Life Cycle Assessment Applied to an ORC System Operating Under Two Modes: Evaluation of Two LCIA Methods

Ronelly J. De Souza[a], João Luiz M. Neto[b], Carlos A. C. dos Santos[b], and Mauro Reini[a]

[a] *Department of Engineering and Architecture, University of Trieste, Italy, ronellyjose.desouza@phd.units.it, CA, reini@units.it*
[b] *Department of Mechanical Engineering, Federal University of Paraiba, João Pessoa, Brazil, eng.joaomedeiros@gmail.com, carloscabralsantos@ct.ufpb.br*

Abstract:

Life Cycle Assessment (LCA) is a remarkable tool that allows decision-makers to reduce the environmental impact, identify possible improvements, and compare the environmental performance of products and services. Thus, considering the increasing interest in the environmental assessment of thermal systems, this work applies the LCA tool in a proposed cogeneration system, previously studied by the authors, comparing different Life Cycle Impact Assessment (LCIA) methods for two distinct operation modes, namely, Organic Rankine Cycle - Simple (ORC-S) and Organic Rankine Cycle - Combined (ORC-C). The LCIA methods considered for this study are Eco-Indicator 99 (Hierarchist, Average weighting – H,A) and ReCiPe Endpoint (Humanitarian, Average weighting – H,A). The considered functional unit is 1 kWh of produced electricity. The cogeneration system comprises mainly an ORC system working with R134a and a piece of equipment operating as the heat sink. The latter is what defines the system operation mode, i.e., a cooling tower (ORC-S) or an Absorption Chiller (ORC-C). The system was designed to partially meet the power and thermal demands of a lab facility, located in the Federal University of Paraíba, Northeast – Brazil, and to be powered by ICE exhaust gases. Simulations have been performed through open-source software openLCA version 1.10.3, running the Life Cycle Inventory (LCI) database Ecoinvent 3.7.1. The results have confirmed the importance of LCA on a trade-off decision once it adds valuable information beyond the thermodynamic and economic ones. Also, the results have shown that the environmental impacts for electricity energy produced from the ORC-C mode are, at least, 6 times higher than those of ORC-S. Among the main reasons for that is the cooling energy from absorption chiller and the high consumption levels of fossil fuels throughout the life cycle of each studied component.

Keywords:

Life Cycle Assessment, Cogeneration, Comparative analysis, Eco-Indicator 99, ReCiPe.

1. Introduction

Energy and environmental issues are increasingly gaining prominence in the scientific community. The world demand for energy is growing, and it is necessary to have new technologies aimed at economic and environmental concerns. According to the International Energy Agency [1], from 1973 to 2015, global energy consumption grew about 200%. Such a scenario motivates the search for new configurations to meet global demands and minimize costs linked to power generation. The focus is to obtain the maximum thermodynamic potential from the resources through energy efficiency strategies and to reduce the environmental impact associated with energy production.

In the Paris agreement, 195 countries adopted the first universal and legally binding global climate pact, defining a global action plan to mitigate climate change and try keeping global warming below +2°C compared to the pre-industrial era [2]. Regarding Europe, a carbon neutrality target was set by 2050 [3]. The Intergovernmental Panel on Climate Change clearly states that it is urgent to limit global warming to +1.5°C instead of +2°C [4]. One of the main causes of these environmental problems lies in the widespread use of fossil fuels for energy purposes.

In that sense, cogeneration technologies have been attractive options in the energy market. The principle underpinning cogeneration systems is the simultaneous production of different energy services from a single fuel. The use of absorption cooling and heating systems has been essential in the production of thermal energy in the forms of cooling, cold, and hot water [5-6]. These thermal energy systems can be driven by waste heat [7], solar energy, and a combination of energy resources.

Environmental assessments aim to identify and determine the place, magnitude, causes, and environmental impact associated to thermodynamic inefficiencies in energy conversion systems [8]. Such evaluation provides a global perspective of a complex system using integrated analysis of energy, and environment. This type of assessment is performed for each component of the system, identifying its relative importance for the overall environmental impact of the system [9]. In environmental assessments, a one-dimensional characterization indicator is obtained by applying Life Cycle Assessment (LCA) [10], which is a standardized methodology for quantifying the potential environmental impacts of a product, service, or activity throughout its life cycle.

Environmental evaluations have been applied to different cogeneration and trigeneration systems [11-12]. This includes renewable energy [13], conventional steam compression systems [14], water humidification and treatment systems [15], and even chemical processes and systems, such as the production of methanol [16], glycerol [17], and liquid hydrogen [18].

This study aims to apply the LCA tool to a proposed cogeneration system previously studied by the authors, comparing different Life Cycle Impact Assessment (LCIA) methods for two distinct operating modes, namely, ORC-S and ORC-C. The LCIA methods adopted for this study are Eco-Indicator 99 (H,A) and ReCiPe Endpoint (H,A). The functional unit considered is 1 kWh of produced electricity. The cogeneration system mainly comprises the heat source (engine exhaust gases), an organic Rankine cycle (ORC) working with R134a, and a piece of equipment operating as a sink. The latter is what defines the operating mode of the system, i.e., a cooling tower (ORC-S) or a H2O-LiBr absorption chiller (ORC-C).

2. System description and utilization

In the previous study [19], the cogeneration system under consideration has been analysed operating in two different modes: 1) ORC-S (Simple organic Rankine cycle), which is connected to a cooling tower (Fig. 1); 2) ORC-C (Combined organic Rankine cycle), which uses the cooling capacity of an absorption refrigeration system to reject the heat, especially when condensation temperature is under the ambient one (Fig. 2).

2.1. System description

First, it is important to keep in mind the scope of the present study. The cogeneration system comprises an organic Rankine cycle, a heat exchange in the air-conditioned room, an absorption refrigeration system, two storage tanks and a heat exchange receiving heat from an internal combustion engine exhaustion. However, as depicted in Figs. 1 and 2, the scope of this work is the ORC system (condenser, liquid accumulator, pump, steam generator, expander) plus other components depending on the operation mode of the system.

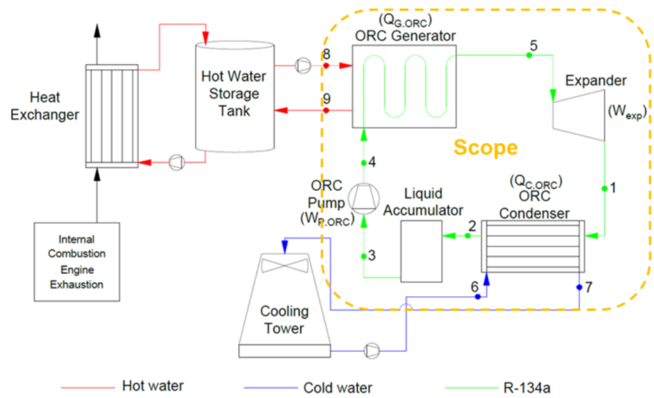

Fig. 1. Cogeneration system (ORC-S) proposed by Souza et al. 2020 [19].

The ORC consists of a steam generator, an expander device (which in this case is a scroll expander), a condenser, a liquid accumulator, and a pump. The ORC function proceeds as following: after going through the expansion process (point 1), the saturated vapour of R134a enters the condenser where the heat rejection will occur. When leaving the condenser (point 2), the working fluid, which is at saturated liquid state, is sent to a liquid accumulator to ensure a compressed liquid state at point 3. The pump will then provide the necessary pressure to the R134a stream get into the ORC generator, where it will receive the energy from the heat source. When leaving the generator (point 5), the stream is at superheated state and enters the expander, which will ultimately transform heat energy into mechanical energy. After it, the cycle restarts with the R134a stream passing through point 1.

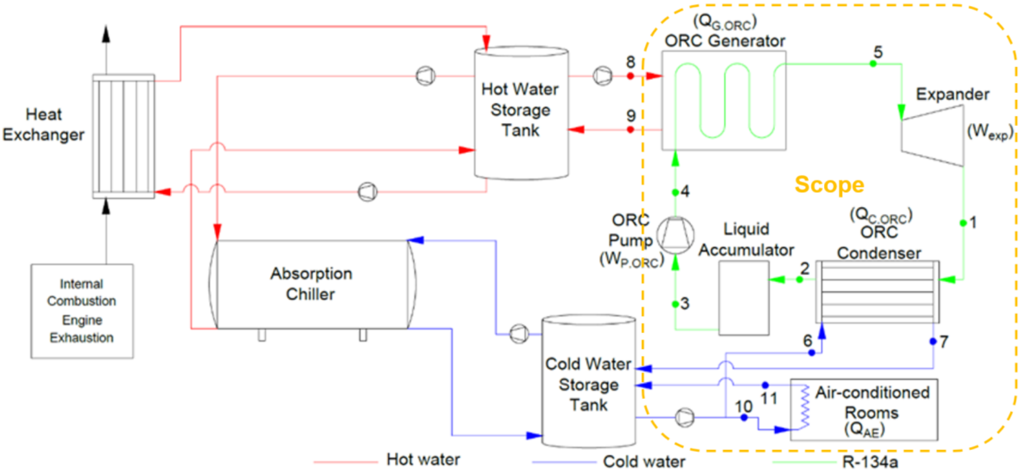

Fig. 2. Cogeneration system (ORC-C) proposed by Souza et al. 2020 [19].

One of the main differences between ORC-S and ORC-C is how the heat is removed in the condensation process. Essentially, the condensation principle is the same, however, for the ORC-S (Fig. 1), points 6 and 7 correspond to a cooled water stream provided by a cooling tower, whereas for the ORC-C (Fig. 2), the same two points correspond to the cold-water stream, supplied by the cold-water storage tank, responsible for removing the heat rejected from the ORC system and the heat present in the air-conditioned room (points 10 and 11 – Fig. 2). Hence, for both ORC operation modes, points 6, 7, 10, and 11 are pipeline sections carrying liquid water since the heat exchange within them involves only sensible heat. For more details regarding the description and operation of both ORC modes, please refer to [19].

2.2. System utilization

A case-study approach was adopted by [19] to help understand how the cogeneration system could meet energy supply demands of a real building. The building chosen is part of the Institute of Sustainable Energy (IES) facilities located at the Federal University of Paraíba (UFPB), João Pessoa, Northeast Brazil. As described in the aforementioned work, the IES facilities consist of three blocks: IES-1, IES-2, and IES-3 (Fig. 3). However, the case-study aim was using the cogeneration system products only for block IES-1 ground floor, which comprises the secretariat, coordination, and auditorium.

Fig. 3. UFPB campus I entire structure (left) and IES facilities set of blocks Souza et al. 2020 [19].

According to Souza et al. 2020 [19], the ORC-S and ORC-C are able to deliver, respectively, about 0.85 kW and 1.3 kW of mechanical power under their maximum allowed pressure ratio. After some assumptions regarding the mechanical/electrical power conversion efficiency and the work-load days, it was concluded that the cogeneration systems can meet, respectively, up to 24.5% and 37.5% of the annual energy consumption of the IES-1 specified rooms.

3. Life cycle assessment

As it is widespread in literature, Life Cycle Assessment (LCA) is an important part of the process of exergoenvironmental analysis since it calculates the environmental impact values obtained through a quantifier method. In other words, LCA is an analysis tool that permits to evaluate the potential environmental impacts in each phase of a product or service life cycle, i.e., from the extraction of the raw materials to its disposal. Basically, LCA comprises four steps:

1. Goal and scope: definition of the object of study as well as its boundaries.
2. Life cycle inventory (LCI): determines all inputs and outputs linked to the object of study defined previously.
3. Life cycle impact assessment (LCIA): takes the data produced in step 2 and allocates the corresponding potential impacts on the environment (resources and ecosystems) and human health.
4. Interpretation: aims to identify what is causing major environmental impacts and, ultimately, to indicate improvements.

3.1. Definition of goal and scope

This step of the LCA mainly describes the aim and boundaries of the object of study. The aim part includes definitions of the studied system, product, or activity, as well as its lifetime, while the boundaries can incorporate raw material extraction (as well as its processing and manufacturing phases), transportation, utilization, maintenance, and disposal [20]. This methodology is called "cradle-to-grave" approach since it evaluates the life cycle from raw materials extraction to its discarding [21]. Another methodology found in literature is the "cradle-to-gate" approach, which is used for studies in which the assessment is performed up to a certain stage in the life cycle of a product or service [22].

The goal of this study is to evaluate the environmental impact of the cogeneration operation modes indicated in Figs. 1 and 2, and previously studied by Souza et al. 2020 [19]. As presented in section 2, in the mentioned work, the authors assessed the cogeneration system from a thermodynamic and exergoeconomic viewpoint. Therefore, the present work stands as a continuation of the project and intends to increment the comprehensive data basis for decision makers. Yet, readers should be aware of a limitation of this work since the disposal stage of the studied system was not taken into account. Consequently, the applied methodology was "cradle-to-gate" since the LCA analysis is performed from the raw materials extraction up to the operation of the system in the IES facilities (Fig. 3). For both operation modes, the LCA analysis have considered the raw materials and energy consumption to manufacture each component, transportation from the manufacturer facility to the operation facility, thermal sources, electricity consumption for operation, working fluid, and the obtained product.

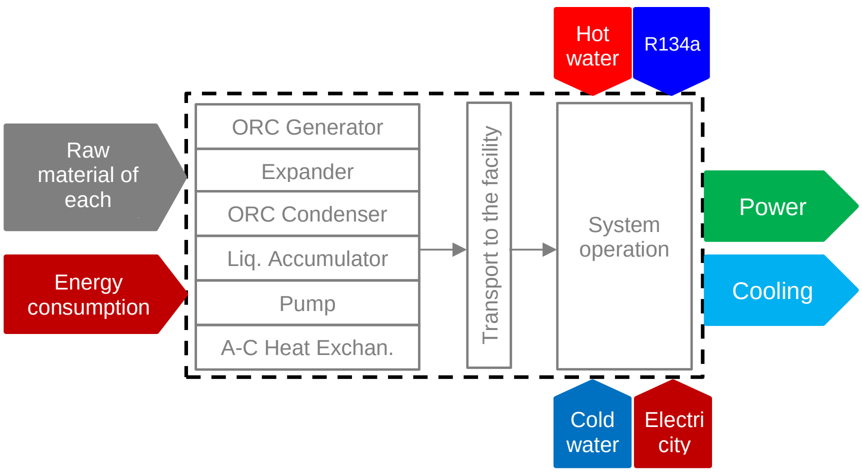

Fig. 4. System boundaries for the ORC-C operation mode.

There are a couple of distinctions between ORC-S and ORC-C that were used to perform this comparative analysis. The essential difference is that the system boundary of the ORC-C operation mode (Fig. 4) includes an air-conditioning heat exchanger, a cold-water stream (provided by an absorption chiller), and the cooling as another product. Instead, the system boundary of the ORC-S operation mode does not include neither an air-conditioning heat exchanger nor a cooling stream as another product, and the water for condensation is provided by a cooling tower (Fig. 5).

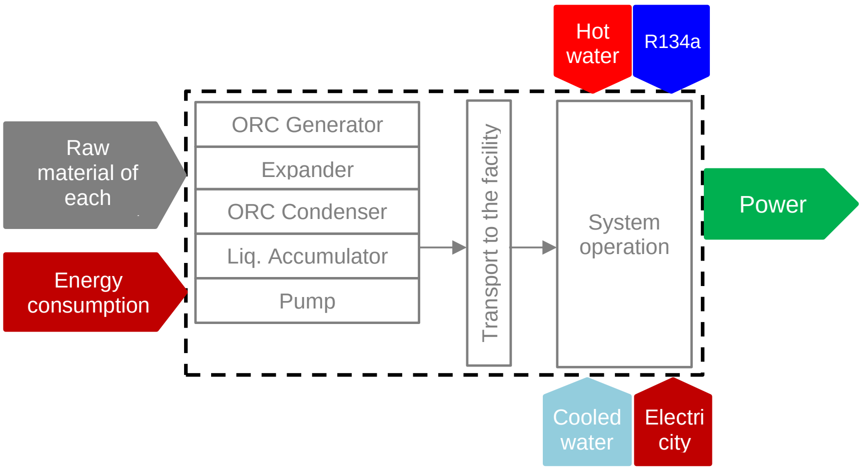

Fig. 5. System boundaries for the ORC-S operation mode.

The ORC system's lifetime is 20 years, according to recommendation from the selected manufacturer [23]. However, in order to be coherent with the previous mentioned study [19], the lifetime considered for this work was 17 years.

3.2. Inventory description (LCI)

As previously described, Life Cycle Inventory is the stage of the LCA where all inputs and outputs are associated to the object of study. For this study, inputs were considered for the two main phases of the system's life cycle: manufacturing of components and system operation. For the first one, it was considered the raw materials and energy consumption based on each component's mass. For the second one, it was considered the heat source, heat sink, working fluid, and electricity necessary to run the system. More details about the data of each component are reported in the next section, Table 1. The transportation from the component's manufacturer to the system's operation place was also considered in the simulation (section 3.2.2).

3.2.1. Component's data

The components reported in this section are those regarding the ORC-C operation mode, since, from the components point of view, the only difference between this mode and the ORC-S is that, for the last one, the air-conditioning heat exchanger is not included. Table 1 presents all the components as well as their mass, material composition, type of transportation considered, and total distance.

The expander mass was obtained from its manufacturer [24] and the pump was considered proportional to the expander (in terms of weight). For the ORC generator and ORC condenser it was assumed the shell and tube heat exchanger type and their mass were calculated through equations (1) and (2), while the air-conditioning heat exchanger mass was calculated using equations (1) and (3) [25]. The liquid accumulator mass was considered proportional to that of the ORC condenser.

$$M_{comp} = \rho \cdot A_{th} \cdot \delta \qquad (1)$$

In Eq. (1), M_{comp} is the mass of a given component in kg; ρ is the density of the material in kg/m^3; A_{th} is the total heat transfer area within the component in m^2; and *δ* is the thickness of the tubes in m.

$$A_{th1} = \frac{\dot{Q}}{U \cdot \Delta T_{lm}} \qquad (2)$$

Equation (2) comprises the overall heat transfer coefficient *U* (W/m²K), the heat transferred Q (kW), and ΔT_{lm} which is the log mean temperature difference (K). In Eq. (3), D_i is the tube diameter (m), and *L* is the length of the tube (m).

$$A_{th1} = n \cdot \pi \cdot D_i \cdot L \tag{3}$$

Table 1. Component's inventory: mass, raw materials, transportation type, and distance.

Component	Mass [kg]	Raw Materials	Transport	Distance [km]
ORC Generator	23.5	1.4% Stainless steel, 10% Iron-nickel-chromium alloy, 88.6% Copper.	Lorry EURO 6, Sea container ship	7590
Expander	5	48.2% Stainless steel, 29.2% Reinforcing steel, 14.4% Chromium steel pipe, 3.9% Copper, 2.2% Aluminium, 1.2% Iron-nickel-chromium alloy, 0.9% Polymer.	Lorry EURO 6, Sea container ship	7590
ORC Condenser	21.5	18.4% Chromium steel pipe, 71.4% Stainless steel, 10.2% Iron-nickel-chromium alloy.	Lorry EURO 6, Sea container ship	7590
Liq. Accumulator	20	100% Carbon steel.	Lorry EURO 6, Sea container ship	7590
Pump	5	88.4% Cast iron, 11.6% Stainless steel.	Lorry EURO 6, Sea container ship	7590
A-C Heat Exch.	10.5	80% Copper, 20% Stainless steel.	Lorry EURO 6, Sea container ship	7590

3.2.2. Transportation data

As mentioned before, the selected manufacturer of ORC systems is Electratherm [23], located in the city of Oakwood, southeast of USA. For this study, transportation from the raw materials extraction place to the manufacturer location was not considered. Transport from Oakwood city to Miami Port is made by EURO 6 lorry for about 1140 km; then, from Miami Port to Recife Port (Brazil) it is made by a sea container ship for about 6300 km; and, from Recife Port to IES buildings facilities (Fig. 3), in the city of João Pessoa, it is made also by EURO 6 lorry for about 150 km. A schematic diagram of such transportation routes is presented in Fig. 6.

Fig. 6. Schematic diagram of all transport routes.

3.2.3. System operation

The operation of both modes happens in a similar way. ORC-C and ORC-S are provided with the same kind of heat source, electricity, and working fluid. However, for ORC-C mode, the heat sink is the cooling energy from an absorption chiller operated with heat from a natural gas operated cogeneration unit. For the ORC-S mode, it was considered the total amount of water (from the cooling tower) necessary throughout the entire system lifetime. More details may be found in Tab. 2.

The total amount of cooled water consumed by the ORC-S mode and of working fluid were estimated based on literature. According to Burkhardt et al. [26], during the operation of a combined cycle natural gas plant, the consumed water per unit of energy is 1.4 L/kWh. As the total electric energy produced by the system throughout its lifetime is 86.7 MWh, and assuming water density of 1000 kg/m^3, the total amount of water is 121380 kg. As per working fluid, Cioccolanti et al. [27] claimed that a rate of 11.56 t/MWe has been assumed to LCA analysis about ORC systems. According to Honeywell Chemicals [28], the lifetime of the refrigerant R134a is 13 years.

Since the ORC system's lifetime considered for this work is 17 years and assuming a loss factor of 2%, the total amount of R134a is 13.1 kg.

Table 2. Description of utilities necessary to run both operation modes.

	Operation modes	
	ORC-C	ORC-S
Heat: from a 160 kWe cogeneration unit (lambda=1) burning natural gas *	■	■
Electricity: electricity available on the low voltage level Brazil North-eastern in 2014 *	■	■
Working fluid: R134a (13.1 kg)	■	■
Cooling energy: from absorption chiller operated with heat from a natural gas cogeneration unit *	■	
Cooled water (from cooling tower): softened water used in sectors such as cooling and boiler feed *		■

* Description from Ecoinvent 3.7.1 database.

3.3. Life cycle impact assessment (LCIA)

After gathering all the information relative to the inventory step, the LCIA step associates those pieces of information to the potential impact they can cause to the environment and human health. To do so, the LCIA step was developed within the openLCA software [29] version 1.10.3 running the Ecoinvent 3.7.1 database [30]. Following the standards of ISO 14040 [31] and ISO 14044 [32], the software performed the simulation of the present comparative study based on the selection of the following LCIA methods: Eco-Indicator 99 (Hierarchist, Average weighting – H,A) (EI-99) and ReCiPe Endpoint (Humanitarian, Average weighting – H,A). According to Marques et al. [33], EI-99 is still a traditional LCIA method for LCA, however ReCiPe method has been standing as the successor of EI-99. Moreover, according to the National Institute for Public Health and the Environment [34] the methods and information used within ReCiPe are the latest and in harmony with current scientific knowledge.

Both LCIA methods are characterized as Endpoint methods, which is easier for decision makers to understand. These types of methods collect the calculated environmental damages and group them into three categories [35]:

- Human Health: diseases related to environmental causes; it is considered the number of diseases as well as its duration and lost life years due to premature death.
- Ecosystem Quality: damage to species diversity, such as specific kinds of plants and lower organisms.
- Natural Resources: considers the surplus of energy in the future, necessary to obtain mineral and fossil resources.

4. Results and discussion

4.1. Impacts and LCIA comparison for energy production from both ORC modes

Table 3 and Table 4 present the total impact contributions for EI-99 and ReCiPe, respectively, for both ORC operation modes. The results in both tables were generated considering the three main phases together (Fig. 4 and 5), i.e., manufacturing, transportation, and system operation. It was also considered 1 kWh of produced electricity as the functional unit. The values for ORC-S and ORC-C are shown concerning each impact category and presented in millipoints (mPt) and percentage.

The Resources category provided a considerably high contribution to the overall impacts. As observed in Table 3, the mentioned impact category provided the highest environmental impacts for both ORC-S (82.60%) and ORC-C (72.63%), although the absolute value for ORC-C (626.85 mPt) is almost six times higher compared to that of ORC-S (105.47 mPt). It should be highlighted that, in this case, the higher percentage for ORC-S was in fact expected since, for the simulation, it was considered the total amount of softened water that would be used by the cooling tower throughout the entire lifetime of the system. Moreover, it is worth noting that, according to the present results, the fossil fuel impact category, as expected, is by far the greatest villain to the environmental impacts for both LCIA methods, as can be observed in Tables 3 and 4.

Still according to Table 3, the Human Health and Ecosystem categories contributed with the least percentages of impacts. However, the impacts generated by the ORC-C mode are still very high compared to those of ORC-S. For Human Health the total impact of ORC-C was ten times higher, mainly caused by respiratory effects (92.36 mPt), climate change (69.38 mPt), and carcinogenic effects (40.29 mPt). For ORC-S, the only category with value higher than 10 mPt was climate change (11.19 mPt). The impact caused in the Ecosystem produced similar results to those for Human Health. The difference is that the total impacts caused by ORC-C were fourteen times higher and the main source of impacts was due to ecotoxicity for both operation modes.

The main source of impacts for such higher values for the ORC-C mode is the energy cooling coming from the absorption chiller. As shown in Fig. 8, the energy cooling contributes with 85% of the total impacts related to the system operation phase, while the heat source contributes with 14%. The main causes for such high contribution were CO_2 emissions, noble gases emissions, water consumption, and natural gas consumption, which are related to the life cycle of the process for obtaining the cooling energy (Table 2).

Table 3. Overall contribution of the EI-99 impact categories for both ORC operation modes

	ECOSYSTEM				HUMAN HEALTH				RESOURCES			
	ORC-S		ORC-C		ORC-S		ORC-C		ORC-S		ORC-C	
Impact category	**[mPt]**	**%**	**[mPt]**	**%**	**[mPt]**	**%**	**[mPt]**	**%**	**[mPt]**	**%**	**[mPt]**	**%**
Acidification and eutrophication	0.63	0.49	5.60	0.65								
Ecotoxicity	1.27	0.99	26.22	3.04								
Land occupation	0.48	0.38	2.26	0.26								
Carcinogenic impacts					2.23	1.75	40.29	4.67				
Climate change					11.19	8.77	69.38	8.04				
Ionising radiation					0.01	0.004	0.14	0.016				
Ozone layer depletion					0.01	0.007	0.04	0.004				
Respiratory effects					6.40	5.01	92.36	10.7				
Fossil fuels									105.23	82.41	620.37	71.87
Mineral extraction									0.24	0.19	6.48	0.75
TOTAL	2.38	**1.86**	34.08	**3.95**	19.84	**15.54**	202.21	**23.43**	105.47	**82.60**	626.85	**72.63**

Table 4 presents a similar analysis for both operation modes, but for the ReCiPe method. Standing as a successor of EI-99 (as mentioned in section 3.3), this method provides a more detailed analysis for the same three categories analysed by EI-99, especially for Ecosystem and Human Health. The percentages for both modes were very similar in this method (about 19% for Ecosystem, 31% for Human Health, and 50% for Resources). For the three main categories, the ORC-C presented approximately six times higher impacts compared to those of ORC-S. Ecosystem category now incorporates nine impact categories, including climate change which presents the highest impact share (around 18% for both modes). Also, Human Health category now comprises six impact categories and, differently from EI-99, the climate change impact category makes now a significantly higher contribution (around 28% for both modes).

Table 4. Overall contribution of the ReCiPe impact categories for both ORC operation modes

	ECOSYSTEM				HUMAN HEALTH				RESOURCES			
	ORC-S		ORC-C		ORC-S		ORC-C		ORC-S		ORC-C	
Impact category	**[mPt]**	**%**	**[mPt]**	**%**	**[mPt]**	**%**	**[mPt]**	**%**	**[mPt]**	**%**	**[mPt]**	**%**
Agricultural land occupation	0.15	0.07	2.60	0.20								
Urban land occupation	0.10	0.05	1.59	0.12								
Climate change	36.55	18.25	225.93	17.34								
Freshwater ecotoxicity	0.01	0.007	0.09	0.0069								
Freshwater eutrophication	0.00	0.002	0.13	0.0097								
Marine ecotoxicity	0.00	0.0006	0.02	0.0012								
Natural land transformation	0.98	0.49	5.15	0.40								
Terrestrial acidification	0.03	0.01	0.20	0.015								
Terrestrial ecotoxicity	0.03	0.02	0.10	0.0079								
Climate change					57.82	28.87	357.44	27.44				
Human toxicity					1.38	0.69	18.59	1.43				
Ionising radiation					0.00	0.001	0.08	0.0063				
Ozone depletion					0.02	0.01	0.08	0.0062				
Particulate matter formation					3.32	1.66	39.53	3.03				
Photochemical oxidant formation					0.07	0.04	0.66	0.051				
Fossil resource depletion									95.27	47.57	593.02	45.52
Metal resource depletion									4.54	2.27	57.64	4.42
TOTAL	37.86	**18.90**	235.80	**18.10**	62.61	**31.26**	416.39	**31.96**	99.81	**49.83**	650.65	**49.94**

Among the main causes for the higher share from the climate change impact category (Table 4), there is the extraction of natural gas, gas distribution, and the generation, transmission, and distribution of electric power. The results are air emissions accounting for carbon dioxide, dinitrogen monoxide, and methane. Amongst them, the highest contributor by far is the CO_2 emissions, which account for 99.7%. For the ORC-S mode, the CO_2 emissions contributed with 1.65 kg CO_2/kWh of electricity production, whereas for the ORC-C mode the CO_2 emissions contributed with 9.16 kg CO_2/kWh of electricity production. The main reason for such higher CO_2 emission for ORC-C is the heat production, from natural gas, to feed the absorption chiller responsible to provide the cooling energy for that operation mode.

4.2. Impacts and LCIA comparison for production, transportation, and system operation phases from both ORC modes

The aim of this section is to provide detailed information about the different phases described in the goal and scope of the present LCA (section 3.1). As presented in Fig. 4 and 5, the main phases for both ORC modes are the production of each component, the transportation to the IES facility, and the operation of the system. Detailed information about input data such as materials, components mass, and distances are shown in Tables 1 and 2. It is important to bear in mind that, for this section, the production and transportation phases were accounted together as their reference unit is the same (kg). On the other hand, the system operation phase is based on a reference unit of energy (kWh).

Figure 7 presents the environmental impact levels, calculated through EI-99 and ReCiPe, for the production, transportation, and system operation phases, only for the ORC-S mode. As observed on the left-hand side chart, both LCIA simulations resulted in approximately 105 Pt (for the total mass of the components), with a difference of 1.97% for EI-99. Still in the same chart, the order of the components (from left to right) follows the descending order of their mass, especially for EI-99. For the case of ReCiPe, the descending order was "broken" in the condenser. It is also in this same equipment where the ReCiPe simulation resulted in a higher value compared to that of EI-99. The same happened for the liquid accumulator, expander, and pump. This can be explained by the fact that, for these components, it was considered a percentage of steel among their raw materials. Therefore, with the more up-to-date data of the ReCiPe method [36] and the fact that the ReCiPe indicators are more detailed than those of EI-99 [37], it supports a more accurate model also for the steel production chain.

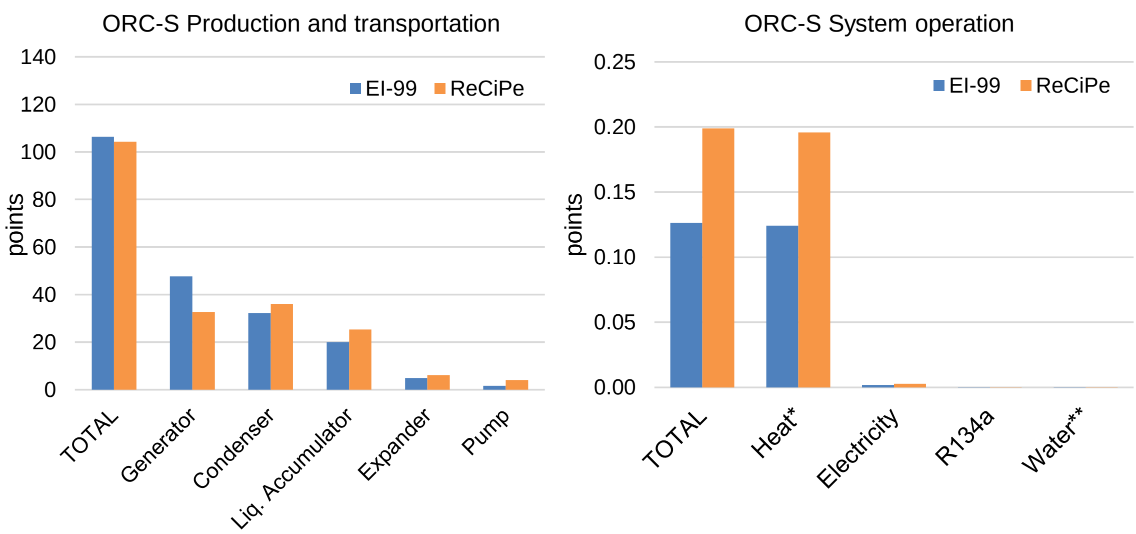

*Fig. 7. ORC-S environmental impacts for the phase of Production and Transportation (for each component's total mass) and System Operation (for 1 kWh of produced energy). Comparison between EI-99 and ReCiPe methods. *Heat from cogeneration, **Water from cooling tower*

The graph on the right-hand side of Fig. 7 shows the environmental impact levels for the ORC-S operation phase, also for both EI-99 and ReCiPe. As observed, the heat source obtained from a cogeneration system is by far the greatest contributor for the impacts derived from this phase, from both LCIA perspectives. The reason for this is due to the production and supply chain of the natural gas, especially when it comes to climate change effects regarding the Ecosystem and Human Health categories. The discrepancy between both LCIA methods (57.39% more for the ReCiPe) could be attributed also to the more up-to-date and detailed ReCiPe database.

Likewise, Figure 8 shows the environmental impact levels for the ORC-C mode, also for both LCIA methods and for the production, transportation, and system operation phases. The graph on the left-hand side is similar to that of Fig. 7, especially the results for the generator, condenser, liquid accumulator, expander, and pump. The difference is that now it is included the air-conditioning heat exchanger, which is the reason for the higher total environmental impact level. For that reason, the production and transportation phases of the

ORC-C mode generate an impact around 9% and 15% higher than those of the ORC-S mode, for EI-99 and ReCiPe methods respectively. Moreover, the total EI-99 impact result is now 7.38% higher than that of ReCiPe due to the higher impact levels resulted from the EI-99 simulation for the air-conditioning heat exchanger.

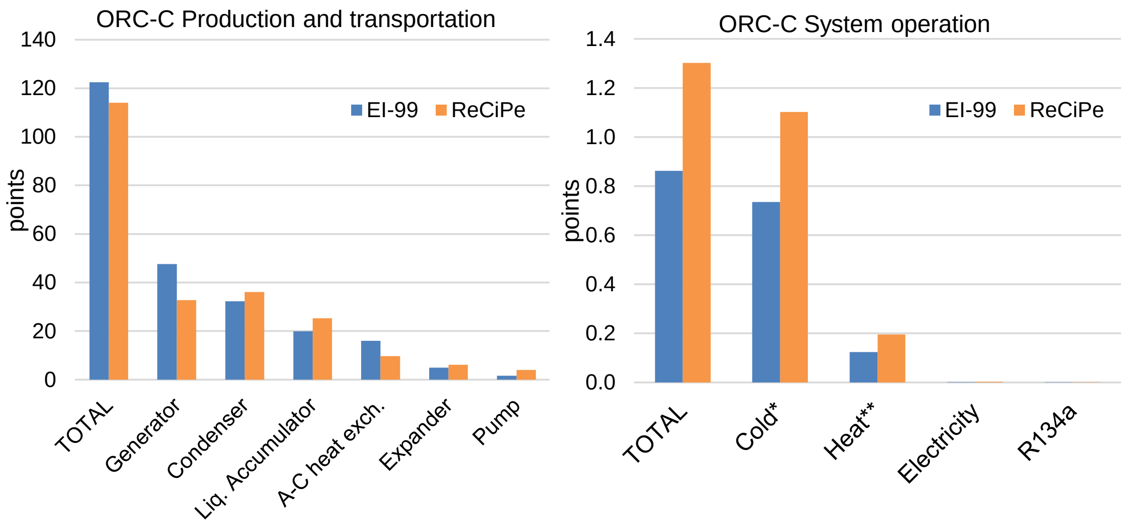

*Fig. 8. ORC-C environmental impacts for the phase of Production and Transportation (for each component's total mass) and System Operation (for 1 kWh of produced energy). Comparison between EI-99 and ReCiPe methods. *Cold water from absorption chiller, **Heat from cogeneration*

The graph on the right-hand side of Fig. 8 presents the environmental impact levels for the ORC-C operation phase, also for EI-99 and ReCiPe. This time, the cooling energy from the absorption chiller is the main contributor to the total impacts due to the high CO_2 emissions resulting from its heat source, i.e., the heat production through a cogeneration system using natural gas as the energy source. The other utilities necessary to run the system (heat, electricity, and working fluid) accounts for the same impact levels as for the ORC-S. For this reason, with total impact levels of 0.86 and 1.30 Pt for EI-99 and ReCiPe, respectively, the ORC-C operation mode causes an environmental impact almost seven times higher compared to that of ORC-S, for each kWh of produced electricity.

4.3. Dominance analysis

According to Baumann et al. [38], a useful method to identify the major contributors to the environmental burden of a product in a LCA is the dominance analysis. It simply compares the relative importance between each composition item that makes part of a given object of study. Bearing such definition in mind, this section aims to identify the main sources of environmental impacts within the production, transportation, and system operation phases described in section 3.1. Due to the more up-to-date and detailed database of the ReCiPe method (as mentioned in section 4.1), such impacts are presented through the results obtained only through this method.

For the next section, the results are presented in three groups of charts: 1) production, 2) common operation system utilities for both ORC modes plus transportation, 3) processes representing the sink for each ORC mode. The liquid accumulator and the air-conditioning heat exchanger were kept outside the first group of charts because the former was considered made only by one kind of raw material (steel) and the later makes part of only one ORC mode.

4.3.1. Dominance analysis through the ReCiPe method

As can be seen from Fig. 9, the most dominant production processes causing the higher environmental impacts for the production phase of both ORC modes are copper, ferrochromium, and cast iron.

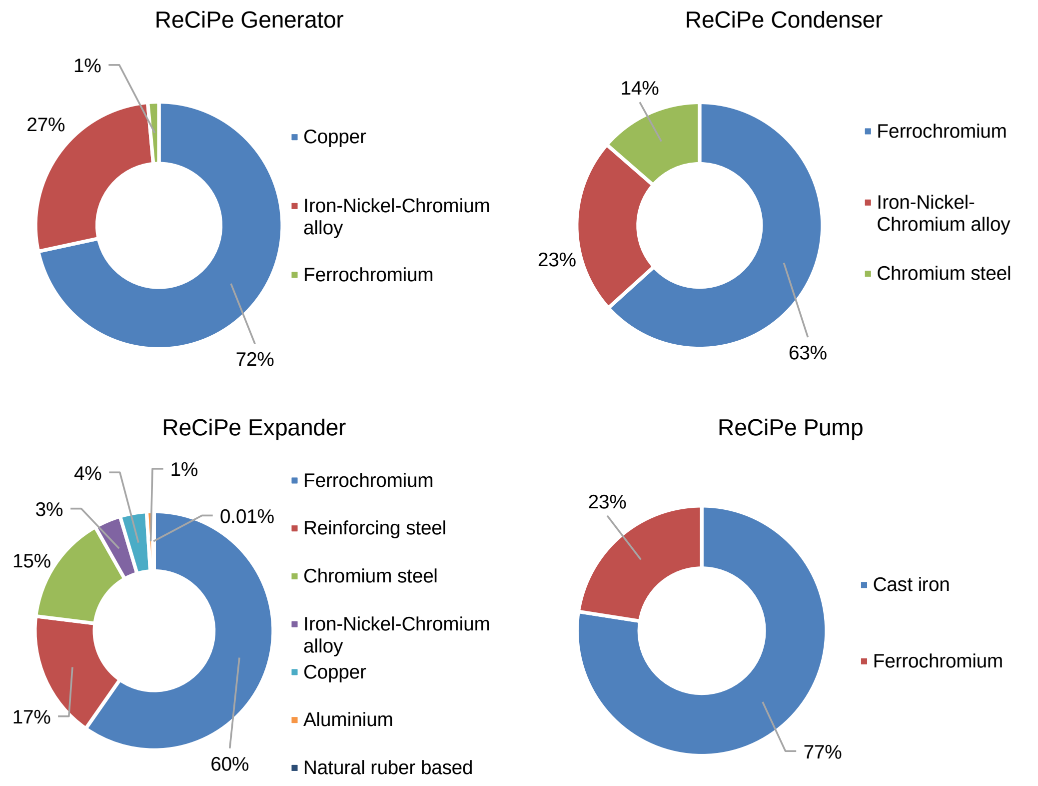

Fig. 9. Dominance analysis for common components of both ORC operation modes.

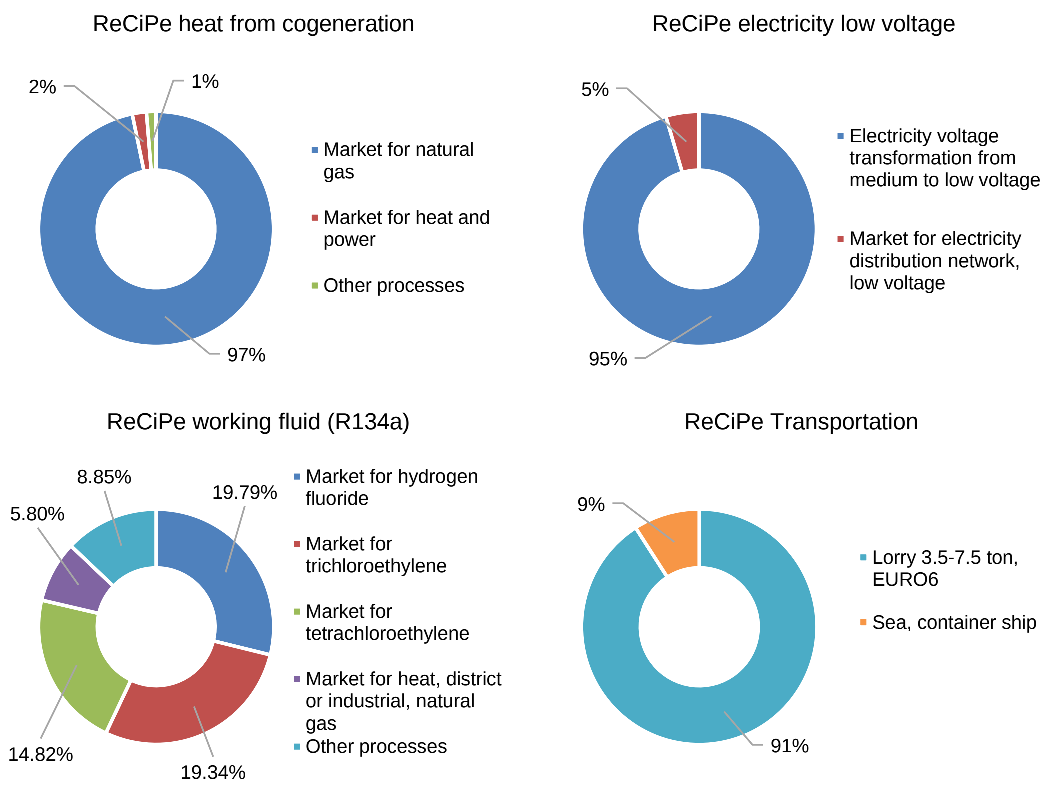

Fig. 10. Dominance analysis of common operation utilities (for both ORC modes) plus transportation

Copper is in fact characterized by very intensive energy-consuming extraction and production phases, which results in high environmental impacts mainly due to the electricity production from hard coal [39] in producing countries such as China that had a share of 40% of the total world processed copper in 2019 [40]. The iron-based industry is indeed one of the most energy-demanding and CO_2 emitters among the main heavy industry sectors [41].

Figure 10 shows the dominance analysis for the heat source, electricity consumption, and working fluid used in the ORC operation phase, as well as for the transportation phase. As expected, the major impact contributor for the heat production is the consumption of natural gas due to the reasons already presented in section 4.1. As for the electricity, the highest share is for the electricity voltage transformation from medium to low voltage. This is probably due to the need for more complex equipment to perform such transformation. The analysis for the working fluid shows an even contribution between the main substances that comprise the R134a, which demonstrate equivalent energy consumption throughout its production, although it has a very low impact contribution (Fig. 8). When it comes to the transportation phase, the results showed a much higher contribution for the lorry. This might be reasonably inferred if it is compared the amount of load that a lorry and ship can carry, instead of the distances. A ship can carry around 20 thousand more loads compared to a lorry. Thus, the number of emissions per kg of transported goods will be much smaller when transported through a ship container.

The last two charts (Fig. 11), show the dominance analysis for the considered processes responsible for acting as the ORC heat sink. As the cooling energy process is powered by natural gas, its major contribution to such process was in fact expected and the main causes, as mentioned in section 4.1, are emissions such as CO_2, and noble gases, as well as water consumption. For the case of water from a cooling tower, it was considered softened water, which requires indeed more electricity if compared to the other elements of its obtaining process.

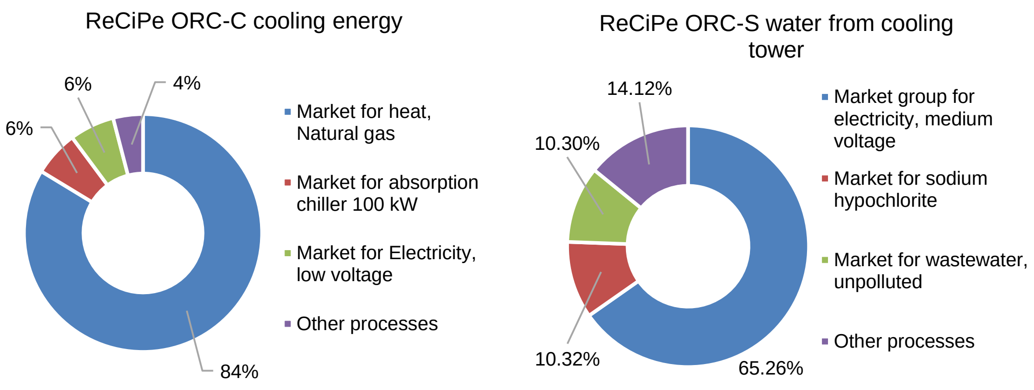

Fig. 11. Dominance analysis for the processes representing the heat sink for each ORC mode.

5. Conclusions

Considering the increasing interest in the environmental assessment of thermal systems, this paper performed a Life Cycle Assessment of an ORC system working under two different operation modes, comparing two different LCIA methods. The mentioned ORC system was previously studied by the authors through a thermodynamic and economic viewpoint and, thus, the present paper stands as a continuation of the project intending to increment the database for decision-makers.

The defined scope were the two ORC operation modes, ORC-S and ORC-C. The most important difference between them is the heat sink, i.e., the ORC-S condenser heat is removed by a cooling tower whereas the ORC-C condenser heat is removed by a cooling water stream from an absorption chiller, besides consider an air-conditioning space room. Therefore, in more detail, the main difference is on the production and transportation phases (as there is one more component for the ORC-C), and on the operation phase (since the cooling is an additional product for the case of ORC-C).

The analysis of the total environmental impacts produced by each kWh of generated electricity demonstrated a higher contribution of the Resources category, for both EI-99 and ReCiPe and both ORC modes. In the case of EI-99, it represented more than 70% for ORC-C and more than 80% for ORC-S, whereas in the case of ReCiPe it corresponds to about 50% for each ORC mode. The main reason for that is the utilization of fossil fuels throughout the life cycle of each process (Table 3 and 4).

The Human Health and Ecosystem categories represented a smaller part of the total impacts resulting from the EI-99 method. However, the same categories together corresponded to almost 50% of the total impacts for the ReCiPe method since it is a more up-to-date and detailed LCIA method (as explained in section 4.2). From that percentage, 46% relates to climate change alone, which has as its main villain, the natural gas production chain, resulting in 1.65 kg CO2/kWh for ORC-S and 9.16 kg CO2/kWh for ORC-C. Moreover, the ORC-C mode resulted in, at least, 6 times more impacts (both LCIA methods) when compared to the ORC-S mode, but specifically in the case of EI-99, this difference can reach around 14 times.

Regarding the production and transportation phases, the impacts are, in general, directly proportional to each component's mass (for both ORC modes). However, when it comes to the ReCiPe method, results showed that this proportionality is altered for components with steel in their composition. When it comes to the operation phase, the highest impact contributions are accounted to the heat source (ORC-S) and the cooling energy (ORC-C).

Acknowledgments

The second author gratefully acknowledges the financial support of FAPESQ/CAPES – Brazil.

Nomenclature

LCA	Life Cycle Assessment
ORC-S	Organic Rankine Cycle – Simple
ORC-C	Organic Rankine Cycle - Combined
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
IES	Institute of Sustainable Energy
mPt	millipoints
EI-99	Eco-Indicator 99

References

[1] IEA – International Energy Agency. Key World Energy Statistics 2017 – Available at: <http://www.iea.org/statistics/> [accessed 2.2.2021].

[2] UNFCCC—United Nations Framework Convention on Climate Change. The Paris Agreement. 2015. Available at: <https://unfccc.int/sites/default/files/english_paris_agreement.pdf> [accessed 3.4.2021]

[3] European Commission. European Green Deal (2019) Bruxelas. Available at: <https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0008.02/DOC_1&format=PDF> [accessed 15.4.2021]

[4] Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., et al. IPCC, 2018: Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. Available at: <https://www.ipcc.ch/site/assets/uploads/sites/2/2018/07/SR15_SPM_version_stand_alone_LR.pdf> [accessed 10.4.2021].

[5] Ochoa A.A.V., Dutra J.C.C., Henríquez J.R.G., Dos Santos C.A.C. Dynamic study of a single effect absorption chiller using the pair LiBr/H2O. Energy Convers Manag 2016;108:30-42.

[6] Ochoa A.A.V., Dutra J.C.C., Henríquez J.R.G., Dos Santos C.A.C., Rohatgi J. The influence of the overall heat transfer coefficients in the dynamic behavior of a single effect absorption chiller using the pair LiBr/H2O. Energy Convers Manag 2017;136:270-82.

[7] Angrisani G., Akisawa A., Marrasso E., Roselli C., Sasso M. Performance assessment of cogeneration and trigeneration systems for small scale applications. Energy Convers Manag 2016;125:194-208.

[8] Cavalcanti E.J.C. Exergoeconomic and exergoenvironmental analyses of an integrated solar combined cycle system. Renew Sustain Energy Rev 2017;67:507-19.

[9] Cavalcanti E.J., Carvalho M., Ochoa A.A.V. Exergoeconomic and exergoenvironmental comparison of diesel-biodiesel blends in a direct injection engine at variable loads. Energy Convers Manag 2019;183:450-61.

[10] García S.G., Montequín V.R., Fernandez R.L., Fernandez F.O. Evaluation of the synergies in cogeneration with steel waste gases based on Life Cycle Assessment: a combined coke oven and steelmaking gas case study. J Clean Prod 2019;217:576-83.

[11] Chitsaz A., Sadeghi M., Sadeghi M., Ghanbarloo E. Exergoenvironmental comparison of internal reforming against external reforming in a cogeneration system based on solid oxide fuel cell using an evolutionary algorithm. Energy 2018;144:420-31.

[12] Gładysz P., Saari J., Czarnowska L. Thermo-ecological cost analysis of cogeneration and polygeneration energy systems-Case study for thermal conversion of biomass. Renew Energy 2020;145:1748-60.

[13] Hashemian N., Noorpoor A. Assessment and multi-criteria optimization of a solar and biomass-based multi-generation system: thermodynamic, exergoeconomic and exergoenvironmental aspects. Energy Convers Manag 2019;195:788-97.

[14] Rocha D., Silva R.J. Exergoenvironmental analysis of a ultra-supercritical coalfired power plant. J Clean Prod 2019;231:671-82.

[15] Ghofrani I., Moosavi A. Exergoeconomic optimization and environmental analysis of a novel solar-trigeneration system for heating, cooling and power production purpose. Energy Convers Manag 2020;205:112349.

[16] Blumberg T., Lee Y.D., Morosuk T., Tsatsaronis G. Exergoenvironmental analysis of methanol production by steam reforming and autothermal reforming of natural gas. Energy 2019;181:1273-84.

[17] Aghbashlo M., Tabatabaei M., Rastegari H., Ghaziaskar H.S. Optimization of continuous glycerol esterification with acetic acid based on exergoeconomic and exergoenvironmental approaches. Sustainable Production and Consumption 2019;17:62-73.

[18] Ansarinasab H., Mehrpooya M., Sadeghzadeh M. An exergy-based investigation on hydrogen liquefaction plant-exergy, exergoeconomic, and exergoenvironmental analyses. J Clean Prod 2019;210:530-41.

[19] Souza R.J., Dos Santos C.A.C., Ochoa A.A.V., Marques A.S., Neto J.L.M., Michima J.L.M. Proposal and 3E (energy, exergy, and exergoeconomic) assessment of a cogeneration system using an organic Rankine cycle and an Absorption Refrigeration System in the Northeast Brazil: Thermodynamic investigation of a facility case study. Energy Convers. Manag 2020;217:113002.

[20] Cavalcanti E.J.C., Carvalho M., Ochoa A.A.V. Exergoeconomic and exergoenvironmental comparison of diesel-biodiesel blends in a direct injection engine at variable loads. Energy Conversion and Management 2019;183:450-61.

[21] Rossi F., Parisi M.L., Maranghi S., Manfrida G., Basosi R., Sinicropi A. Environmental impact analysis applied to solar pasteurization systems. Journal of Cleaner Production 2019;212:1368-1380.

[22] Bahlawan H., Poganietz W.R., Spina P.R., Venturini M. Cradle-to-gate life cycle assessment of energy systems for residential applications by accounting for scaling effects. Applied Thermal Engineering 2020;171:115062.

[23] ElectraTherm Inc. by BITZER Group. Available at: <https://electratherm.com/> [accessed 15.1.2022]

[24] Sanden International (USA), Inc. Available at: <https://www.sanden.com/scrollcompressors.html> [accessed 15.1.2022]

[25] Exergoenvironmental model of Organic Rankine Cycle system including the manufacture and leakage of working fluid. Energy 2018;145:52-64.

[26] Burkhardt J.J., Heath G.A., Turchi C.S. Life Cycle Assessment of a Parabolic Trough Concentrating Solar Power Plant and the Impacts of Key Design Alternatives. Environmental Science & Technology 2011;45(6):2457-2464.

[27] Cioccolanti L., Hamedani S.R., Villarini M. Environmental and energy assessment of a small-scale solar Organic Rankine Cycle trigeneration system based on Compound Parabolic Collectors. Energy Convers Manag 2019;198:111829.

[28] Honeywell Chemicals. Available at: <https://www.honeywell-refrigerants.com/india/product/tag/all-refrigerants/> [accessed 15.1.2022]

[29] OpenLCA 1.10.3, GreenDelta. Available at: <http://www.openlca.org> [accessed 22.1.2021]

[30] Ecoinvent Database 3.7.1. Available at: <https://nexus.openlca.org/databases> [accessed 22.1.2021]

[31] International Organization for Standardization. ISO 14040: 2006: environmental management - life cycle assessment - principles and framework. Geneva: ISO; 2006a.

[32] International Organization for Standardization. ISO 14044: 2006: environmental management - life cycle assessment - requirements and guidelines. Geneva: ISO; 2006b.

[33] Marques A.S., Carvalho M., Ochoa A.A.V., Abrahão R., Santos C.A.C. Life cycle assessment and comparative exergoenvironmental evaluation of a micro-trigeneration system. Energy 2021;2016:119310.

[34] National Institute for Public Health and the Environment. Netherland 2016. Available at: <https://www.rivm.nl/bibliotheek/rapporten/2016-0104.pdf> [accessed 2.2.2022]

[35] Eco-indicator 99 Manual for Designers - Pre-Sustainability. Available at: <https://pre-sustainability.com/legacy/download/EI99_Manual.pdf> [accessed 2.2.2022]

[36] Pré Sustainability B.V. Available at: <https://pre-sustainability.com/articles/recipe/> [accessed 15.2.2022]

[37] Wang L., Wu H., Hu Y., Yu Y., Huang K. Environmental Sustainability Assessment of Typical Cathode Materials of Lithium-Ion Battery Based on Three LCA Approaches. Energies 2019:7(2):83

[38] Baumann H., Berlin J., Brunklaus B., Lindkvist M., Löfgren B., Tillman AM. The Usefulness of an Actor's Perspective in LCA. In: Finkbeiner M. (eds) Towards Life Cycle Sustainability Management. Springer 2011, Dordrecht. https://doi.org/10.1007/978-94-007-1899-9_8

[39] Dong D., Oers L.V., Tukker A., Voet E.V.D. Assessing the future environmental impacts of copper production in China: Implications of the energy transition. Journal of Cleaner Production 2020;274:122825

[40] IEA (2021), The Role of Critical Minerals in Clean Energy Transitions, IEA, Paris. Available at: <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions> [accessed 10.3.2022]

[41] IEA (2020), Iron and Steel Technology Roadmap, IEA, Paris. Available at: <https://www.iea.org/reports/iron-and-steel-technology-roadmap> [accessed 10.3.2022]