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Review article

A review of conventional and exergetic life cycle assessments of organic Rankine cycle plants exploiting various low-temperature energy resources

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ABSTRACT

The importance of organic Rankine cycle (ORC) plants to the development of future energy infrastructure is widely acknowledged, due largely to their ability to exploit low-temperature thermal energy sources such as industrial waste heat and renewable energy resources. In this regard, different schemes are being proposed in the literature for the technical and economic developments of ORC plants. Also, the environmental feasibility assessments of ORC-based energy systems have been gaining gradual attention recently, but relative to the technical and economic aspects, the life cycle assessment (LCA) studies on ORC are at an infancy stage. It is therefore aimed in this study to systematically review and collate in a single document, the conventional and exergy-based life cycle assessment studies applied to ORC plants. Doing so, it was found that less than 3% of the over 7000 documents available on ORC in the SCOPUS database analyzed the environmental impact. Also, the ecoinvent was observed as the LCA inventory database most frequently in use, usually in the SimaPro software. Additionally, literature data revealed that the choice of the organic working fluid and the consideration of its leakage over the plant's lifetime have significant effects on the environmental impacts of ORC plants. Moreover, the common methods of conducting the exergy-based LCA (exergoenvironmental analysis) of ORC plants are succinctly reported in this manuscript, including the definitions of the most relevant exergoenvironmental performance metrics. It is hoped that this effort would spur the inclusion of LCA in future analyses of ORC plants, towards the achievement of a more sustainable energy conversion technology.

1. Introduction

The adverse effects of the global reliance on traditional energy systems powered by fossil fuels now live with us today; global warming, wildfire, poor air quality, and shorter human life span are commonplace in the 21st century (Barbir, Veziroğ;lu, & Plass, 1990). To avert the looming environmental tragedies due to the aforementioned effects, the international community has been focusing on the development of several decarbonization strategies towards a cleaner energy infrastructure (Chaubey et al., 2013). In this regard, the use of renewable energy resources such as the sun, wind, geothermal energy, hydropower, etc has been gaining solid traction in almost all the countries of the world (Ellabban et al., 2014). It is however generally believed that more research efforts should still be geared towards the improvement of renewable energy systems, which places this study in the right perspective. Specifically, there is a need to reduce cost, increase reliability, and ultimately increase the commercialization of most renewable energy systems (Islam et al., 2018; Lehtola and Zahedi, 2019; Niu et al., 2019), if they would compete favorably with conventional energy systems.

One conversion technology that is currently in the limelight for potential profitable exploitation of renewable energy sources is the organic Rankine cycle (ORC). It is a Rankine cycle that uses an organic working fluid in place of the conventional water (Ennio and Astolfi, 2016). The organic working fluids have a lower boiling temperature than water, so the ORC is better suited for low-temperature energy sources, which can't easily vapourize water for expansion in the turbine. The basic ORC configuration has four main components; the pump, which increases the pressure of the liquid working fluid; the evaporator, which exchanges heat between an external source and the system to vapourize the high-pressure organic working fluid; the turbine, which expands the high-temperature, high-pressure working fluid for electricity generation and pressure reduction; and the condenser, which removes heat from the low-pressure working fluid leaving the turbine, to change its phase back to liquid at the pump inlet, and the cycle repeats (Tartière and Astolfi,

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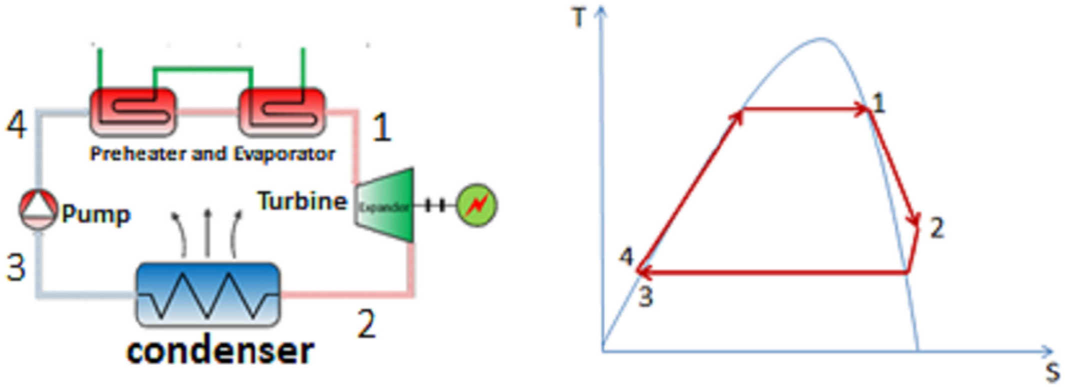

Figure 1. A basic ORC scheme and its Temperature-Entropy diagram.

2017). Figure 1 illustrates these basic processes of the ORC plant. Apart from its versatile application in renewable energy systems, ORC is also very useful for recovering and utilizing waste heat from several industrial processes (Campana et al., 2013; Mahmoudi et al., 2018; Tchanche et al., 2011).

A lot of research efforts have been made in the literature towards the improvement of ORC plants (P. Liu, Shu and Tian, 2019; Manfrida et al., 2018). In a bid to improve efficiency, authors have proposed several advanced schemes applied to the various low-temperature energy sources (Ge et al., 2018; Jang and Lee, 2018; Petrollese et al., 2018; Radulovic and Beleno Castaneda, 2014). Additionally, the optimization attempts in the literature have also considered the economic and environmental performances (Cioccolanti et al., 2019; Gerber and Maréchal, 2012; Oyekale et al., 2019). However, the research on the life cycle assessment of ORC plants remains scattered, with no unified information on the most viable method to be adopted in this regard. To address this, it is aimed in this paper to review the various conventional and exergetic life cycle assessments (LCA) reported in the literature on ORC plants. It is believed that such a review paper can spur the consideration of environmental impacts of ORC plants in the future, thereby improving sustainability. The specific questions that guided the structure of this review paper are:

- How much do researchers embrace the environmental feasibility assessment of ORC plants based on LCA?
- What life cycle impact assessment (LCIA) and computational tools are commonly employed in the literature for the LCA of ORC plants?
- How is the exergy-based LCA of ORC plants commonly approached in the literature?

The methodology adopted in the search of relevant published articles is summarized in section 2, followed by the synthesis of conventional LCA of ORC plants in section 3, the synthesis of exergy-based LCA studies in section 4, the authors' outlook in section 5, and the conclusion in section 6.

2. Methodology

The systematic quantitative approach of the literature review was employed in this study. It involves four distinct stages: the planning stage, the filtering stage, the clustering stage, and the reporting stage (X. Liu, Falcone and Alimonti, 2018). The search scope is set in the planning stage, which includes the definition of the search keywords, the search engine, and the year bracket of studies. The SCOPUS advanced search engine was used in this study, using the following keywords:

i. Organic Rankine Cycle (ORC) Life Cycle Assessment (LCA)
ii. Organic Rankine Cycle (ORC) Environmental Impact Assessment
iii. Exergo-environmental Assessment of Organic Rankine Cycle (ORC) Plants

No year limitation was set for the search, and the afore-listed keywords yielded 80, 124, and 5 documents, respectively, most of which were published in the last 10 years.

The filtering stage of the systematic quantitative literature review entails the setting of inclusion and exclusion criteria to filter out the irrelevant studies obtained from the literature search. In this paper, the keywords and abstracts of the various studies were skimmed and the papers that simply calculated carbon emissions without due recourse to the LCA approach were excluded. Also, the several papers that overlapped from the keywords searched were sought and reconciled at this stage.

The clustering stage involves grouping the studies with similar scopes and themes that can be discussed together. In this study, all the papers that employed the conventional LCA approach were grouped and separated from those that studied exergy-based LCA of ORC plants. Also, studies were grouped based on the type of heat source that powers the ORC, both for the conventional and exergy-based studies.

Finally, the grouped sub-themes are employed as sectional headings and sub-headings to document the state of the art of the topic in the reporting stage. In this paper, the above-mentioned groupings in the clustering stage are the basis for the organization of sections 3 and 4 below.

3. Conventional life cycle assessment of ORC plants

The conventional LCA of any system would generally involve four main steps ("Environmental management — Life cycle assessment — Requirements and guidelines," n.d.): (i) definition of goal and scope of the study; (ii) life cycle inventory (LCI) analysis; (iii) life cycle impact assessment (LCIA); and (iv) interpretation of results. The details of these steps are summarized in the following paragraphs.

In the goal and scope definition step, the functional unit (FU) and study boundaries should be clearly stated. The functional unit is often tied to the purpose of the overall system under investigation, usually scaled down for easy analysis. In the case of an energy generation system, the FU could focus on the generation of 1 kWh of electric power from the retrofitted geothermal system. The boundary is used in LCA to represent the scope of production stage/time being considered in the study. It might be one of the following: from cradle-to-grave (from the extraction of raw materials for construction of each system component to disposal of system components at the end of life); cradle-to-gate (raw material extraction to product manufacture, just before product usage); gate-to-grave (from product manufacture to disposal at end of life); and cradle-to-cradle (from raw material extraction to the end of life when waste products are recycled to form raw materials for the same or other products). The most common LCA boundaries are illustrated in Figure 2 ("Example Life Cycle Assessment Stages diagram," n.d.).

In the life cycle inventory (LCI) analysis step, all the flows of materials and energy required to fulfill the study goal (FU) are

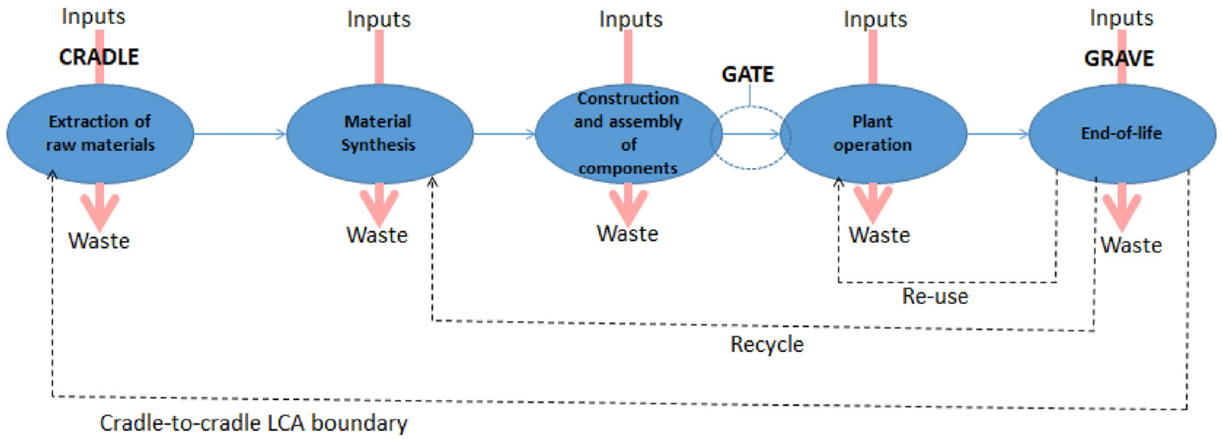

Figure 2. Common life cycle analysis boundaries.

identified and quantified on an input-output basis. The materials and energy flow in reference here include raw materials that would generate useful products/services, the useful products themselves, and waste products, such as emissions. It is the most important and most tasking step in any LCA study, and it requires a vast knowledge of all the processes involved in realizing the set FU. However, a lot of research efforts have been directed into this step of LCA over the years, and enormous open data now exist on common and standard processes in diverse fields. Some of these databases are embedded and dedicated for use in certain LCA programs, while others, adaptable to suit different LCA tools, exist independently. Ecoinvent (Wernet et al., 2016) is the most popular and widely referenced stand-alone LCA database suitable for use in most software as well as in spreadsheets for developing new LCA tools.

In the third LCA step (LCIA), dedicated methods are applied to quantify the impacts that the flow of materials and energy identified under LCI would have on the environment. Similar to the LCI database, most standard software contains a wide range of methods used for impact assessment, and several other new methods are being developed in the literature. For the feasibility studies of the retrofitted geothermal system under discussion, it should be sufficient to use validated life cycle impact assessment methods available in standard software. Several of such impact methods are available in SimaPro ("SimaPro | The world's leading LCA software," n.d.) which is by far the most widely applied LCA software. However, openLCA (Ciroth, 2007), another robust LCA software that is compatible with several impact methods (in-built and imported), is equally gaining wide application in the literature. OpenLCA is particularly popular for its free accessibility, without compromising the level of methodical rigors obtainable in other software. Furthermore, this step of LCA often includes sensitivity analysis, aimed at examining how measured impacts react to certain important variables in the LCA model.

Finally, the impact results are analyzed in step four to interpret the real effects on the environment and to decide on actions to be taken. The main strategies often employed under this step are subjective, depending on the nature of the system under analysis and the study goal. In the case of comparative studies between 2 or more systems or different components of the same system, it is common to normalize the results obtained over the functional unit (per kWh of electricity here, for instance). By so doing, relative environmental impacts could be obtained for different components of a system or amongst different systems. For the components and/or systems with unacceptably high environmental impacts, possible ways of reducing impacts should also be investigated at this stage.

The studies in the literature involving the conventional LCA approach applied to ORC plants are reported in the following sub-sections, grouped based on the heat source type.

3.1. Municipal solid waste and waste heat recovery ORC application

Environmental studies involving ORC application for waste heat recovery applications are reported in this section.

Kythavone and Chaiyat (Kythavone and Chaiyat, 2020) investigated the environmental impact of a small ORC plant fuelled by the combustion of solid medical waste in a municipal solid waste (MSW) incinerator based on life cycle analysis. The goal was to examine the impact of the system on the environment from cradle to grave, for the production of 1 kWh of electricity in Thailand, based on the ReCiPe life cycle impact assessment method. SimaPro software was used for analysis and the life cycle inventory data were obtained from the ecoinvent database embedded in SimaPro. The authors reported very low environmental impact for the investigated ORC based on 18 midpoint and 3 endpoint impact categories, weighted to a single impact point of 0.348 millipoints. Furthermore, results showed that about 87% of the reported environmental impact of the ORC plant was due to the construction of the plant. In another similar study of the same MSW incinerator-powered ORC system, Chaiyat (2021b) extended the investigation to include exergy and economic analysis, but about the same LCA results were reported for the plant. In yet another similar study by Intaniwet and Chaiyat (Intaniwet and Chaiyat, 2017), the authors investigated the LCA-based environmental impact of hybridizing hyacinth solid wastes with the municipal solid waste in 50-50 ratio, as fuel for a 20 kW ORC plant in Thailand. Reports showed that 0.6078 kg of CO_2-eq is emitted for the production of 1 kWh of electricity from the ORC plant, with a levelized electricity costing per carbon dioxide intensity that is about 20% lower than what obtains in the country from standard energy plants.

Uusitalo et al. (Uusitalo et al., 2016) applied the LCA method to investigate the possibilities of reducing greenhouse gases from biogas engines by recovering the exhaust gases for electricity production by ORC plants. Comparing two scenarios, with and without ORC for waste heat recovery from biogas engine for further electricity generation, the authors reported that between 280 and 820 tCO_2,eq could be reduced per annum with ORC waste heat recovery. Similarly, Walsh and Thornley (Walsh and Thornley, 2013) estimated the quantity of greenhouse gas emissions that could be reduced by recovering waste heat in a coke production process industry, for electricity production with an ORC plant. The authors reported the possibility of cutting about 11 kt CO_2 per annum with the ORC waste heat to the electricity process. Lin et al. (2016) assessed the environmental impacts of integrating the ORC plant for waste heat recovery in the electric arc furnace steel industry, in comparison with the use of wood pellets instead of heavy oil in the business-as-usual scenario. Ecoinvent database and real plant data were used for inventory analysis and the ReCiPe method in Simapro software for the life cycle impact assessment (LCIA). The authors reported that integration of an ORC plant for heat recovery and electricity generation in the electric arc furnace steelmaking industry would reduce environmental impact on human health by 2.3% relative to the business-as-usual scenario, and it would reduce the total endpoint scores by about 1.3% (0.27 points). Bacenetti et al. (Bacenetti et al., 2019) equally applied the LCA approach to investigate the environmental sustainability of biogas-powered combined heat and power (CHP) plants when ORC is integrated to recover waste heat from the combustor and to produce additional electricity. About ten real biogas CHP plants were studied in this context, and results showed that integration of ORC would lead to a reduction in the overall environmental impact by about 1.6–5.8%.

Hickenbottom et al. (2018) used an ORC powered by a generic low-grade heat as a benchmark to compare the environmental feasibility of a new osmotic heat engine (OHE). The study assumed 20 years of operations for the two plants and reported that the ORC plant is more environmentally friendly than the OHE system, although the latter can be employed to decarbonize fossil-fuelled power plants better than the ORC technology.

Li (2019) studied the environmental impacts of various low-temperature ORC plants using different working fluids. The cradle to grave LCA approach adopted assumed a functional unit of 30 kW of electricity production from the plant. The study investigated particularly the environmental effect of working fluid leakage on environmental impacts of the ORC plants and found that the effects are very significant. Specifically, about 30% of ORC GWP was found to be due to leakage of R227ea working fluid, 28% for R245fa, and 24% for R236ea.

Liu et al. (C. Liu et al., 2013) studied the environmental impacts of ORC plants exploiting low-temperature waste heat energy resources, considering different working fluids. Production of 1 kWh of electricity was taken as the functional unit, and the inventory data were obtained from the literature and the National database in Chine. The contributions of the different phases of the project to the overall environmental impact were in focus in the study, and results revealed that the construction phase contributed the most to the GWP and eutrophication potential of the plant, for all the working fluids considered.

Wang et al. (Wang et al., 2015) investigated the environmental impacts of integrating ORC with cement production lines in China for the generation of electricity from waste heat in cement production processes. Based on the generation of 1 kWh of electricity, the LCA conducted revealed that the ORC plant integration can lead to a reduction in CO_2 emission by 7743–9628 tons for a 4000 t/d cement production process.

The key points from the conventional LCA of municipal solid waste and waste-heat ORC plants are summarized in Table 1.

3.2. Biomass-fired ORC plants

Perilhon et al. (Perilhon et al., 2012) carried out the life cycle analysis of a 2 MW ORC plant fired by woody biomass. The study illustrated the step-by-step approach of conducting LCA. The IMPACT 2002 + LCIA was used in SimaPro to interpret the environmental impacts of the ORC plant, implying that the plant is friendlier to the environment than fossil fuels. The authors also cautioned that default data in software should be used with care in LCA analysis since most of the software are black boxes with closed operational procedures. Ruiz et al. (Ruiz et al., 2018) studied the environmental implication of integrating an ORC plant into a pellet-making plant for combined heat and power (CHP) generation from the combustion of residue woody biomass, among other objectives. Results of the comprehensive LCA showed that the ORC integration had no significant environmental effect on the entire bioenergy process. Although some environmental impact points were scored by the integration, their effects were offset by other production and transportation processes of the ORC component. Furthermore, Stoppato and Benato (Stoppato and Benato, 2020) investigated the environmental impacts and the main activities contributing to these impacts during the life of a biomass-fired ORC CHP plant located in Italy. The inventory analysis employed real data of the operational plant and standard databases such as the Ecoinvent 3. Different LCIA methods were also employed in the SimaPro software for the analysis, yielding that the most significant environmental impacts are due to biomass production and combustion, contributing about 71% of the total impacts. Additionally, the authors reported that leakage of working fluid in the system contributed the second-highest environmental impact at about 19% of the total. Gonzalez-Garcia and Bacenetti (González-García and Bacenetti, 2019) equally analyzed a biomass-fired ORC CHP plant based on a real case study located in Italy. The reported also that biomass combustion is the environmental hotspot for many impact categories evaluated, with the worst impacts on human toxicity and eutrophication.

The key points from the conventional LCA of biomass ORC plants are summarized in Table 2.

3.3. Geothermal ORC plants

Dawo et al. (2021) employed a geothermal ORC plant to compare the potential of replacing the popular R245fa working fluid often used in the design by some low-GWP alternatives. The data of an existing plant in Germany were used for analysis, assuming 30 years plant life. It was obtained that using R1233zd(E) as ORC working fluid instead of the popular R245fa can lead to 67% reduction in CO_2-eq emissions from the system.

Chaiyat (2021a) analyzed a multigeneration system including a 10 kW geothermal ORC plant. The system was assessed for techno-economic and environmental performace, the latter based on the LCA approach. The cradle-to-grave impacts of the system were computed on the basis of enegy and exergy models, obtaining the single-point impacts as 0.0250 Pt and 0.1223 Pt, respectively, for 20 years of plant operation. Very similar results are reported in another article by the same author(s) (Chaiyat et al., 2020), for a similar poly-generation energy system powered primarily by geothermal energy. In the latter study, a new method was derived for assessing the environmental impact of the system based on a single point, obtained as 0.026 Pt. Also, the LCA of combined cooling, heating, and power plant integrating a 10 kW ORC was assessed in another study by the author(s) (Chaiyat et al., 2021), reporting about 0.0631 Pt as the single-point environmental impact of the system.

Gerber and Marechal (Gerber and Maréchal, 2012) compared the environomic performance of 3 different cycle configurations for the production of electricity or cogeneration of district heating and power from an enhanced geothermal system (EGS) in Switzerland. Following the standard LCA procedure for the operation of the plant in 30 years, the authors reported that cogeneration of heat and power in the EGS would reduce environmental impact (CO_2 emission) by about 37% relative to single electricity production.

Fiasch et al. (Fiaschi et al., 2021) conducted a preliminary LCA to compare the impacts of subcritical and supercritical ORC configurations for the exploitation of geothermal energy in Italy. The Ecoinvent database was used in the openLCA software to model the systems. Results showed that a subcritical ORC is likely to have a slightly higher impact (about 3.4%) than the supercritical ORC based on the ReCiPe 2016 Endpoint life cycle impact assessment (LCIA) method.

Heberle et al. (Heberle et al., 2016) investigated the environmental impacts of geothermal plants in Germany based on 1-stage and 2-stage subcritical, and supercritical ORC configurations. The LCA of the different plant configurations were conducted, using as ORC working fluids some so-called low-GWP working fluids such as R1233zd and R1234yf instead of the common R245fa and R134a. Results showed that using R1233zd instead of R245fa in subcritical ORC plants can reduce environmental impact (CO_2-eq) by about 78% and that a 2-stage ORC plant can be more favorable for geothermal plants in Germany.

Matuszewska et al. (Matuszewska et al., 2018) developed an approach for LCA of EGS ORC plants using the Ecoinvent database for inventory analysis and the ecological scarcity (ecoscarcity) LCIA. The study demonstrated how LCA can be integrated with thermo-economic models for robust optimization of planned geothermal plants in Switzerland.

The key points from the conventional LCA of geothermal ORC plants are summarized in Table 3.

3.4. Solar and hybrid solar ORC plants

Ruzzenenti et al. (2014) studied the environmental sustainability of a small-scale ORC CHP plant exploiting solar-geothermal energy resources. The study demonstrated that exploitation of solar-geothermal energy sources by ORC plants is an environmentally-favorable solution in the context of sustainable development, especially in cases where geothermal wells are in existence and previously abandoned.

Cioccolanti et al. (2019) employed the LCA approach to study the environmental performance of a small-scale solar ORC plant rated nominally at 3.5 kW. The environmental impact from cradle to gate was assessed for the plant assuming 20 years of operation. The study identified that the solar multiple (SM) is an important parameter that must be

Table 1. Highlights of conventional LCA of municipal solid waste and waste-heat ORC plants.

ORC Heat Source	LCA FU	Boundary	Inventory Database	LCIA Method	Tool/ Software	Remark	Reference(s)
MSW incinerator burning infectious medical waste	1 kWh of electricity	Cradle to grave, Thailand	SimaPro embedded Ecoinvent	ReCiPe 2016 (Mid-point/end-point)	SimaPro	For a plant life of 20 years, a very small single point environmental impact of 0.348 mPt was obtained for the plant, with the construction phase responsible for about 87 %.	(Chaiyat, 2021b; Kythavone and Chaiyat, 2020)
MSW-Hyacinth combustion	1 kWh of electricity	Cradle to grave, Thailand	SimaPro embedded Ecoinvent	ReCiPe 2016 (Mid-point/end-point)	SimaPro	The study revealed that 0.6078 kg of CO_2-eq is emitted for the production of 1 kWh of electricity from the ORC plant, with about 0.18 kg of CO_2-eq from the combustion of 1 kg of the newly introduced hyacinth fuel.	(Intaniwet and Chaiyat, 2017)
Waste heat from biogas engine	170 kW of electrical power	Cradle to grave, EU	GaBi 6.0 database and literature	GHG emission calculation	GaBi 6.0	For a plant life of 10 years, a scenario whereby ORC is used to produce additional electricity from exhaust gases of a biogas engine led to CO_2 reduction by at least 280 tonnes per annum.	(Uusitalo et al., 2016)
Waste heat recovery in coke production industrial process	1 kg of coking coal	Cradle to grave	NS	GHG emission calculation	SimaPro	Generation of electricity from waste heat could save 11 kt of CO_2 per annum.	(Walsh and Thornley, 2013)
Waste heat recovery from electric arc furnace steelmaking	200 kW of electrical power	Cradle to gate	Ecoinvent	ReCiPe	SimaPro	Based on the ReCiPe LCIA method, integration of an ORC plant for heat recovery and electricity generation would reduce environmental impact on human health by 2.3% relative to the business-as-usual scenario, and it would reduce the total endpoint scores by about 1.3% (0.27 points).	(Lin et al., 2016)
Recovery of waste heat from biogas combined heat and power systems	1 MWh of electricity	Cradle to grave	Real data from plant operators	ReCiPe	SimaPro	Adoption of ORC for waste heat recovery in biogas CHP plants can reduce environmental impacts by about 1.6–5.8%, compared to cases where the waste heat is not recovered.	(Bacenetti et al., 2019)
ORC from a generic low-grade heat source	1 kWh of electrical energy	Cradle to grave	Literature data and GaBi database	TRACI (US EPA)	GaBi	Based on 20 years lifetime of the plant, the authors reported that ORC as a benchmark technology outperformed a new osmotic heat engine technology in terms of environmental feasibility.	(Hickenbottom et al., 2018)
A generic low-temperature heat source	30 kW of electricity production	Cradle to grave	Literature data	Selected indicators (GWP–CO_2–eq, Eutrophication, Acidification, etc)	Excel	The study investigated particularly the environmental effect of working fluid leakage on environmental impacts of ORC plants and found that the effects are very significant. Specifically, about 30% of ORC GWP was found to be due to leakage of R227ea working fluid, 28% for R245fa, and 24% for R236ea.	(Li, 2019)
Generic waste heat ORC	1 kWh of electricity production	Cradle to grave	Literature data and National (Chinese) database	Environmental Toxicology and Environmental Chemical Society; IPCC	NS	The contributions of the different phases of the project to the overall environmental impact were in focus in the study, and results revealed that the construction phase contributed the most to the GWP and eutrophication potential of the plant, based on different working fluids.	(C. Liu et al., 2013)
Waste heat recovery ORC	1 kWh of electricity	Cradle to grave	Literature data and Chinese database	Selected indicators (GWP–CO_2–eq, Eutrophication, Acidification)	NS	The study showed that the aa production of electricity by ORC using waste heat of cement production process can lead to a reduction in CO_2 emission by 7743–9628 tons for a 4000 t/ d cement production process.	(Wang et al., 2015)

NS – not specified.

carefully selected to achieve an environmentally benign solar-ORC plant. It was demonstrated specifically that for the small-scale system assessed in the study, doubling the solar field area from 50 m^2 to 100 m^2 could reduce the environmental impact from 140 μPt/kWh to 104 μPt/kWh.

Liu et al. (S. Liu, Yang, Yu and Li, 2021) assessed the environmental impact of a solar-ORC plant integrated with an ammonia synthesis system based on the LCA. The goal was to quantify the impact of the integrated plant from its design and construction stage to the very end when it is decommissioned and dismantled. Results showed generally low environmental impacts for the integrated plant relative to other ammonia processing technologies. Specifically, environmental impact was obtained at about 0.69 $CO_{2\text{-eq}}$/kg of ammonia, based on the GWP midpoint indicator and at about 0.0000817 pt based on the human health endpoint indicator.

The key points from the conventional LCA of solar and solar hybrid ORC plants are summarized in Table 4.

4. Exergy-based life cycle assessment

The exergy-based LCA, also called exergoenvironmental analysis, fuses the conventional LCA approach with exergy analysis of a system, and environmental impacts are determined for the system based on some pre-defined metrics. This section reports the studies available in the literature on exergoenvironmental analysis of ORC plants powered by different heat sources.

4.1. Municipal solid waste and waste heat recovery ORC application

Ahmadi et al. (Ahmadi et al., 2012) adopted the exergoenvironmental metrics defined by exergy destruction and efficiency to assess an integrated ORC plant generating power, heat, and cooling. A gas turbine originally generates power in the integrated system, and the thermal energy rejected by the gas turbine is exploited by the ORC unit for additional power generation. A single-effect absorption chiller was used for cooling energy generation in the integrated system. The study identified the system parameters that contribute significantly to the environmental impact of the system, listing gas turbine inlet temperature, gas turbine isentropic efficiency, and pressure ratio among such parameters. Additionally, Altinkaynak and Ozturk (Altinkaynak and Ozturk, 2022) employed the same exergoenvironmental metrics to analyze an integrated energy system that can generate power, heat, cooling, and hydrogen. The system parameters were varied and the impacts of such variations of the performance metrics were recorded. Overall, the authors opined that the proposed system has a very low environmental impact with an exergoenvironmental impact factor of only 0.596.

Ding et al. (2018) assessed the exergoenvironmental performance of an ORC plant fired by a generic low-temperature heat source. The study focused specifically on the effect of ORC working fluid on the environmental performance, with due attention given to the working fluid leakage throughout the plant life. The LCA employed the Ecoindicator 99 method to allocate environmental points to the exergy streams. Several working fluids were compared in the analysis, and the main results showed that environmental impacts of the working fluid could be as high as over 75% of the entire plant's impact, depending on the type of working fluid applied. Moreover, results revealed that the contribution of working fluid leakage is substantial and shouldn't be neglected in environmental studies of ORC plants.

Ghorbani et al. (Ghorbani et al., 2020) employed the ecoindicator 99 to apportion environmental impact points to exergy streams in an integrated system comprising a solid-oxide fuel cell, a gas turbine, and an ORC. Here too, the ORC recovers heat from the gas turbine power plant to generate additional power. R407C and R404A were compared as ORC working fluids, and the thermodynamic parameters of the system were taken as decision variables to optimize the exergoenvironmental impacts of the system.

Table 2. Highlights of conventional LCA of biomass ORC plants.

ORC Heat Source	LCA FU	Boundary	Inventory Database	LCIA Method	Tool/ Software	Remark	Reference(s)
Biomass-fired ORC plant	1 MJ of electricity	Cradle to grave	Literature data and software-embedded database	IMPACT 2002+	SimaPro	Wood as fuel for an ORC plant is environmentally benign, especially if the woody fuels are waste products available at no or little cost. It is essential to pay due attention to some default values provided by the software, as some of them could be wrong.	(Perilhon et al., 2012)
ORC CHP plant fired by waste woody biomass from pelletization process	1 MJ of net energy	Cradle to grave	Real plant data and ecoinvent	ILCD	SimaPro	Integration of ORC to the pellet-making industrial process had no significant effects on the entire bioenergy process. Although some environmental impact points were scored by the integration, their effects were offset by other production and transportation processes of the ORC component.	(Ruiz et al., 2018)
An ORC CHP plant fired by woody biomass	1 kWh of electricity production	Cradle to grave	Real-life data from 5 years of operation of the plant located in Italy, and from the manufacturer; Ecoinvent 3; Agri-footprint; USA Input-Output Database; EU and DK Input-Output Database; LCA Food DK	IPCC 2013 GWP100y; ReCiPe 2016; Cummulative Energy Demand (CED); Greenhouse Gas protocol.		Based on the 15 years of plant operation assumed in the study, it was reported that the biomass production process and working fluid leakage contribute the most to the environmental impact of the system, standing at about 90% for both.	(Stoppato and Benato, 2020)
Biomass-fired ORC CHP plant in Italy	1 kWh of electricity production	Cradle to gate	Literature data and software-embedded database	ReCiPe Midpoint (H) 1.12	SimaPro	Biomass combustion was identified as the hotspot for many impact categories evaluated, especially human toxicity and eutrophication which were reported to have the worst environmental profiles.	(González-García and Bacenetti, 2019)

Ochoa et al. (Ochoa, Gutierrez and Forero, 2020) employed the ecoindicator 99 points to examine the exergy-based environmental impact of an ORC generating electricity using the heat recovered from a natural gas-fired internal combustion engine (ICE). The total life cycle of the plant was considered, ranging from the construction stage to the decommissioning phase of the plant. Considering acetone as the ORC working fluid, the study identified the turbine as the component with the highest environmental impact, with impact points of about 3015. In another study (Ochoa, Prada and Duarte-Forero, 2020), the authors extended the exergoenvironmental assessment of the same plant to the advanced method, where exergy-based environmental impacts were attributed to either the internal mechanism of a given component (endogenous) or due to its interaction with other components of the system (exogenous) (Petrakopoulou et al., 2013; Petrakopoulou et al., 2012). The authors identified in the advanced study that environmental impacts of the heat exchangers are mostly endogenous, which positions them as the components with high potential to improve the environmental impact of the system.

Mofrad et al. (Golbaten Mofrad, Zandi, Salehi and Khoshgoftar Manesh, 2020) studied the exergoenvironmental impact of an ORC plant producing electricity from waste heat recovered from an integrated refrigeration cycle. The ecoindicator 99 approach was employed in the LCA phase of the study to apportion environmental impact points to the different exergy streams and system components. Two ORC working fluids, R744 and R744A, were compared, and the effects of system parameters on environmental impacts were assessed for each. Results identified R744A as the working fluid with the highest environmental impact that could be about 32% higher than the average for the system product. The overall environmental impact rate of the system was estimated at 149 mPts/h.

4.2. Biomass-fired ORC plants

Ebadollahi et al. (Ebadollahi et al., 2021) investigated the exergoenvironmental impacts of an integrated combined cooling and power plant employing 2 ORC systems and 2 ejector cooling cycles (ECC). The

Table 3. Highlights of conventional LCA of geothermal ORC plants.

ORC Heat Source	LCA FU	Boundary	Inventory Database	LCIA Method	Tool/Software	Remark	Reference(s)
Enhanced Geothermal System (EGS)	Construction, operation, and dismantling of 1 EGS	Cradle to grave	Literature data and Ecoinvent	Intergovernmental Panel on Climate Change (IPCC) and Ecoindicator 99	NS	The authors reported that cogeneration of heat and power in an enhanced geothermal system would reduce environmental impact (CO_2 emission) by about 37% relative to single electricity production.	(Gerber and Maréchal, 2012)
Geothermal ORC plant	1 kWh of electricity	Cradle to grave	Literature data and Ecoinvent	NS	GaBi	The study obtained that using R1233zd (E) as ORC working fluid instead of the popular R245fa can lead to a 67% reduction in CO2-eq emissions from the system.	(Dawo et al., 2021)
Geothermal ORC plant	1 kJ of net energy	Cradle to grave	SimaPro embedded database	ReCiPe 2016	SimaPro	The environmental impact of an integrated energy system with ORC integrated was correlated to a single point, obtained as 0.0250Pt and 0.1223Pt based on energy and exergy, respectively, for 20 years of plant operation.	(Chaiyat, 2021a)
Geothermal ORC plant	1 kJ of net energy	Cradle to grave	SimaPro embedded database	ReCiPe 2016	SimaPro	A single environmental impact of 0.0250 was reported for a poly-generation system with a lifetime assumption of 20 years.	(Chaiyat et al., 2020)
Geothermal ORC plant	1 kJ of net energy	Cradle to grave	SimaPro embedded database	ReCiPe 2016	SimaPro	A single environmental impact of 0.0631 was reported for a multi-generation system with a lifetime assumption of 20 years.	(Chaiyat et al., 2021)
Geothermal ORC plant	1 MWh of electricity production	Cradle to grave	Ecoinvent	ReCiPe 2016 Endpoint	openLCA	Comparing the environmental impacts of two different ORC configurations for the geothermal power plant, it was obtained that a subcritical ORC is likely to have a higher impact (about 3.4%) than the supercritical ORC.	(Fiaschi et al., 2021)
Geothermal ORC plants	1 kWh of net electrical energy	Cradle to grave	Literature data, Ecoinvent and PROBAS	Selected impact categories (CO2-eq, Energy Demand, Eutrophication, Acidification)	GaBi	The study revealed that using some low-GHG working fluid such as R1233zd instead of R245fa in subcritical ORC plants can reduce environmental impact (CO2-eq) by about 78% and that a 2-stage ORC plant can be more favorable for geothermal plants in Germany.	(Heberle et al., 2016)
Enhanced Geothermal System ORC plant	1 kWh of output energy	Cradle to grave	Simulation data and Ecoinvent	Ecological scarcity	NS (LCA integrated into thermo-economic optimization)	The study demonstrated how LCA can be integrated with thermo-economic models for the optimal development of geothermal plants in Switzerland.	(Matuszewska et al., 2018)

NS – not specified.

Table 4. Conventional LCA of solar and solar hybrid ORC plants.

ORC Heat Source	LCA FU	Boundary	Inventory Database	LCIA Method	Tool/ Software	Remark	Reference(s)
Solar ORC plant	1 kWh of primary energy production	Cradle to gate	Literature data and Ecoinvent	IMPACT 2002+; IPCC 2013 GWP 100a; cumulative energy demand (CED)	SimaPro	The study identified that the solar multiple (SM) is an important parameter that must be carefully selected to achieve an environmentally benign solar-ORC plant. It was demonstrated specifically that doubling the solar field area from 50 m2 to 100 m2 can reduce the environmental impact from 140 μPt/kWh to 104 μPt/kWh.	(Cioccolanti et al., 2019)
Solar-Geothermal ORC plant	1 year of electrical and thermal energy production	Cradle to gate	Ecoinvent	CML 2011 baseline	SimaPro	The study demonstrated that the exploitation of solar-geothermal energy sources by ORC plants is an environmentally-favorable solution in the context of sustainable development.	(Ruzzenenti et al., 2014)
Solar ORC integrated with an ammonia synthesis plant	1.83 kWh of electricity or 1 kg of ammonia production	Cradle to grave	Life plant/ literature data; Ecoinvent	CIA-LP and ReCiPe 2016 Endpoint (H)	SimaPro	Low environmental impacts were obtained generally for the integrated plant, specifically at about 0.69 $CO_{2\text{-eq}}$/kg of ammonia, based on GWP midpoint, and about 0.0000817 pt based on endpoint human health indicator.	(S. Liu et al., 2021)

LCA was based on the ecoindicator 99 system with all the plants' phases (cradle to grave) considered. In all, the environmental impact of about 4026 mPts/GJ was obtained for the system, implying according to the authors, that the system is more environmentally viable for a vast majority of other renewable energy systems.

Also, Parham et al. (Parham et al., 2017) claimed to apply the exergoenvironmental method to assess the environmental performance of a multi-generation plant involving ORC. However, the exergoenvironmental approach adopted doesn't take into account the environmental LCA of the system as is commonly done. The ORC plant produced power, while cooling and hydrogen are produced by integrated units of the system. The parameters used for the so-called exergoenvironmental analysis in the study simply defined some parameters as functions of exergy destruction and exergy efficiency for the system. This approach of the exergy-based environmental analysis had been proposed by other authors in the literature (Hacatoglu et al., 2013; Ratlamwala, Dincer and Gadalla, 2013; Ratlamwala, Dincer and Reddy, 2013). Additionally, Adebayo et al. (Adebayo et al., 2022) employed this approach to assess a multi-generation energy system that produces electricity, cooling, domestic hot water, and hydrogen. Effects of several parameters on the system performance were examined and those that were unfavourable to the environmental sustainability of the system were identified.

4.3. Geothermal ORC plants

Boyaghchi and Nazer (Ahmadi Boyaghchi and Nazer, 2017) studied an integrated energy system comprising of geothermal-powered ORC plant and magnetic refrigeration system powered by a concentrated photovoltaic thermal plant. The eco-Indicator method was adopted for the life cycle analysis, for integration with exergy analysis to determine the exergoenvironmental performance of the system. The authors reported that the total environmental impact (EI) of the integrated plant could be reduced by about 3.8% by varying the turbine inlet pressure.

Gurbuz et al. (Gürbüz et al., 2022) aimed to close the gap they observed existing regarding environmental impact assessments of geothermal-driven ORC plants by applying the LCA approach to a two-stage ORC plant. The traditional and the so-called enhanced exergoenvironmental methods were employed in the study; they both adopted the ecoindicator 99 points for the LCA approach, which was integrated with the conventional and advanced exergy concepts. Environmental impacts were determined for each of the components and the overall system. Results identified the condenser as the component with the highest environmental impacts, obtained specifically as 1386 Pt/h for the traditional exergoenvironmental approach. The enhanced approach entails that part of this point is due to the impacts of the components themselves (endogenous) and due to their connection with other system components (exogenous). Also, some of the environmental impacts are avoidable, and some others are unavoidable. The authors reported in this study that about 716 Pt/h of the exogenous impact is avoidable for the condenser.

Fiaschi e al (Fiaschi et al., 2021). also assessed the environmental impact of a geothermal ORC plant using the exergoenvironmental method. In the study, a detailed LCA of the plant was initially conducted based on the ReCiPe LCIA method and openLCA software, focusing also each of the plant components. Then, all the impact categories in the LCIA method were weighted to obtain single-point environmental impact for each of the components. Next, the environmental impact points were integrated with the exergy performance of the components and the system to obtain exergo-environmental impacts. The study reported that the environmental impacts of the ORC heat exchangers contributed substantially to the overall impact, second only to the geothermal well construction.

4.4. Solar and hybrid solar ORC plants

Boyaghchi and Chavoshi (Boyaghchi and Chavoshi, 2018) studied the exergy-based environmental performance of a micro dual ORC plant exploiting solar energy. The environmental impact was calculated considering the solar parameters monthly. Several working fluids were considered for the ORC, and the effects of the thermodynamics parameters of the system on environmental impacts were equally investigated. The ecoindicator 99 approach was used for the LCA component of the exergoenvironmental assessment. Results showed that increasing the turbine pressure led to the lowest environmental impact with the meteorological data of April of the year.

Mousavi et al. (Mousavi et al., 2022) proposed a solar-powered ORC electricity plant integrated with a diffusion absorption refrigeration cooling system. Here too, the ecoindicator 99 was used to apportion environmental impact points to exergy streams of the system over its entire life cycle. The impacts were measured for the different components of the ORC plant, and results identified the expander as the component with the highest environmental impact, followed by the heat exchanger. Specifically, about 30% of the exergoenvironmemtal points were attributed to the expander, at about 204 Pts, and about 22% for the heat exchanger, with about 154 Pts.

Zandi et al. (Zandi et al., 2021) applied the exergoenvironmental method to assess the environmental impact of a solar-driven ORC plant integrated with the refrigeration cycle for the production of cooling. The ecoindicator 99 approach was employed in the LCA phase of the study to allocate environmental impact points to the system components and streams. Different working fluids were equally considered for the ORC plant, and the effects of system parameters on environmental impacts were assessed. Results identified R744A as the working fluid with the highest environmental impact that could be about 32% higher than the average for the system product. The overall environmental impact rate of the system was estimated at 149 mPts/h.

Table 5 summarizes the various exergoenvironmental studies of ORC plants reported herein, responding directly to some queries on whether or not the ecoindicator 99 LCIA method was used, if the LCA covers the cradle-to-grave boundary, and if the direct environmental impacts of emissions of pollutants were considered.

5. Authors' outlook

Environmental impact assessment through the LCA approach is not yet widely integrated into the design and optimization studies of ORC plants in the open literature. Although the search of 'Organic Rankine Cycle' keywords on the Scopus database yielded 7041 documents, only 209 documents were found relating to LCA, even when different keywords were used for the search. This amounts to less than 3% of the total documents relating to ORC, justifying that environmental assessment of ORC plants is not very well embraced yet in the literature.

Also, the review of the conventional LCA of ORC plants revealed that an ecoinvent database is a veritable tool for inventory analyses and that most of the studies adopt the use of standard software for the life cycle impact assessment. Amongst the available software in use, SimaPro is by far the most common, followed by GaBi. However, these two tools are not open access and require paid licenses. On the other hand, the openLCA is also gaining wide recognition in the literature, and it has the advantage that it is open access and can be used by anyone at no cost. All the software have provisions for the inventory database and the LCIA methods. In some instances, the analysis software doesn't include some desired inventory data, in which case an external database such as the ecoinvent is imported into the software. Additionally, several LCIA methods are used, and the choice in any study often depends on its goal and scope.

The conventionally LCA of ORC plants equally revealed that the choice of organic working fluid has a significant effect on the environmental impact of the system. Although many authors don't consider leakage of working fluid in ORC environmental impact assessment, results from a few studies that considered leakages showed that the effects are not negligible.

Furthermore, it is clear from the foregoing literature review that two main approaches exist for carrying out the exergoenvironmental assessment of ORC and integrated plants. One of them defines environmental impact metrics from the exergy destruction and exergy efficiency of the components and the overall system, without any clear recourse to the conventional LCA. The authors of this approach think that increasing the exergy efficiency of a system would lead to lower fuel consumption, which would in turn reduce the environmental impact of the system. Although this argument is correct, in our opinion; only very few studies adopted this approach in the context of exergoenvironmental analysis of ORC plants.

Conversely, in the second and the most common approach of exergoenvironmental analysis of ORC plants, the conventional LCA is first conducted, the results of which enables allocation of environmental impacts as points to the exergy streams of the system. Thus, next to the goal and scope definition and inventory analysis based on the system model, it is common to adopt the ecoindicator-99 (EI-99) impact identifier to assign environmental impact to component/system streams. The EI-99 method obtains a single environmental index for processes and products by weighting in hierarch perspective three main damage aspects: ecosystem quality, human health, and natural resources (Goedkoop and Spriensma, 2001). The method provides indices in millipoints (mPts) or points (Pts) for several processes and products based on the LCA international standards (Meyer et al., 2009). EI-99 points have been defined in the literature per unit size (weight) for several types of materials, such that if the material type and size of a component are known in a new study, the overall LCA simply entails multiple the size by the pre-defined EI-99 points per size for the respective material types. This somewhat reduces the efforts required in exergoenvironmental analyses of energy systems. Suffice it to mention that several conventional LCA studies of ORC plants also adopt the EI-99 points to analyze environmental impacts (Blanco et al., 2020; Ochoa, Gutierrez, et al., 2020; Valencia et al., 2021; Valencia Ochoa, Vanegas Chamorro and Churio Silvera, 2022). The higher the EI-99 points obtained for each exergy stream or system component, the higher the damage done by such process/component to the environment. After the environmental impacts in points have been assigned to system components/streams, the exergoenvironmental variables are calculated, for exergy-based LCA evaluation of the system.

Meyer et al. (Meyer et al., 2009) who first applied the exergoenvironmental method, proposed an exergoenvironmental balance equation. The balance equations at the component level are defined below in Eqs. (1) and (2), has become the bedrock of the exergoenvironmental analysis today,

$$\sum B_i + B_q + (Y + B^{PF}) = \sum B_o + B_w \tag{1}$$

$$\sum b_i E_i + b_q Q + (Y + B^{PF}) = \sum b_o E_o + b_w W \tag{2}$$

Table 5. Excerpts from exergy-based life cycle assessment of ORC plants.

ORC Heat Source	Use of the Ecoindicator 99 LCIA method	Cradle to grave life cycle boundary consideration	Environmental impacts of pollutants emissions consideration	Reference(s)
Geothermal energy	Yes	Yes	No	(Ahmadi Boyaghchi and Nazer, 2017)
Geothermal energy	Yes	Yes	Yes	(Gürbüz et al., 2022)
Geothermal energy	No (ReCiPe from an LCA approach, weighted as single points)	Yes	No	(Fiaschi et al., 2021)
Biomass energy	Yes	Yes	No	(Ebadollahi et al., 2021)
Biomass energy	No	No	No	(Parham et al., 2017)
Biomass energy	No	No	No	(Adebayo et al., 2022)
Waste heat	No	No	No	(Ahmadi et al., 2012)
Waste heat	No	No	No	(Altinkaynak and Ozturk, 2022)
Generic	Yes	Yes	Yes	(Ding et al., 2018)
Waste heat	Yes	Yes	No	(Ghorbani et al., 2020)
Waste heat	Yes	Yes	No	(Ochoa, Gutierrez, et al., 2020)
Solar energy	Yes	Yes	No	(Boyaghchi and Chavoshi, 2018)
Solar energy	Yes	Yes	No	(Mousavi et al., 2022)
Solar energy	Yes	Yes	No	(Zandi et al., 2021)

where B is the environmental impact rate, expressed as the product of the specific environmental impact of a stream (b, Pts/MWh) and exergy rate (E, MWh/h), subscripts i, o, q and w represent inlet flow to a component, exit flow from the component, the flow of heat to and the flow of work from the component, respectively, B^{PF} is the environmental impact rate due to pollutant formation in the component and Y is the environmental impact rate related to the component, obtained as a sum of impacts due to its construction, Y^{CO}, operation, and maintenance, Y^{OM} and disposal, Y^{DI}. Also, B^{PF} for a component is given in Eq. (3):

$$B^{PF} = \sum_{n} b_n{}^{PF} (\dot{m}_{n,out} - \dot{m}_{n,in}) \tag{3}$$

where $b_n{}^{PF}$ is the specific environmental impact due to emission of pollutant n from a component (Pts/kg), with mass flow rates $\dot{m}_{n,in}$ at the inlet of the component and $\dot{m}_{n,out}$ at the exit. Eq. (3) applies mostly to a system where emissions are possible and prominent, such as in biomass or fossil-fuelled ORC plant. It is the basis for the responses in column 4 of Table 2. The main exergoenvironmental parameters commonly used to evaluate the environmental performance of each system and its components are: mean specific fuel exergoenvironmental impact (b_F), definined in Eq. (4); mean specific product exergoenvironmental impact (b_P), defined in Eq. (5); exergoenvironmental impact rate due to irreversibility in system component (B_I), defined in Eq. (6); total exergoenvironmental impact rate (R), defined in Eq. (7); exergoenvironmental factor (f_b), defined in Eq. (8); specific exergoenvironmental impact relative difference (r_b), defined in Eq. (9); and exergoenvironmental impact per unit energy produced (EIE), defined in Eq. (10).

$$b_{F,k} = \frac{B_{F,k}}{E_{F,k}} \tag{4}$$

$$b_{P,k} = \frac{B_{P,k}}{E_{P,k}} \tag{5}$$

$$B_{I,k} = b_{F,k} \times I_k \tag{6}$$

$$R_k = B_{I,k} + Y_k \tag{7}$$

$$f_{b,k} = \frac{Y_k}{B_{I,k} + Y_k} \tag{8}$$

$$r_{b,k} = \frac{b_{P,k} - b_{F,k}}{b_{F,k}} \tag{9}$$

$$EIE_k = \frac{R_k}{\dot{W}_{net}} \tag{10}$$

Subscript k is an identifier for each component, while subscripts F and P represent fuel and product exergy in and out of the component k, respectively.

6. Conclusions

The conventional and exergy-based life cycle assessments of organic Rankine cycle and integrated power plants have been systematically reviewed in this article. The systematic qualitative approach of the literature review was adopted, comprising the planning, filtering, clustering, and reporting stages. The main findings can be summarized as:

- The researchers have not quite embraced the environmental feasibility assessment of ORC plants. Specifically, less than 3% of the total studies on ORC plant (about 7000 on the SCOPUS database) considered the environmental feasibility based on LCA;
- The ecoinvent database is the most applied for life cycle inventory analysis of ORC plants, usually in the SimaPro software;
- The choice of an organic working fluid and its leakages over the plant's lifetime reportedly contribute significantly to the environmental impacts of ORC systems;
- The exergoenvironmental assessment should fuse the conventional LCA with exergy analysis, and the definitions of the most significant performance metrics are reported in section 5 of this article. The use of the ecoindicator 99 in the LCA part simplifies the execution of exergoenvironmental analysis, as is widely implemented in the literature.

The authors believe that future analyses of ORC plants should incorporate the LCA, either conventional or exergy-based, and we hope that this research effort can spur its implementation.

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