Journal of Engineering and Sustainable Development
https://jeasd.uomustansiriyah.edu.iq/index.php/jeasd
https://doi.org/10.31272/jeasd.27.6.1

Vol. 27, No. 06, November 2023
ISSN 2520-0917

Original Research

AN ENVIRONMENTAL IMPACT ASSESSMENT OF AN ORC-BASED EXHAUST HEAT RECOVERY SYSTEM FOR APPLICATION IN VEHICLES

Julius Thaddaeus[1*], Ikeokwu Innocent Ezeaku[2]

[1]*Federal University Wukari - Nigeria*
[2]*Abia State University, Uturu - Nigeria*
[1]https://orcid.org/0000-0001-6397-8573
[2]https://orcid.org/0009-0008-9030-2227

Received 11/07/2023 ***Revised 06/09/2023*** ***Accepted 13/10/2023***

Abstract: The paper presents the study performed to assess the environmental consequences of a proposed organic Rankine cycle-based exhaust heat recovery system for application in vehicles. A life-cycle assessment of fifteen (15) midpoints and two (2) endpoint levels was performed using the SimaPro database to determine the potential environmental consequences of the main parts of the proposed system resulting from the various raw materials used in these parts. The performance results of the organic Rankine cycle-based exhaust heat recovery system show that it can generate up to 3.10 kW of net power output from the engine exhaust, which otherwise is released into the environment as waste heat, with a thermal efficiency of 6.36%. The life-cycle assessment results show that the presence of steel in these components is responsible for the majority of these environmental consequences. The evaporator showed the highest impact potential, with values ranging from 37% in marine eutrophication to 72% in ionizing radiation. From the two (2) endpoint impact assessments, it is clear that the pump has the maximum human health impact potential of 0.0138 DALY, with the condenser having the lowest contribution of 0.0005 DALY. The evaporator and condenser contribute 2297.25 PDF.m^2.yr and 158.30 PDF.m^2.yr ecosystem quality impact potentials, respectively, as the highest and lowest. Therefore, the organic Rankine cycle-based exhaust heat recovery system has relatively little impact potential on climate change threats, with a value of 1.37E-03 kgCO$_2$.

Keywords: *Environmental impact potential; Exhaust heat recovery; Life-cycle assessment; Long-haul trucks; Organic Rankine cycle*

1. Introduction

Motivated by environmental worries about rising greenhouse gas (GHG) emissions from mainly fossil fuel combustion for power, these emissions have severe climatic repercussions in the form of air pollution and global warming threats. These environmental threats and the need for clean and efficient energies have recently sparked increasing interest in WHR (waste heat recovery) technologies among researchers. Reducing carbon dioxide (CO_2) emissions requires complementary technologies to improve energy efficiency, investigate renewable energies, and implement carbon capture, use, and storage [1–3]. Therefore, increasing renewable energy use and energy efficiency technologies have become critical elements of a better sustainable energy system that can result in an approximately 77% reduction in global CO_2 emissions by 2050 [4]. At the 2012 summit on energy technology perspectives in France [5], participating member states agreed to work towards achieving a decrease of approximately half of the 123 Gt of CO_2 emissions between 2015 and 2050 by

**Corresponding Author*:
thaddeus.julius@fuwukari.edu.ng

utilizing technologies that support clean and efficient energy use.

It is also worth noting that transportation is among the sectors that substantively contribute to global CO_2 emissions. According to reports, the transportation industry accounts for 16.2% of worldwide GHG (greenhouse gas) emissions, with road transportation accounting for 11.9%, causing significant environmental damage. Trucks account for approximately 22% of GHGs in the transportation industry [6], which is the foundation for this study. As a result, capturing a portion of the exergy in this waste stream has immense potential for reducing CO_2 emissions while boosting engine thermal efficiency. The proposed ORC module for the exhaust heat recovery (EHR) system is intended for use in long-haul vehicles [7].

Because of its simplicity and ability to recover energy more effectively from low- to medium-grade heat sources, the ORC (organic Rankine cycle) has been the most investigated WHR technology recently. Due to the quality of heat obtainable in the exhaust gas of vehicle internal combustion engines (ICEs), studies have shown that the ORC system has an immense possibility for successful exhaust heat recovery (EHR) application in the transportation sector [8–12]. The ORC system works the same way as the steam Rankine cycle but uses organic compounds as working fluids instead of the water found in the traditional Rankine cycle. The design of the ORC system is challenging because of the different working fluid alternatives and plant layouts available; consequently, several studies exist on WF (working fluid) and layout selection for optimum operation of the system's components [13–15]. The application of ORC-based EHR systems in the transportation sector has gained increased research interest most recently, owing to their impressive potential in emissions reduction and efficient energy use. These potentials make it imperative to evaluate the overall environmental impacts of this proposed technology before finding its proper way into the global market.

One useful environmental impact assessment tool for this task is life cycle assessment (LCA). LCA has been successfully used to assess the implications of wind farms [16,17], solar power [18], hydropower [19], and refuse-to-electricity [20] on our environment. LCA studies have also been conducted for a variety of ORC-based applications. Stoppato and Benato [21] analyzed the global environmental impact of a cogenerative ORC system attached to a commercial biomass boiler unit, whereas [22] evaluated the LCA of an ORC system that used R-123 as a WF for power production. Lin [23] investigated the environmental consequences and advantages of ORC devices for power generation and wood pellet fuel for electric arc furnaces. The study found that switching from heavy fuel oil to wood pellets minimizes the system's environmental impact. According to a comparative LCA of an osmotic engine and an ORC for electric power generation from a low-temperature heat source [24], an 80% reduction of the environmental implications of these plants can be achieved. To assess their environmental impact, the ORC module, a solid waste incinerator, and the LCA of medical waste were all examined further [25]. Using the LCA process, [26] investigated the environmental implications of an ORC power system for WHR.

The literature review revealed many studies on the application of the ORC plant for WHR and low-grade heat harvest. The review also shows reports on successful environmental impact studies on solar, hydropower, geothermal, and wind power. Interestingly, the consequences of ORC devices on our environment closely relate to the system configuration, the materials used, the WFs, and the size of the power plants [27]. However, for ORC-based EHR systems for application in on-road vehicles, no LCA studies have been reported, making this a challenging topic to carry out via the LCA procedure. Thus, the interest of this study is an ORC-based EHR system for application in on-road vehicles with the following specific objectives: (1) design an ORC-based EHR system for application in vehicles (2) measure the thermal performance of the designed system; (3) carry out a life cycle analysis (LCA) of the proposed system based on ORC sizing data from previous work [7]; and (4) investigate the effects of the LCA results on the heat recovery function of the system.

The goals of this study include to:

i. calculate the environmental LCA of the proposed ORC-based EHR system
ii. determine the system element with the highest impact on our environment
iii. identify how to mitigate these environmental impacts
iv. calculate the net CO_2 emissions reduction of the proposed EHR model

The scope also includes material needs for the building and operation phases of the ORC-based EHR system. The system boundaries comprise the energy flows and materials associated with the building, operation, and disposal stages of the four (4) primary constituents of the proposed ORC module of size 3.10kW net power generation and a 20-year lifespan.

2. Materials and Methods

2.1. Exhaust Heat Recovery System Description

The proposed model is an ORC-based EHR system comprised of a 6-cylinder diesel truck engine with the characteristics listed in Table 1 coupled to an ORC loop composed of the evaporator, recuperate, condenser, pump, radial turbine, and WF tank, as seen in Fig. 1. The model recovers a part of the energy in the exhaust gas stream of long-haul trucks. The exhaust gas temperature is the heat source, which exchanges heat with the WF of the ORC module in the evaporator.

Table 1. Yuchai 7.26l Characteristics, [28]

Item	Specification
Model	YC6A280-30
Displacement $(litre)$	7.26
Stroke/ Bore (mm)	132/108
Compression ratio	17.5
Number of cylinders	6
Number of valves	4
Maximum torque (Nm)	1100
Maximum power (kW)	206

Note: Maximum Torque @ 1400-1600rpm, $_{\text{Power}}$ @ 2300rpm

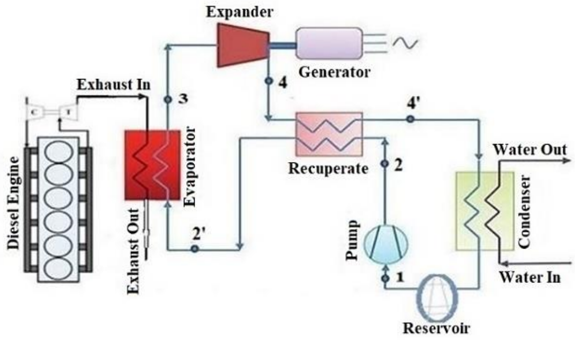

Figure 1. Schematic layout of the ORC Unit

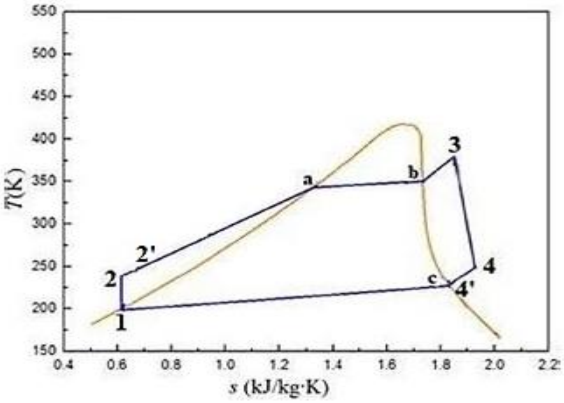

Figure 2. T-S diagram of the ORC System for R245fa Working fluid

The saturated working fluid undergoes an isentropic compression in the pump (*process 1–2*). After being preheated in the recuperator, (*process 2–2′*) enters the evaporator to absorb the thermal energy of the exhaust gas and vaporizes (*process 2′-3*). Subsequently, the high enthalpy working fluid expands in the turbine to the condenser pressure generating power (*process 3–4*). The superheated fluid flows through the recuperator (*process 4–4′*) to the condenser, then condenses back to saturated liquid (*process 4′-1*), and the cycle repeats.

2.2. Mathematical Equations of The Proposed EHR System

The proposed ORC-based system was modeled on GT-suite software with a maximum truck speed of 119km/hr as an input variable to the engine model. The exhaust temperatures and mass flow rates from the engine serve as input variables to the ORC system with R245fa as the working fluid. The technique investigates the WF conditions at each point of the thermodynamic process depicted in Fig. 2, whereas Table 2 displays the mathematical modeling equations for each component of the ORC system.

Table 2. Modeling Equations of the Proposed EHR System

Component	**Performance Equation**
Pump	$\dot{W}_p = \frac{\dot{m}_{wf}(h_{2'} - h_1)}{\eta_p}$
Evaporator	$\dot{Q}_{evap} = \dot{Q}_{in} = \dot{m}_{wf}(h_{2'} - h_3)$
Condenser	$\dot{Q}_{cond} = \dot{m}_{wf}(h_4 - h_1)$
Turbine	$\dot{W}_{turb} = \dot{W}_{wf}(h_3 - h_{4'})\eta_{isen}$
Net Power Output	$\dot{W}_{net} = \dot{W}_{turb} - \dot{W}_p$
Thermal Efficiency	$\eta_{th} = \frac{h_3 - h_4}{h_3 - h_{4'}}$

2.3. Life Cycle Assessment (LCA) of the Proposed EHR System

The environmental impact of the ORC-based EHR system designed for truck use has been studied. Fig. 3 presents a simplified tree representation of the ORC model implemented in the commercial software SimaPro [29]. SimaPro is a highly reliable, global standard, and comprehensive database employed in interpreting the life-cycle assessment (LCA) scores. It was used to build the ORC system and perform the life cycle analysis. The LCA was detailed using ISO Standard series 14040 for principles and standards and series 14044 for requirements and guidance, with four (4) prescribed processes consisting of goal and scope definitions, life cycle inventory, impact assessment, and interpretation.

2.3.1. Life-cycle inventory assessment.

The life cycle inventory evaluation considers all energy inputs, raw materials, and outputs during the EHR system's life. The raw materials used in this study are those used in the evaporator/recuperator, plate condenser, turbine/generator, pump, and ancillary components (WF tank, pipelines, and valves).

The electrical power consumption of the ORC-based EHR system is offset by the power generated by the ORC plant and thus ignored. As a result, the net power generated represents the electrical energy production.

2.3.2. Impact assessment.

The ReCiPe 2016 method [30] was used to identify and analyze 15 (fifteen) midpoints in (Table 3) and 2 (two) endpoints (Table 4) environmental impact indicators. It is an improved LCA evaluation technique for streamlining life cycle inventory outputs into a more consistent number of indicator scores that represent the relative severity of the environmental impact categories.

The midpoint-level indicators are evaluated as follows:

Midpoint characterized value:

$$CV_j = CF_j * x_i \qquad (1)$$

Where CF_j = characterized factor of each category for j

x_i = quantity of each material for j

Midpoint characterized factor:

$$CFm_x = \sum_j CV_j \qquad (2)$$

For the endpoint level indicators, a characterized value of the endpoint (CFe) can be evaluated using each midpoint characterization factor and a midpoint-to-endpoint characterization factor ($F_{m-e,c,a}$), the conversion factor effect concerned with cultural perspective (c) and area of protection (a), as follows:

$$CFe_{X,c} = CFm_{x,c} * F_{m-e,c,a} \qquad (3)$$

The single score indicator (I_s) is assessed using a normalized normalization impact value (Np), a normalization reference value (Nr), a broader context (Bc), a weighting impact point (Wp) indicator, and weighting factor (Wf), as follows:

$$Np_j = \frac{CFm_{x,c}}{Nr_j * Bc_j} \qquad (4)$$

$$Wf_{j,policy} = \frac{CFm_{x,c,reference\ year}}{CFm_{x,c,target\ year}} \qquad (5)$$

$$Wp_j = Wf_{j,policy} * Np_j \qquad (6)$$

$$I_s = \sum_j Wp_j \qquad (7)$$

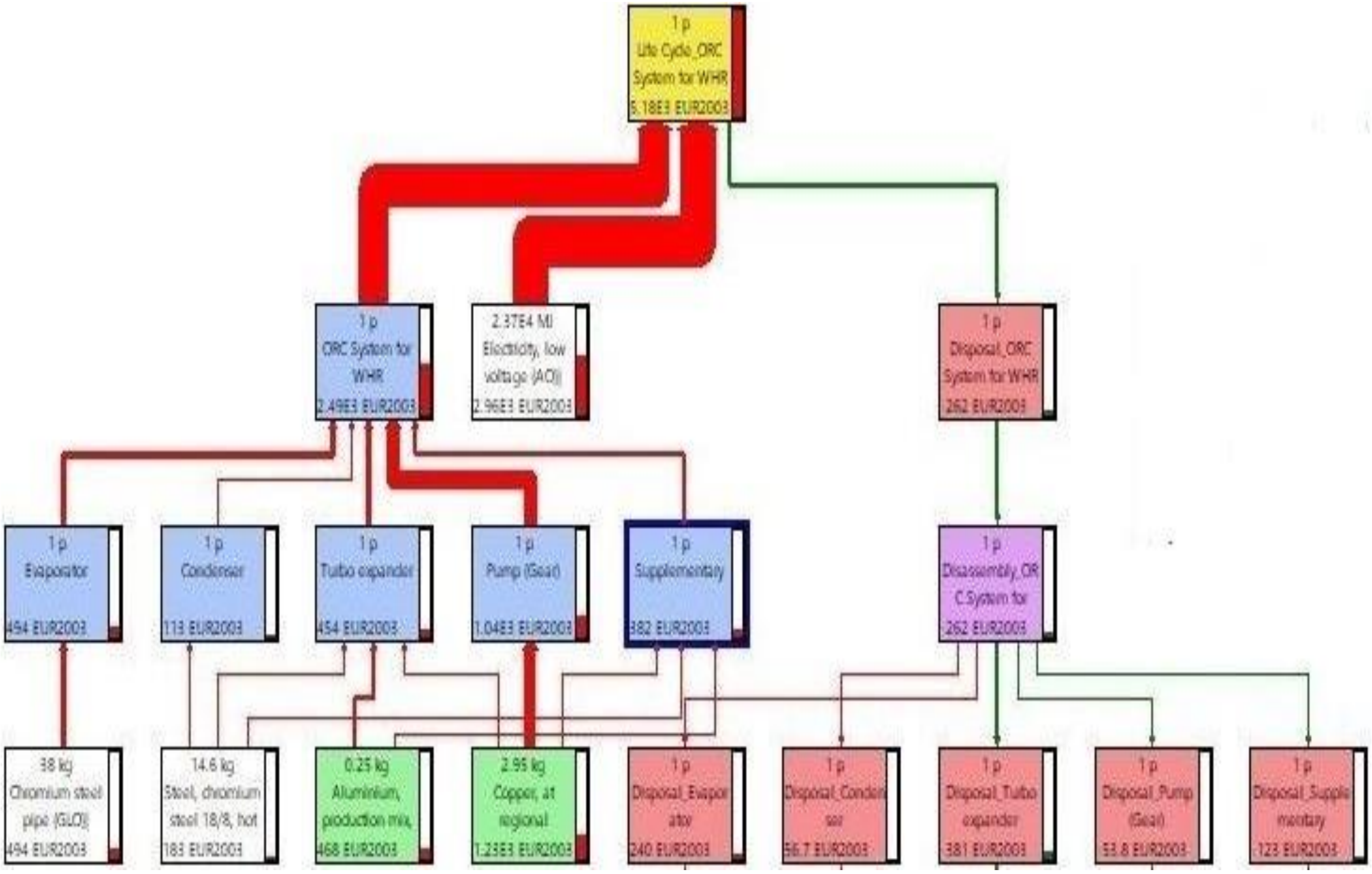

Figure 3. Tree representation of the system in the life cycle analysis

Table 3. Midpoint Impact Categories

Impact Category	**Description** [30, 31]
Climate change, *CC* (kg $CO_{2\ eq}$)	An increase in radiative forcing capacity leads to increases in the atmospheric temperature by the emission of greenhouse gases.
Photochemical oxidant, *PO* (kg NMVOC)	Air pollution causes photochemical reactions of NOx and non-methane volatile organic compounds (NMVOCs).
Ozone depletion, *OD* (kg CFC-11 $_{eq}$)	Anthropogenic pollutants cause ozone layer depletion.
Human toxicity, *HT* (kg 1,4 DCB $_{eq}$)	Some industries use hazardous substances that are dangerous or toxic. The release of these substances into the environment and subsequent exposure affects various species and disease incidences.
Particulate matter, *PM* (kg $PM_{10\ eq}$)	Particulate matter (2.5–10 µm in diameter) of organic and inorganic substances.
Marine acidification, *MA* (kg 1,4 DCB eq)	Massive amounts of absorbed carbon dioxide by the Marine water as carbonic acid leads to a decrease in the marine pH.
Freshwater ecotoxicity, *FE* (kg 1,4 DCB $_{eq}$)	The release of harmful compounds from the power grid and nonferrous metals has effects on the freshwater ecology.

Freshwater acidification, *FA* (kg $SO_{2\ eq}$)	Acidic substances from the emission of nitrogen oxide (NOx) and sulfur dioxide (SO_2) find their way into the freshwater body, thereby affecting the pH level.
Terrestrial acidification, *TA* (kg $SO_{2\ eq}$)	The release of inorganic acids into the atmosphere alters the acidity of soil.
Freshwater eutrophication, *FEU* (kg $P_{\ eq}$)	Accumulation of nutrients in water overstimulates plant growth, which reduces the O_2 level.
Marine eutrophication, *MEU* (kg $N_{\ eq}$)	An increase in nitrogen and/or phosphorus compounds reduces oxygen and water quality.
Ionizing radiation, *IR* (kg $U_{235\ eq}$)	Anthropogenic emissions of radionuclides to our environment are generated in the nuclear fuel cycle, the burning of coal, and the removal of phosphate rock.
Land occupation, *LO* (m^2a)	Biodiversity depends on the size of the area and land use. Fauna and flora are affected by the land occupation.
Land transformation, *LT* (m^2)	Land transformation of natural areas that have a high human intervention, such as urban and agricultural land.
Water availability, *WA* (m^3)	Water-related impacts are dependent upon water consumption for humans and the ecosystem.

Table 4. Endpoint Impact Categories

Impact Category	**Description** [32, 33]
Human health (DALY)	The environmental impacts on human health are responsible for the years of potential life lost due to premature death and the years of productive life lost due to disability relative to standard life expectancy.
Ecosystem Quality (PDF.m^2. yr.)	Detail effects on all living things (Plants, animals, and organisms), interactions with each other, and as well with their natural environment.

2.3.3. Interpretation.

The LCA results are used to investigate the environmental implications of the proposed ORC-based EHR model. Furthermore, the EHR plant's results are compared to other published research to justify this impact assessment study.

3. Results and Discussion

3.1. Orc-Based EHR System Performance

Table 5 shows the setup parameters for the proposed ORC-based EHR module with R245fa as the WF, while Table 6 shows the thermal performance. The suggested system has a net power production of 3.10 kW at 119 km/hr, a thermal efficiency of 6.36%, a CO_2 reduction of 3.07%, an electrical consumption of 0.38 kW, and a power output of 3.48 kW.

Table 5. Simulation Conditions

Parameter	**Condition**
Speed (km/hr)	119
Ambient Temperature (℃)	26.85
Working Fluid flowrate, $\dot{m}_{wf}\ (kg/s)$	0.231
Exhaust Flowrate, $\dot{m}_{exh}\ (kg/s)$	0.123

Cooling Water Flowrate, $\dot{m}_w$ (kg/s)	3.21
Exhaust gas temperature (℃)	461

Table 6. Model Results

Performance Indicator	Value
Power Output (kW)	3.48
Pump Consumption (kW)	0.38
Net Power Output (kW)	3.10
Thermal Efficiency (%)	6.36
CO_2 Savings (%)	3.07

3.2 Inventory Analysis of the ORC-Based EHR System

Table 7 shows the life cycle inventory of the raw materials used in the manufacturing and assembly of the ORC-based EHR system described in the study for long-haul truck applications. Due to a lack of data on the decommissioning phase, this article mainly addressed the environmental implications of building and assembly. The energy consumed by the pump during operation is offset by the electricity generated by the ORC device during the operational phase. The life cycle inventory and environmental impact assessment provided in this study are crucial components of the ORC module.

Table 7. Life Cycle Inventory of the proposed ORC-based EHR System [7], [27]

Component	Part	Raw Material	Quantity (kg)
Evaporator/Recuperator (Shell & tube)	Fitting in & out tubes	Stainless steel	0.16
	Tubes (850mm)	Stainless steel	23.48
	Shell	Stainless steel	11.74
	Extra Canning	Stainless steel	2.62
Plate Condenser	Front & back plate	Stainless steel	0.46
	Plates (300mmx200mm)	Stainless steel	7.85
	Fitting in & out tubes	Stainless steel	0.19
	Fitting tube cooling	Stainless steel	0.52
Turbine/Generator	Turbine + Couplings + Valves	Reinforcing steel	2.80
		Low-alloyed steel	4.62
		Chromium steel	1.01
		Copper	0.27
		Aluminum	0.16
		Iron-nickel-chromium	0.10
		Polyethylene, HDPE	0.10
Pump	Casing, Gear, Axle, Bearing & Shaft seal	Cast iron	22.60
		Copper	4.70
		Polyvinylchloride	0.56
		Synthetic rubber	0.14
Supplementary Systems	Bypass Valve	Stainless steel	3.34
		Copper	0.28
	Piping	Stainless steel	1.22
		Elastomer	0.81
		Steel	11.49
	Tanks	LLDPE	2.07
		Aluminium	0.10
		Elastomer	0.20

3.3 Environmental Impact Potential of the EHR System

Fig. 4 shows the detailed LCIA outcomes of the proposed ORC-based EHR System's main components for each environmental impact category. The raw materials from Table 7 are utilized to interpret the LCIA at the midpoint and endpoint levels evaluated in the SimaPro software, as detailed in this part and the subsequent section. The plotted results show that the presence of steel in the system is majorly driving climate change impact.

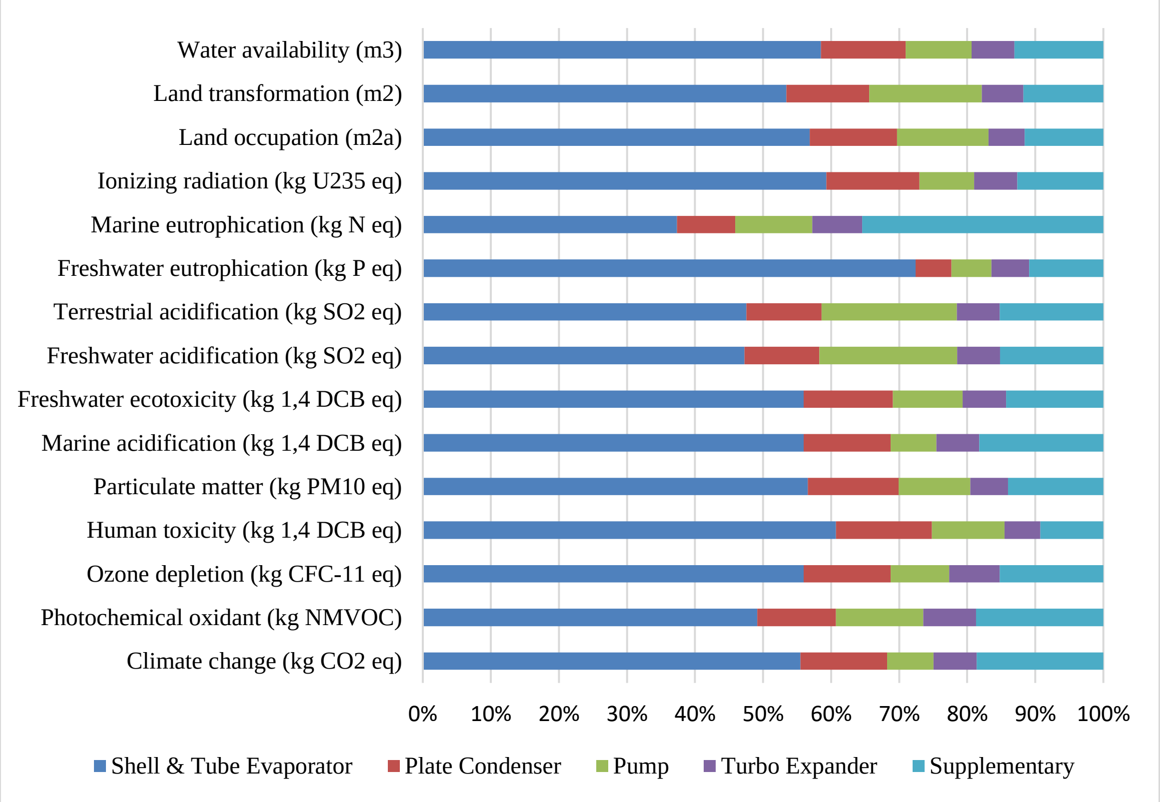

Figure 4. Percentage Contributions of ORC Components of Environmental Impact Categ

The shell and tube evaporator designed in this proposed system is made up of mainly stainless steel and thus accounts for up to 55% of the total climate change impact potential of the model. Next is a 19% contribution from the supplementary system, 13% from the plate condenser, 7% and 6% from the pump and turbine/generator, respectively. These results only point to the evaporator as an area of optimization for climate change impact reduction. Fig. 4 also presents photochemical oxidants as another potential environmental impact category of the proposed system. The plot reveals that 49% of this negative impact is from the evaporator, with 19%, 13%, 11%, and 8% contributed by supplementary systems, pump, condenser, and turbine, respectively. This result indicates that the presence of steel in the evaporator influences the release of photochemical oxidants since the evaporator is mainly composed of steel material and has the highest impact.

The evaporator is also responsible for 56% of the system's ozone depletion impact, followed by supplementary components accounting for 15%, the condenser for 13%, and 9% and 7% from the pump and turbine, respectively. For human toxicity impact with carbon monoxide (CO), NOx, and SO_2 as primary pollutants, the evaporator accounts for up to 61% of the overall potential, followed by the condenser at 14% and the turbine at 5%. The pump and auxiliary components account for 11% and 9% of the overall consequences. Another consequence of the system is the potential harm that terrestrial acidification has on ecosystem quality. The result shows the evaporator component having an impact potential of 48%, while the turbine has the lowest (6%). The impact of the gear pump is 20%, while the supplementary pump and the condenser have 15% and 11%, respectively. The analyzed result also depicts the evaporator component as being responsible for 72% of the entire freshwater eutrophication impact category of the module under consideration, whereas the supplemental, turbine, pump, and condenser components are responsible for 11%, 6%, 6%, and 5%, respectively. In this scenario, the pump and turbine have similar impact potential, with the condenser having the least.

NOx, ammonium ions (NH_4), and nitrate ions (NO_3) emissions are the primary influencers on the EHR system's marine eutrophication impact potential. The evaporator and auxiliary components have close impact potentials of 37% and 36%, respectively, while the pump, condenser, and turbine settled for 11%, 9%, and 7%, respectively. The evaporator accounts for 59% of the EHR system's ionization radiation potential, followed by the condenser (14%), the supplementary (13%), and the pump and turbine (8% and 6%, respectively). Furthermore, the assessment results show that the evaporator accounts for 57% of the land occupation potential, and the condenser and pump account for 13% each. The supplementary parts and the turbine account for 12% and 5% of the total impact, respectively.

This effect is dependent on the spaces occupied by the system's multiple components; consequently, the potential impact is a function of the sizes of these components. The evaporator contributes 53% of the land transformation effect potential, followed by the pump (17%), the supplementary and condenser (12% each), and the turbine (6%). For water availability effects, the evaporator is responsible for 59%, followed by 13% from the supplementary, 12% from the condenser, 10% from the pump, and 6% from the turbine. Interestingly, the result of the water availability impact is that the high water demand by the evaporator occurs at the construction stage and not during the operation phase. Hence, the evaporator construction accounts for up to 59% compared to the condenser, which accounts for only 12%.

Table 8 summarizes the proposed ORC-based EHR system's overall environmental consequences, detailing the total values of the fifteen distinct impact categories studied using the ReCiPe 2016 method from the simaPro software database. Table 8 also shows the overall results of the different impact categories for the main elements of the suggested system.

Table 8. Summary of the Midpoint Environment Impacts of the ORC-based EHR System

Impact Category	Unit	Evaporator	Condenser	Pump	Turbine	Supplementary	ORC System	Total
Climate change	kg CO$_2$ eq	1.68E-04	3.84E-05	2.05E-05	1.92E-05	5.62E-05	1.37E -03	1.67E -03
Photochemical oxidant	kg NMVOC	2.63E-08	6.20E-09	6.85E-09	4.13E-09	1.00E-08	2.56E-07	3.10E-07
Ozone depletion	kg CFC-11 eq	2.29E-08	5.22E-09	3.51E-09	3.04E-09	6.21E-09	3.35E-07	3.75E-07
Human toxicity	kg 1,4 DCB eq	1.16E -03	2.69E -04	2.04E -04	1.01E -04	1.77E -04	2.87E -04	2.20E -03
Particulate matter	kg PM$_{10}$ eq	2.16E -04	5.07E-05	4.02E-05	2.11E-05	5.34E-05	1.14E -03	1.52E -03
Marine acidification	kg 1,4 DCB eq	3.05	6.98E -01	3.66E -01	3.44E -01	9.94E -01	2.52E 01	3.06E 01
Freshwater ecotoxicity	kg 1,4 DCB eq	6.45	1.51	1.18	7.36E -01	1.65	2.27E 01	3.42E 01
Freshwater acidification	kg SO$_2$ eq	1.81	4.19E -01	7.75E -01	2.39E -01	5.81E -01	2.58E 01	2.96E 01
Terrestrial acidification	kg SO$_2$ eq	11.77	2.73	4.92	1.56	3.77	1.64E 02	1.89E 02
Freshwater eutrophication	kg P eq	3.76E -02	2.72E -03	3.03E -03	2.89E -03	5.64E -03	5.92E -01	6.44E -01
Marine eutrophication	kg N eq	1.72E -01	3.92E -02	5.22E -02	3.35E -02	1.63E -01	3.55	4.01
Ionizing radiation	kg U$_{235}$ eq	2.66E-08	6.15E-09	3.62E-09	2.85E-09	5.68E-09	3.25E-07	3.70E-07
Land occupation	m^{2}a	4.27	9.66E -01	1.01	3.99E -01	8.69E -01	1.47E 01	2.22E 01
Land transformation	m^2	1.07E 01	2.43	3.31	1.22	2.36	1.13E 02	1.33E 02
Water availability	m^3	5.77E -03	1.23E -03	9.56E -04	6.19E -04	1.29E -03	7.98E -03	1.79E -02

3.3 Endpoint Impact Potential of the ORC-Based EHR System

Fig. 5 depicts the environmental consequences of the ORC-based EHR system life cycle on the health of humans. This impact category accounts for the years lost owing to early death and the lower quality of life due to illness years as assessed by Disability Adjusted Life Year (DALY) [34]. From the outcomes of this work, the pump, as an element of the EHR system, contributes 0.0138 DALY, the highest impact relative to the others. The turbine comes in second with 0.0058 DALY and supplementary liable for 0.0044 DALY. The evaporator and condenser are responsible for 0.0023 and 0.0005 DALY, respectively.

Ecosystem quality refers to the protection area that accounts for impacts on our natural environment. Fig. 6 presents the results of this endpoint impact potential of the proposed EHR system measured in the Potentially Disappeared Fraction of species (PDF) responsible for species richness that may be potentially lost due to environmental mechanisms, [35]. The result shows the evaporator with the highest impact potential of 2297.25 PDF.m^2.yr, followed by condenser, supplemental, turbine, and pump impact potentials of 528.41PDF.m^2.yr, 410.46PDF.m^2.yr, 202.85PDF.m^2.yr, and 158.30PDF.m^2.yr, respectively.

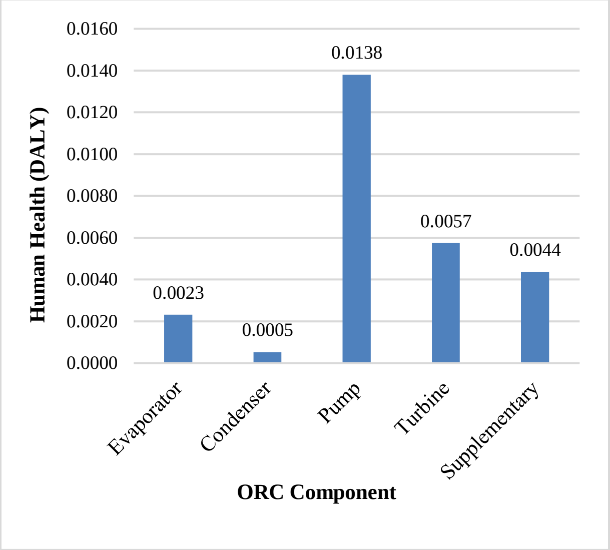

Figure 5. Endpoint Impact of the EHR System on Human Health

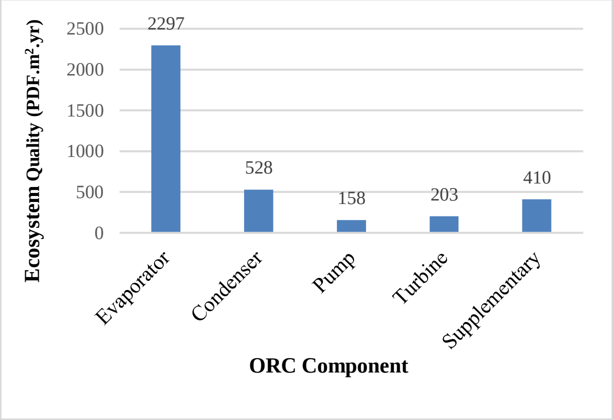

Figure 6. Endpoint Impacts of the EHR System on Ecosystem Quality

3.4 Weighted Impact Potentials of the Proposed EHR System

Fig. 7 presents the normalized and weighted environmental impact potentials of the ORC-based EHR system evaluated to compare the severity of the different impact potentials. The results reveal that terrestrial acidification has the most potential for substantial environmental damage, followed by land transformation and freshwater ecotoxicity. Others include marine and freshwater acidification, as well as land occupancy. The plot shows that the rest has little or no significant impact potential.

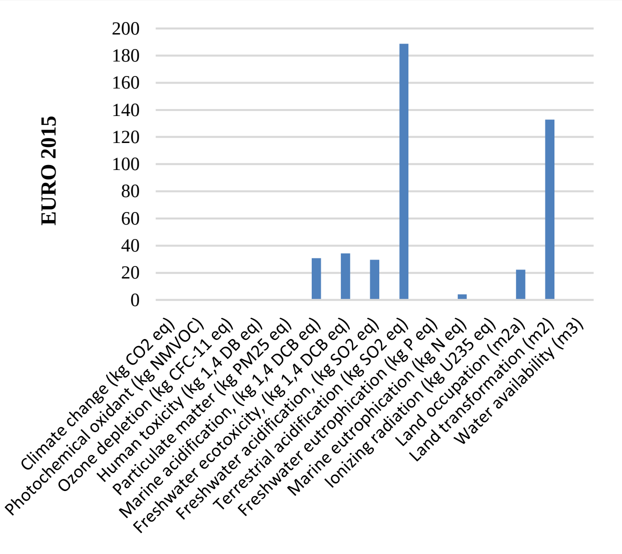

Figure 7. The Weighted Impact Potential of the EHR System

4. Conclusions

The study developed an environmental impact model of an ORC system proposed for EHR implementation in on-road vehicles for the functional environmental consequences description. GT-Suite and SimaPro software were utilized for developing the ORC and the LCA models, respectively. The thermal performance of the proposed ORC-based EHR system achieved includes net power generation of up to 3.10 kW from the exhaust heat of long-haul truck engines, with 6.36% thermal efficiency, and 3.07% CO_2 savings. According to the LCA results, the evaporator is the highest contributor to the system's midpoint-level impact categories, while the condenser, turbine, and pump exhibited varying contributions behind the evaporator in different impact categories. Human health: 2.57E-02 DALY; and ecosystem quality: 2.34E-04 PDF.m^2.yr is the endpoint effect level results. The normalized and weighted results showed a relatively small climate change impact category. This demonstrates that the negative environmental impacts of the proposed ORC-based HER system cannot undermine its intended exhaust heat recovery aim. However, the study showed high terrestrial acidification potential.

Acknowledgment

Not Applicable

Abbreviations

CC	climate change
CO	carbon monoxide
CO_2	carbon dioxide
EHR	Exhaust Heat Recovery
FA	freshwater acidification
FE	freshwater ecotoxicity
FEU	freshwater eutrophication
GHG	greenhouse gas
H_2S	hydrogen sulfide
HCl	hydrogen chloride
HDPE	high-density polyethylene
HT	human toxicity
ICEs	internal combustion engines
IR	ionizing radiation
ISO	international organization for standardization
LCA	life cycle assessment
LLDPE	linear low-density polyethylene
LO	land occupation
LT	land transformation
MA	marine acidification
MEU	marine eutrophication
NH_4	ammonium ion
NO_3	nitrate ion
NOx	nitrogen oxide
O_2	oxygen
OD	ozone depletion
ORC	organic Rankine cycle
PDF	potentially disappeared fraction
PM	particulate matter
PO	photochemical oxidant
SO_2	sulfur dioxide
TA	terrestrial acidification
t-s	temperature – entropy
WA	water availability
WHR	Waste heat recovery

Greek symbols

$\dot{m}_r$	Mass flow rate [kg/s]
$\dot{W}$	work done [kW]
h	Enthalpy [kJ/kg]
η	Efficiency [%]

Subscripts

cond	condenser
evap	evaporator
exh	exhaust
p	pump
in	Inlet
out	Outlet
th	Thermal
turb	Turbine

Conflicts of Interest

The authors declare that they have no competing interests.

Authors' Contribution Statement

i. Julius Thaddaeus: Conceptualization
ii. Ezeaku Ikeokwu Innocent: Work design

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