ENVIRONMENTAL ANALYSIS OF A SMALL SCALE MARINE ORC

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ABSTRACT

The Marine ORC prototype unit is based on a conventional low-temperature subcritical Organic Rankine Cycle and has been designed as a waste heat recovery system for the jacket water of marine diesel auxiliary internal combustion engines (ICEs). The system has a nominal power output of 5 kWe and its working fluid is R134a. In the present work, the key remarks of the life cycle analysis on the experimental test rig, installed in Athens, are presented. The inventory has been assembled using manufacturer's data combined with assumptions from literature and the analysis of the impacts has been conducted using the ReCiPe 2016 method. The system was evaluated in coupling with the auxiliary ICE and was compared against an ICE that could produce on annual basis equal MWh to the coupled ICE-marine ORC system. In fact, the ICE-marine ORC system enhanced the environmental performance up to 3% on many impact categories, apart from the mineral resources and the marine and terrestrial ecotoxicity which is related to the extended use of copper-based materials. Moreover, the study was expanded by analyzing the contribution of the ORC components in the total impact assessment. In fact, the working fluid has a major impact on the ozone depletion and the global warming categories with a share of 91% and 78%, respectively. In terms of mineral resources scarcity and ecotoxicity, the motors/generators and the heat exchangers of the ORC have the largest contribution, owing to their large metal masses.

1 INTRODUCTION

Based on the study from International Maritime Organization (2021), shipping accounted for almost 2.9% of the global greenhouse gas (GHG) emissions in 2018, which corresponded to a value of 1,076 million tonnes CO_2. In order to reduce the emissions, a number of improvements has been suggested, including energy-efficiency measures and the increase in the penetration of near-zero carbon footprint fuels. In this perspective, the implementation of waste heat recovery (WHR) can lead to considerable emission savings, given the excessive heat losses in the exhaust gases and the jacket cooling water (Hoang 2018). Taking into consideration the relatively low temperatures of the aforementioned waste heat, Organic Rankine Cycle (ORC) is one of the best candidates to exploit such heat streams towards power production and the consequent increase in the overall system's efficiency. In fact, reviews on waste heat recovery on marine applications propose as main candidate for WHR the steam Rankine cycle, the ORC and the Kalina cycle, with the ORC being the only, so far, proposed option for WHR from heat sources below 100 °C in maritime applications (Singh and Pedersen 2016, Zhu et al. 2020).. Several studies have focused on the optimization of the ORC system for marine applications on energy, exergy and economic level (Song et al. 2015, Yang and Yeh 2014).

However, to the best of the authors' knowledge, there are only a few studies discussing the environmental impact of ORC systems and none, in particular, for WHR in marine applications ORCs. Life Cycle Analysis (LCA) is an assessment method developed to quantify the environmental impact of a product, by taking into account its entire life cycle, from the raw materials production to the waste management (ISO 2006, Finnveden et al. 2009).

Walsh and Thornley (2012) conducted an LCA for an ORC driven by WHR in the production of metallurgical coke. The net power output of the proposed ORC system was estimated to be 550 kW.

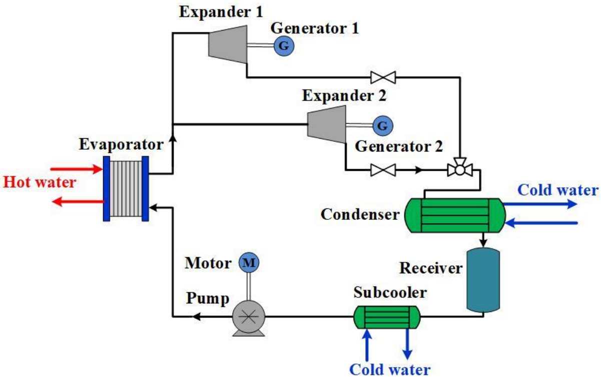
However, the environmental impacts on the life cycle basis were improved by less than 1%. Liu et al. (2013) used a simplified model, proposed by the Ecological Environment Research Center of Chinese Academy, to analyze the environmental performance of a conventional subcritical ORC dedicated for WHR, taking into consideration the use of different working fluids. The authors concluded that, in most impact categories, R113 was the best performing working fluid. A similar approach was followed by Wang et al. (2015) for a 10 kW subcritical ORC, designed to be driven by the WHR from cement production. A first detailed LCA on ORCs was published by Heberle et al. (2016), analyzing the environmental performance of different geothermal ORC plant configurations and working fluids. The results indicated that the use of ultra-low GWP fluids (e.g., R1233zd) can decrease the GWP impact by 4 times compared to the use of conventional working fluids (e.g., R245fa). This statement is also confirmed by the analysis of Dawo et al. (2021), in which the usage of R1233zd(E) was found to decrease the CO_2-equivalent emissions of a large scale geothermal ORC by 67.1% compared to the case that R245fa was used as working fluid.

In this study, the environmental performance of an experimental small-scale ORC unit for marine applications (marine ORC), developed in the National Technical University of Athens (NTUA), Greece, is investigated. The analysis is conducted in Simapro software, following the procedure of ISO 14040:2006, as discussed more thoroughly in the following sections.

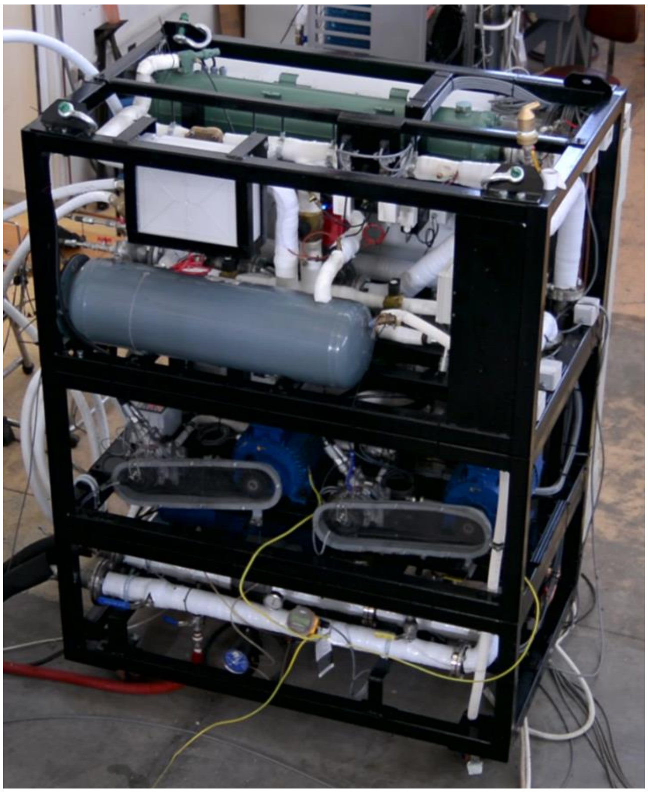
2 SYSTEM DESCRIPTION

The marine ORC prototype is a small-scale subcritical ORC. The system is operating with R134a and has a nominal power output of 5 kWe. As the system was developed to exploit the waste heat from the jacket cooling water of a ship's auxiliary internal combustion engine (ICE), the heat source for the lab experiments was simulated by a gas boiler with a nominal thermal output of 90 kW. The heat source temperature ranges between 80-90 °C, which corresponded to an ORC evaporation pressure of 25 bar. The design pressure ratio was set at 2.3. The mass flows determined for the design power production, dictated the use of two scroll expanders in parallel to have feasible volumetric flow rates and rotational speeds per expander for the rated power output. Considering that the expanders resulted from the modification of off-the-shelf open-drive scroll compressors, a limited range was available in terms of volumetric displacement, leading to the selection of two expanders to handle the design volumetric flow rates. This configuration also allows for a smoother control of the system during startup in conjunction with the capability of part-load operation, further enhancing its control. Each expander drives an asynchronous generator by means of a belt-pulley (Carraro et al. 2017). Moreover, a subcooler was installed to cool down the stream coming from the receiver and ensure cavitation free operation of the multi-diaphragm pump (Leontaritis et al. 2015). With respect to the types of the used heat exchangers, the evaporator is a plate heat exchanger, while the subcooler and the condenser are of shell and tube type (Pallis et al. 2021). Finally, the total volume of working fluid used for the initial charging of the system was 50 lt (0.05 m^3).

A simplified schematic of the marine ORC prototype, which was considered for the LCA, is shown in **Figure 1(a)**, while **Figure 1(b)** shows an image of the prototype as commissioned in the laboratory. Moreover, **Table 1** provides some key technical specifications of the main ORC components.



(a)



(b)

Figure 1: (a) Schematic and (b) Image of the marine ORC prototype system as commissioned at the Laboratory of Steam Boilers and Thermal Plants, NTUA (Pallis et al. 2021)

Table 1: Technical specifications of marine ORC key components, based on data from (Pallis 2020) and (Carraro et al. 2017)

Component	Manufacturer	Model	Technical data
Scroll expander	Sanden	TRSA12	Design rotational speed (rpm): 1,450 Volumetric displacement (cm³): 121.1
Diaphragm pump	Hydra Cell	G-10X	Design rotational speed (rpm): 960 Maximum global efficiency (%): 48
Evaporator	Alfa Laval	CB60	Number of plates (-): 90
Condenser	Bitzer	K573HB	Heat transfer area (m²): 1.33 Nominal pressure drop (kPa): 59
Subcooler	Bitzer	K123HB	Heat transfer area (m²): 0.3 Nominal pressure drop (kPa): 28

3 LCA MODELLING

According to ISO 14040:2006 the LCA can be divided in four main phases: (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment and (iv) interpretation. The following sections are discussing the application of the ISO methodology in the marine ORC LCA.

3.1 Goal and scope definition

Main aim of the LCA study is the assessment of the environmental footprint of the marine ORC prototype and its comparison to the production of the power surplus entirely by the existing ICE. In this perspective, the analysis will allow to have a quantitative view of possible benefits by the implementation of a WHR ORC as well as identify the key components that require further optimization towards the minimization of the system's environmental impact.

A cradle-to-grave approach is applied, considering all stages from raw material extraction, system manufacturing and commissioning, use phase to the end-of-life, including all transportations. The base case analysis took into consideration all the components of the marine ORC prototype, including the ICE from which the waste heat was extracted. The lifetime of the system was selected to be 20 years, which is common for such systems (Li 2019, Roumpedakis et al. 2020a, Riva et al. 2021). Finally, the functional unit was set to be 1 kWh of produced net electricity.

3.2 Inventory analysis

The inventory included a detailed listing of all the available data for inputs and outputs of materials/processes and energy consumptions over the life cycle of the investigated system. A number of components, including the receiver tank, the piping, the mass of the working fluid and the shell and tube heat exchangers of the marine ORC prototype (condenser and subcooler) were modelled based on data from manufacturers and collected data during the prototype commissioning. For the rest of the system's components, ecoinvent v3.6 database was used along with a number of assumptions, the most important of which are listed below:

- Refrigerant losses due to leakages are estimated to be 2% on annual basis (Heberle et al. 2016, Koronaki et al. 2012).
- Given that the lubricant is mixed with the refrigerant during operation a 2% annual loss is also considered for the lubricant on both the cases of pump and expanders.
- Maintenance is neglected, as it is mainly considered to involve the refrigerant refilling, already considered within the respective fluid listing. Furthermore, maintenance issues are mostly assigned to the ICE itself, which is common for the investigated and the reference system. In this framework, the ORC hosts cathodic protection to address the issue of corrosion due to the utilization of seawater, thus preventing the main cause of failures and maintenance for the ORC. Moreover, the two shell and tube heat exchangers (condenser, subcooler) of the system have a seawater resistant design, with tubes made of copper nickel 90-10, to minimize corrosion mechanisms with the seawater.
- The ICE was modeled based on an existing dataset in ecoinvent and appropriate scaling. For the scale of the marine ORC, the corresponding ICE capacity was equal to 150 kWe.
- As cooling water in the condenser and the subcooler are both rejected back to the sea, no water consumption was considered in the respective components use phase. Freshwater of the hot side of the evaporator is circulating in a closed loop, therefore apart from subsystem filling, no further water consumption takes place during use phase.
- With respect to the reference system, no water consumption is considered during use phase as the jacket water heat rejection is realized via a heat exchanger using seawater which is then rejected back to the sea, similarly to the ICE-ORC.
- The plate heat exchanger (evaporator) consists mainly of stainless steel, copper and brass, while the consumed energy for its manufacturing was assumed to be 0.4014 MJ/kg (Adolfsson and Rashid 2016).
- The pump was considered to be made of 21 kg of brass, 20.3 kg of stainless steel (pump's metallic head) and 1 kg of lubricant. Secondary materials were neglected due to significantly smaller masses.
- With respect to the two scroll expanders, they were disassembled and weighed before the system's commissioning. The main body was made of stainless steel (31.6 kg per expander). 0.3 kg of lubricant was also measured per expander.
- For the calculation of the diesel consumption by the ICE, the fuel oil specific consumption of ship diesel engines was taken equal to 181 g/kWhe (Pallis et al. 2021). The rest data for the use phase is presented below in **Table 2**. At this point has to be clarified, that the waste heat recovery is considered to not influence the fuel oil specific consumption.

Table 2: Use phase data, based on Pallis et al. (2021)

Operating hours per year	ORC average electrical efficiency (%)	Average ORC net power output (kW)	Annual ORC power production (kWh)	ORC/ICE power ratio	Annual fuel savings (kg of fuel oil)
6252	4.51	4.06	25123	2.68 %	4365.5

- All transportations were considered from the manufacturing site, each of the prototype’s components was actually sent to the installation site of the prototype in Athens. Most components were constructed within Greece, with the exception of the scroll expanders sent from France, the diaphragm pump manufactured in the United Kingdom and the R134a which is produced in the Netherlands. All international transportations were considered to be realized with >32 metric tons lorries; all domestic transportations were realized with <3.5 metric tons lorries.
- Metals are assumed to be fully recovered, while non-metals are considered to be combusted at the end of their life. For the refrigerant R134a, in accordance with ecoinvent, 90% is assumed to be recovered, while the rest 10% is combusted (Lenova 2018, Roumpedakis et al. 2020a).

3.3 Impact assessment

For the midpoint level, the ReCiPe 2016 Midpoint v.1.02 was used as a commonly applied impact assessment method. On endpoint level, ReCiPe 2016 Endpoint v.1.02 was selected, respectively.

4 RESULTS

4.1 Comparison to reference

In the base case scenario, the considered ICE-ORC system is compared with the operation of the ICE at higher loads to cover the power production by the operation of the ORC. This comparison targeted to identify the key challenges of the ORC system, at prototype level, to out-perform on environmental basis the conventional ICE. In fact, the results at midpoint level (**Figure 2(a)**) show that despite the large amounts of materials used for the construction of the ORC system, the avoided fuel oil consumption results in an improvement in 10 out of 18 impact categories. The largest improvement is identified in the categories of fossil resource scarcity, ionizing radiation and ozone formation in terrestrial ecosystems, which record an improvement of 2-3% mainly due to avoidance of the fuel oil combustion and the respective emissions. As the oil savings by the use of the ORC account for only 2.7% of the total oil consumption on annual basis and an additional footprint is added by the R134a, the effect in the, highly sensitive to fossil fuel emissions, global warming and ozone depletion categories is minimal. This small improvement of 1% in the aforementioned categories comes in agreement with other relevant studies in literature (Walsh and Thornley 2012, Wang et al. 2015) and highlights the necessity for a scale up of the system, which could possibly enhance its environmental performance due to both reduction in materials per kW of produced power as well as the enhanced efficiencies (Pallis et al. 2021). The absolute values of some key impact categories for the two systems on midpoint level are reported in **Table 3**.

On the other hand, the use of ferrous and (mainly) non-ferrous metals for the realization of the ORC has a negative effect in categories, directly affected by metal use and the corresponding emissions, including freshwater, marine and terrestrial ecotoxicity (Liu et al. 2013).

With respect to endpoint level, a similar performance can be observed in **Figure 2(b)**. In all three categories, the ICE-ORC has a better performance than the reference system, however the improvement is between 1-2.7%. In human health and ecosystems, the improvement by only 1%, is mainly affected by the global warming and ozone depletion categories and the corresponding high fuel oil consumption. The largest improvement is identified in the resources category, with a 2.7% decrease compared to the reference, which is mainly attributed to the oil reduction. The respective absolute values on endpoint level are reported in **Table 4**.

Table 3: Quantitative results of impact assessment for ICE-ORC system and reference system per functional unit for key impact categories, at Midpoint Level

Impact category	**ICE-ORC system**	**Reference system**
Global warming (kg $CO_{2,eq}$)	1.857	1.863
Stratospheric ozone depletion (kg CFC-11_{eq})	$3.32 \cdot 10^{-6}$	$3.35 \cdot 10^{-6}$
Water consumption (m^3)	$4.73 \cdot 10^{-3}$	$4.74 \cdot 10^{-3}$
Fossil resource scarcity (kg oil_{eq})	4.12	4.23
Mineral resource scarcity (kg Cu_{eq})	$6.35 \cdot 10^{-3}$	$6.04 \cdot 10^{-3}$

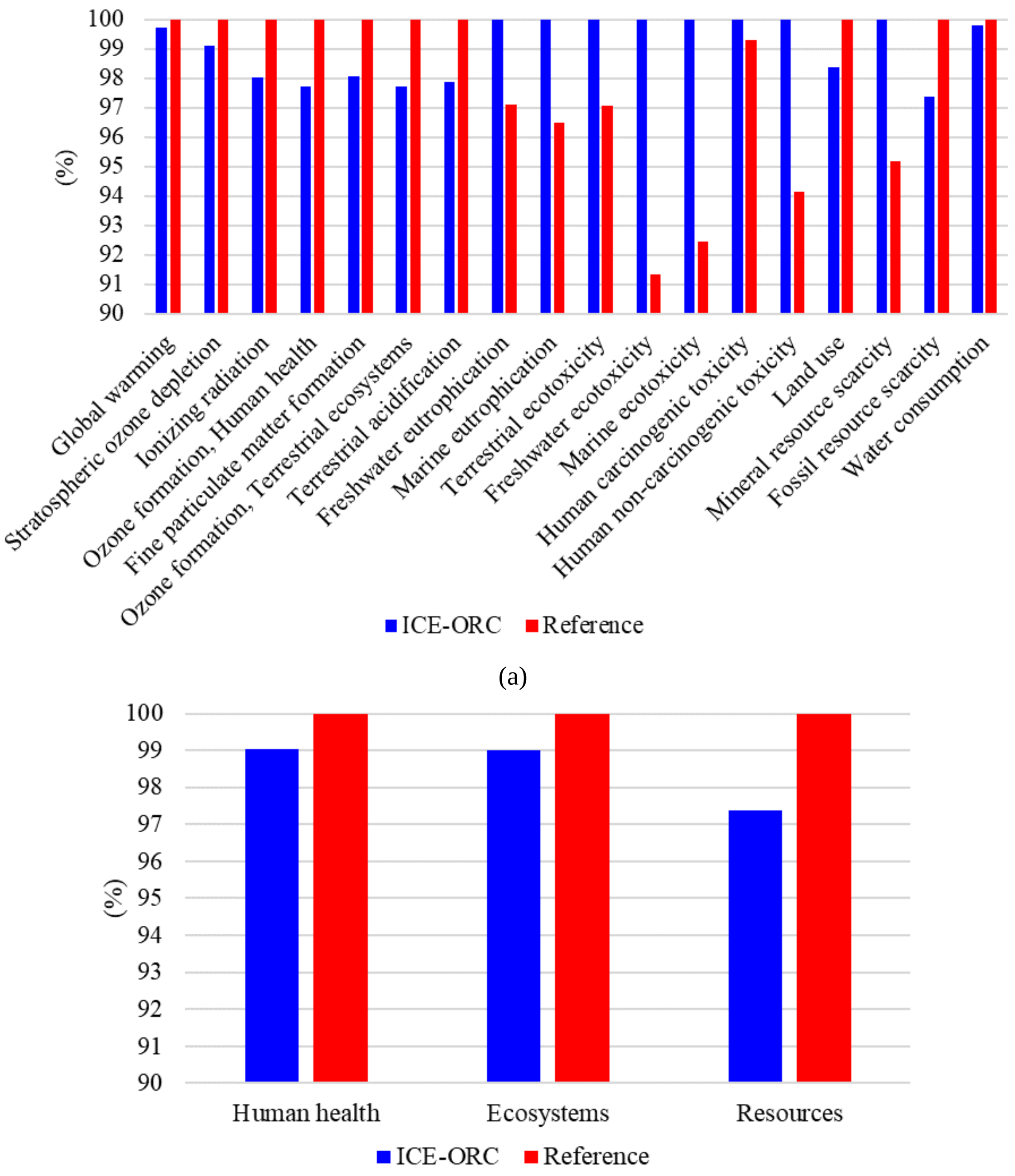


Figure 2: Comparative Impact Assessment results of ICE-marine ORC system in respect with the reference ICE using (a) Midpoint Level and (b) Endpoint Level.

Table 4: Quantitative results of impact assessment for ICE-ORC system and reference system per functional unit for key impact categories, at Endpoint Level

Impact category	ICE-ORC system	Reference system
Human health (DALY)	$5.44 \cdot 10^{-6}$	$5.49 \cdot 10^{-6}$
Ecosystems (species.yr)	$9.96 \cdot 10^{-9}$	$10.06 \cdot 10^{-9}$
Resources (USD2013)	1.85	1.90

4.2 ORC breakdown

Looking deeper into the comparison of the marine ORC with the ICE, it is worth analyzing the contribution of the ORC's components in the total impact of the prototype over its entire life cycle, as shown at midpoint level in **Figure 3** and at endpoint level on **Figure 4**. In this analysis, the ICE and consequently the emissions related to the waste heat generation are excluded from the inventory. The exclusion of the ICE was dictated by the scale of the ORC prototype, which accounts for only a small fraction of the combined ICE-ORC system as was clearly shown by the results of section 4.1. As expected, the use of R134a, with a global warming potential (GWP) of 1430 (Roumpedakis et al. 2020b), results in a 77.6% share in the global warming category, shown in **Figure 3**. On the other hand, the 91% share of R134a in ozone depletion is mainly due to the emissions of R113 and R124 during the life cycle of R134a (Greening and Azapagic 2012) Both R113 and R124 are intermediate products, during the production of R134a, according to the used dataset of ecoinvent (Heck and Moreno Ruiz 2011).

Despite the substantial impact of the refrigerant, the system was, firstly, constructed in 2015 when low-GWP refrigerants and compatible commercial components, such as valves, were scarcely available. Besides, the retrofit of the unit to operate with an environmentally friendly refrigerant would require major modifications such as the replacement of components and piping in order to maintain proper flow conditions. Finally, R134a replacements such as R1234yf and R1234ze(E) are classified as A2L refrigerants, exhibiting flammability issues which, by the time of construction, made them inappropriate for a marine environment. With respect to global warming, the pump's motor and the two generators have also a considerable impact, with a 15.2% share. This is due to the large metal masses of these components, with a total metal mass of 172 kg, in comparison to the 97 kg of the heat exchangers, the 41 kg of the pump and the 32 kg of the scroll expanders. The large masses of electrical steel and copper used in the construction of the system's motor/generators result in large shares on the total impacts on most categories ranging between 30-70%. The considerable mass of the heat exchangers results in high contributions also in several impact categories. The comparable contribution to the motor/generators of approximately 32% of the total impact in freshwater, marine and terrestrial ecotoxicity is mainly justified by the higher copper content in the heat exchangers (Huijbregts et al. 2016). Finally, pump and scroll expanders account for approximately 10-15% each, on categories such as mineral resource scarcity and terrestrial ecotoxicity, due to their brass content (Meshram et al. 2021).

On endpoint level, the high impact of R134a in global warming and ozone depletion, result in 37.7% and 59.2% shares in human health and ecosystems impact categories, respectively. The large metal mass of motor/generators result in a considerable contribution in human health and ecosystems impact categories, with a share of 30.1% and 21.8%, respectively. Moreover, the high metal content of generators/motor results in a 55.41% contribution on resources, followed only by the 23.8% of the diaphragm pump. Ultimately, scroll expanders account for up to 5% contribution with respect to resources and human health, implying the low impact of the two expanders configuration on the environmental footprint of the system. Given that the relative contribution is considered, even the use of a –fictitious– single machine would not halve their influence, supporting this assertion.

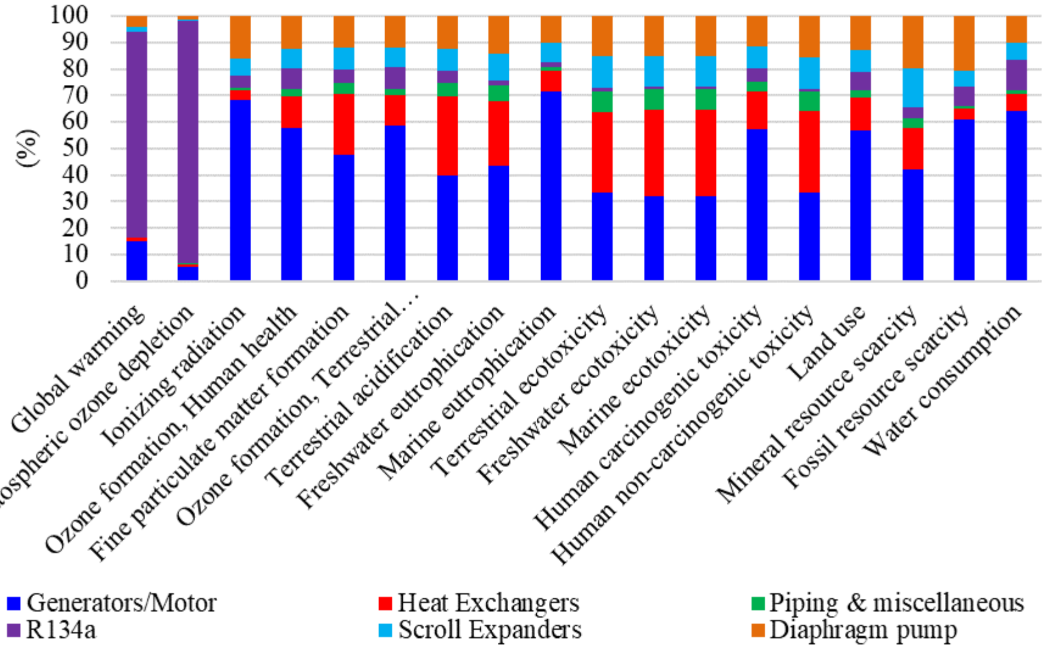


Figure 3: Components contribution on overall results of marine ORC prototype at Midpoint Level.

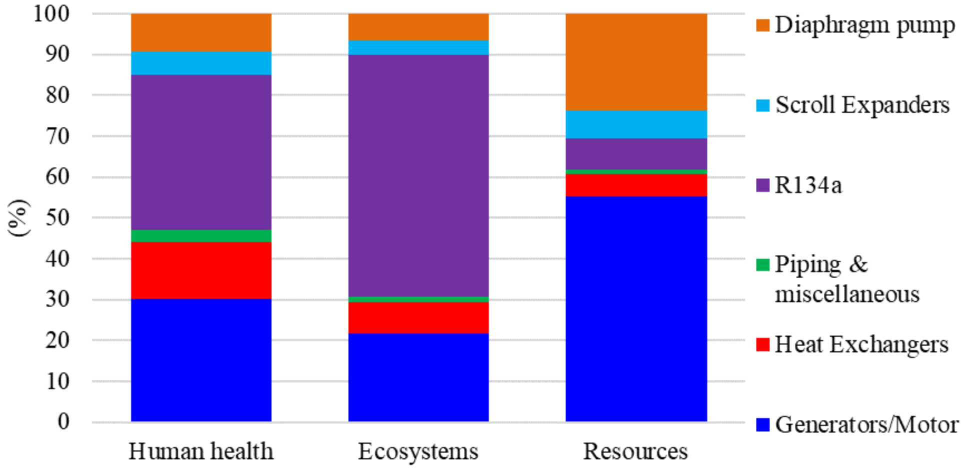


Figure 4: Components contribution on overall results of marine ORC prototype at Endpoint Level.

5 CONCLUSIONS

In this study, the life cycle analysis of a small-scale ORC prototype was investigated. The system was designed for WHR from jacket water of marine ICEs. The analysis was based on data collected during the commissioning of the system and was analyzed in Simapro software. The main conclusions of the study are summarized below:

- The reduced oil consumption by the introduction of the ORC leads to an improvement in both midpoint and endpoint level. However, the improvement is in the range of 1-3% due to the high contribution of the ICE and the corresponding oil consumption in the overall system’s impact.
- With respect to the ORC components contribution, the working fluid R134a has a 78% share in the global warming impact category and a 91% in ozone depletion.
- In most midpoint level impact categories, the motor/generators have the largest share of up to 70% of the total ORC’s contribution.
- At endpoint level, R134a has a 38% and 59% share in human health and ecosystems impact categories, respectively. On the other hand, motor/generators have the largest contribution in the resources category with a value of 55%.

- The large contribution of R134a on global warming and ozone depletion dictates the evaluation of a fluid replacement towards the optimization of the system's environmental performance.
- The ORC system scale-up is expected to enhance the environmental performance of the ICE-ORC system due to further reduction in fuel oil consumption, as suggested also in other relevant studies (Wang et al. 2015, Pallis et al. 2021).

NOMENCLATURE

Abbreviations

GHG	greenhouse gas
GWP	global warming potential
ICE	internal combustion engine
LCA	life cycle analysis
ORC	organic Rankine cycle
WHR	waste heat recovery

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