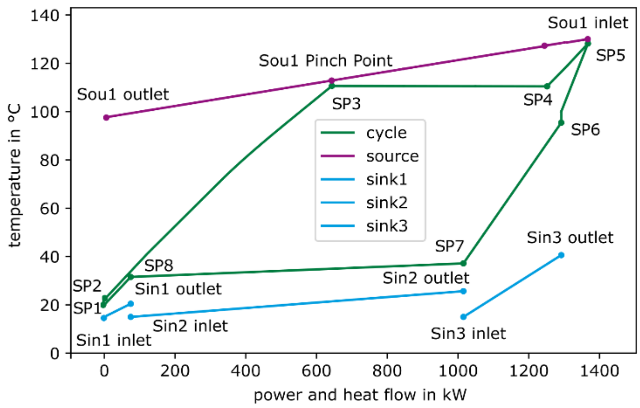

Figure 2: $T - \dot{H}$ diagram of the final ORC process and cross-flow condenser performance

3.2 Life Cycle Inventory Analysis and process modelling

For the inventory analysis the focus was limited to the crucial components of the ORC system and the main materials used. According to the thermodynamic calculation the components were chosen as commercially available products stated in Table 4. For instance, a microchannel condenser by ThermoKey was selected because of its recyclability and reduced environmental impact due to its single material structure made of aluminium and the absence of copper pipes. Further, the expander is a screw compressor model by Bitzer assumed to work in expanding mode.

Table 4: Component list and estimated masses

Basic component	Selected product information	Simplified mass inventory
Housing based on shipping container 20 feet, HC	Steinecker-Containerhandel, Ecoinvent database	Coated steel sheets: 353 kg Steel sections: 1037 kg
Brazed plate heat exchanger (heat input)	BPHEs by SWEP B56Hx240/1P, VH500TMx300/1P	316 stainless steel plates: 435.12 kg
Condenser, direct air-cooled	ThermoKey microchannel condenser (2 units) JMKH2380B-{90}DV	Aluminium extrusion profile: 1448 kg
Centrifugal pump	Grundfos CRNE 10-17	Cast steel: 75 kg Steel parts: 25 kg Electrical sheets: 12.5 kg Copper: 12.5 kg
Screw expander	Bitzer HSN.8591-160 (Screw compressor)	Cast steel: 408 kg Steel parts: 136 kg Electrical sheets: 68 kg Copper: 68 kg
Frequency converter	Bitzer VARIPACK FKU+260	Aluminium: 58 kg Steel sheets: 9 kg Plastic parts: 9 kg Copper: 4 kg
Piping	SIKLA various copper and steel pipes	Copper: 147 kg Steel: 22 kg
Working fluid	R-245fa	R-245fa: 208 kg
Lubricant	RENISO TRITON SEZ 320	Lubricant: 52 kg

As there are no component lists available for public, a simplified mass inventory was estimated. It was composed after screening accessible information and estimating the quantity shares of the main components and materials. This approach was chosen as it yields more specific results compared to the use of generalised factors for power output-specific material masses as done by Heberle *et al.* (2016) and Valencia Ochoa *et al.* (2020). The amount of lubricant in this calculation is set to 25% of the fluid mass, while e.g., Kythavone *et al*. (2019) estimated one third. Transportation from the locations of the selected supplier locations to a hypothetical assembly site in Munich and an imaginary customer located 600 km away e.g. in Berlin were added. Other company processes were neglected as they were not determinable for the theoretical approach. Furthermore, disassembly and disposal of the system at the end of its lifetime were not considered in the evaluation except for fluid losses during decommissioning. The production processes for the components and materials estimated in the mass inventory were implemented using the integrated database of the LCA software *GaBi Education*. Plans for every basic component, the assembly and the transport of the machine were created and available production processes, mainly for the metal materials, were chosen. Processes with average European production conditions or country specific processes for known production locations were selected.

3.3 Scenarios for lifetime and utilization

Scenarios were defined to relate the environmental impacts of the manufacturing of the ORC system to the functional unit of kWh_{el} provided by the system. Two scenarios for the lifespan and three cases for the equivalent operation hours at full load per year were determined. Comparable with the lifespan of refrigeration systems a usual use case of 15 years and a reduced longevity with 12 years of operation were set. A low, a medium, and an optimal utilization case were defined with equivalent operation hours at full load per year of 2500 h/y, 5500 h/y and 8500 h/y. With the net power output at full load the amount of electricity provided in each scenario was calculated to provide the basis for the evaluation of the environmental impacts related to the power generation.

4 RESULTS

4.1 Environmental impacts of the evaporator

The impacts in the category of climate change for the evaporator are discussed in detail because a comparison between the GWP modelled with *GaBi* and the indication provided by the company SWEP is possible. The manufacturer indicates a CO_2 footprint with a total amount of 3058 kg CO_2 equivalents for the chosen plate heat exchangers. The simplified process modelling in *GaBi* with stainless-steel sheet production, stamping and bending process and transportation leads to a total of only 1769 kg CO_{2eq} which is only 58 % of the manufacturer calculation. This example clarifies the gap between the company’s internal calculation of environmental impacts and the incomplete external evaluation. As a result, it must be assumed that the real impacts of the complete product and manufacturing process are substantially higher than the values calculated in this study.

4.2 Environmental impacts of the complete ORC system

The environmental impacts in the 18 categories by *ReCiPe 2016* were calculated after the process modelling in the *GaBi* software. In the category of climate change the sum of emissions in CO_2 equivalents is 95,900 kg CO_{2eq} for the lifetime of 15 years including the estimated losses of R-245fa during the operation (1 % per year) and the recycling of the fluid (recovery rate 80 %). The estimation of operation and recovery losses was based on numbers for commercial refrigeration reported by Schwarz (2005) for the German Environment Agency (UBA). The fluid losses account for 75,100 kg CO_{2eq} because of its high GWP of 1032. Reducing the leakage rate during operation by half could avert 16,100 kg CO_{2eq}. In the ideal case of no maintenance and a fully hermetic system. Therefore, without fluid losses during operation, the unavoidable losses due to recycling still amount to 42,900 CO_{2eq}. Apart from R-245fa, the highest impact in the category of climate change is caused by the heavy aluminum condenser. Its impact is the highest compared to the other machine components in 12 of the 18 categories. The piping, with its high amount of copper, and the complex expander also account for high environmental impacts in several categories.

4.3 Environmental impacts per kWh_{el} provided in different scenarios

To allow for the interpretation of the results, the values for the different impact categories were related to the electricity provided by the ORC system during its lifetime for the different utilization cases. Finally, the impacts for the functional unit of kWh_{el} net grid feed were calculated and compared to the impacts caused by wind power. The environmental impacts for two exemplary scenarios, the worst case with 12 years of operation and low utilization (2500 h/y) and the likely targeted scenario for 15 years of operation and medium utilization (5500 h/y) are shown in Table 5.

Table 5: Environmental impacts (ReCiPe 2016) per kWh_{el} provided in different scenarios

Impact category	**Indicator Abbreviation [Unit]**	**Value per kWh_{el}**			
		2500 h/y, 12 y	**5500 h/y, 15 y**	**8500 h/y, 15 y**	**Mix of German Wind Power** (*GaBi* database)
climate change	GWP [kg CO_2 to air]	0.0386	0.0150	0.0097	0.0105
ozone depletion	ODP [kg CFC-11 to air]	1.88E-09	6.83E-10	4.42E-10	2.69E-09
ionizing radiation	IRP [kBq Co-60 to air]	1.55E-04	5.65E-05	3.66E-05	5.11E-05
fine particulate matter formation	PMFP [kg PM2.5 to air]	9.37E-06	3.41E-06	2.20E-06	7.45E-06
Photochemical oxidant formation: ecosystem quality	EOFP [kg NOx to air]	1.64E-05	5.97E-06	3.86E-06	2.19E-05
Photochemical oxidant formation: human health	HOFP [kg NOx to air]	1.63E-05	5.92E-06	3.83E-06	2.17E-05
terrestrial acidification	TAP [kg SO_2 to air]	2.85E-05	1.04E-05	6.69E-06	2.22E-05
freshwater eutrophication	FEP [kg P to fresh water]	7.76E-09	2.82E-09	1.83E-09	2.07E-08
Marine eutrophication	MEP [kg N to marine water]	8.19E-08	2.98E-08	1.93E-08	1.32E-07
human toxicity: cancer	HTPc [kg 1.4-DCB to urban air]	5.78E-06	2.10E-06	1.36E-06	5.98E-04
human toxicity: non-cancer	HTPnc [kg 1.4-DCB to urban air]	9.47E-04	3.44E-04	2.23E-04	1.60E-03
terrestrial ecotoxicity	TETP [kg 1.4-DCB to industrial soil]	0.0414	0.0151	0.0097	0.052
freshwater ecotoxicity	FETP [kg 1.4-DCB to fresh water]	2.34E-06	8.51E-07	5.50E-07	2.08E-06
marine ecotoxicity	METP [kg 1.4-DCB to marine water]	2.32E-05	8.44E-06	5.46E-06	1.88E-05
land use	LOP [$m^2 \times yr$ annual crop land]	7.99E-04	2.91E-04	1.88E-04	7.95E-04
water use	WCP [m^3 water consumed]	1.06E-04	3.86E-05	2.50E-05	4.03E-05
mineral resource scarcity	SOP [kg Cu]	4.05E-04	1.47E-04	9.54E-05	4.69E-04
fossil resource scarcity	FFP [kg oil]	0.0027	9.63E-04	6.23E-04	3.09E-03

Regarding (future) analyses of the results, it needs to be kept in mind that the real environmental impacts are substantially higher than the values in this study due to the simplicity of the modelling. Regardless, the assumptions implemented in this calculation are sound and grounded in both experience and literature, resulting in safe minimum results of the LCA. Compared to the mixture of types of technology used to generate power from wind in Germany (*GaBi* database, technology mix of onshore and offshore, reference year 2016), the ORC system causes a higher negative impact in several impact categories depending on the lifetime and equivalent hours at full load per year. For the worst-case scenario (12 years, 2500 h/y) the impact is higher compared to wind power in 8 out of 18 categories (higher indicator values for GWP, IRP, PMFP, TAP, FETP, METP, LOP, WCP as stated in Table 5). The ORC system performance in the impact category of climate change, indicated by GWP, is only better in the best-case scenario (15 years, 8500 h/y), as the average value of the wind power is 0.0105 kg CO_{2eq}. This is due to the very high amount of CO_2 equivalent emissions caused by unavoidable operation and recycling losses of the R-245fa. For the medium scenario (15 years, 5500 h/y) the performance in the category of ionizing radiation is also lower than of wind power. With a low utilization (15 years, 2500 h/y), in addition the performance in fine particulate matter formation, terrestrial acidification and water use is lower compared to wind power.

4.4 Recommendations to reduce environmental impacts during the ORC system lifecycle

To reduce the environmental impacts, three main recommendations are stated. First, a low GWP fluid and a hermetic system design with hermetic components and brazed vessels should be used instead of R-245fa since the main part of CO_2 equivalent emissions are caused by unavoidable fluid losses. This change would significantly reduce the impacts in climate change.
Second, the production processes should aim for minimum amounts of copper as it accounts for high negative impacts in several categories. In general, more recycled metals should be used.
Third, the performance compared to wind power in some of the impact categories can only be better if the equivalent hours of full load operation and the lifetime remain high. Otherwise, the environmental impacts remain higher compared to other renewable resources in several categories.

5 CONCLUSION

A life cycle assessment (LCA) according to ISO 14044 was conducted for a theoretical direct air-cooled ORC system made from available industrial components with R-245fa for a source temperature of 130 °C, reflecting the state-of-the-art. To select the main components a thermodynamic calculation with exergetic efficiency optimization was done in advance. Processes for a simplified mass inventory were implemented using the LCA software *Gabi Education.* The environmental impacts were determined in 18 categories with the *ReCiPe 2016* method for different use case scenarios and were compared to wind power to evaluate the long-term perspective in a low-emission society.
The main result of this simplified study is that the majority of CO_2 equivalent emissions are caused by the working fluid R245fa, which thereby can cause greater emissions per kWh of the ORC plant than the mixture of technologies used to generate energy from wind in Germany. Compared to all investigated scenarios by Heberle *et al.* (2016) for large scale geothermal ORC systems with R-245fa, the global warming impact results remain lower as the heat source was not part of the evaluation. For a medium use case (15 years, 5500 h/y) the global warming impact result with 0.0150 kg CO_{2eq} per kWh_{el} is close to the 0.0114 kg CO_{2eq} of the R-123 ORC engine evaluated by Kythavone *et al.* (2019). For low equivalent hours of full load operation, the calculated environmental impacts in several other categories exceed these of wind power.
To reduce the negative global warming impacts of ORC systems, low GWP fluids should be used. This would allow a decrease of the CO_2 equivalents to levels below the emissions caused by wind power technology assessed in this work. A hermetic design is an appropriate method to reduce the emissions of R-245fa during operation, but the unavoidable losses during recycling must be considered. Furthermore, high numbers of equivalent hours of full load operation should be attained and efficient raw materials acquisition and manufacturing processes with low resource consumption should be implemented to reduce the impact of the installed components.

Based on the first study, further research is needed to model the manufacturing and recycling process in detail, to determine the impact of low-GWP working fluid on the power output and to compare the ORC technology to other regenerative sources and their operation and life cycle conditions.

NOMENCLATURE

A	area	(m²)	$\dot{m}$	mass flow rate	(kg/s)
c	specific heat capacity	(J/(kg·K))	NTU	number of transfer units	(-)
$\dot{E}$	exergy flow	(W)	P	power	(W)
η	efficiency	(-)	$\dot{Q}$	rate of heat flow	(W)
$\dot{H}$	enthalpy flow	(J/s)	s	specific enthropy	(kJ/(kg·K))
h	specific enthalpy	(kJ/kg)	T	temperature	(K)
k	thermal transmittance	(W/(m²·K))			

Subscript

amb	ambient	in	input
el	electrical	out	output
eq	equivalent	p	isobaric
gen	generator	sou	source

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