

25<sup>th</sup> ABCM International Congress of Mechanical Engineering  
October 20-25, 2019, Uberlândia, MG, Brazil

COB-2019-0945

## ANALYSIS OF THE EXERGETIC LIFE CYCLE OF RANKINE AND ORGANIC RANKINE CYCLES

**Adriano Souza Leão**

**Pedro Martins de Oliveira**

**Valter Estevão Beal**

**Edna dos Santos Almeida**

**Alex Álisson Bandeira Santos**

SENAI CIMATEC – Integrated Campus of Manufacturing and Technology, Orlando Gomes Avenue 1845, Salvador BA, Brazil

adrianoaleaoeng@outlook.com

pedromartins175@gmail.com

valtereb@fieb.org.br

ednasa@fieb.org.br

alex.santos@fieb.org.br

**Abstract.** *This study assesses the exergetic life cycle of thermodynamic systems based on Rankine and Organic Rankine cycles, covering two dimensions of the exergy namely here operational and embedded. The operational exergy was studied through the concepts of traditional thermodynamics, considering exergetic losses in the boiler and in the condenser. The embedded exergy was investigated considering the pre-operational stages of the system life cycle with the Cumulative Exergy Demand (CExD) method from cradle to gate. The Thermodynamic Sustainability Index (TSI) was estimated as well. The performances of eight scenarios with different inputs and setups were compared. The scenario with the highest operational performance as well as TSI was also the one with the lowest score considering both the magnitude and the quality of embedded exergy. Contrarily, the setup with the lowest operational exergetic efficiency outperformed in terms of embedded exergy. The inputs with the greatest embedment were the fuels, followed by the refrigerants. Except for the ethanol scenarios, the inputs showed low exergetic quality due to the predominance of non-renewable sources. These results can support design and decision-making.*

**Keywords:** *Embedded Exergy, Exergy Analysis, Cumulative Exergy Demand, Life Cycle Assessment, Thermodynamic Cycle*

### 1. INTRODUCTION

In accordance with the first law of thermodynamics, energy can not be destroyed in a process, instead it is transformed. What is consumed and eventually exhausted is usable or available energy, so-called exergy. The exergy concept is widely used to assess the energy efficiency of thermodynamic cycles by estimating the destruction of the potential to perform useful work and identifying its main sources of irreversibility.

The pre-operational stages are not covered in the standard exergetic analysis. In accordance with Rocco et al. (2014), an exergy analysis should be verified by a Life Cycle Assessment (LCA) since the decrease of the internal irreversibility of a given system may not always be accompanied by the reduction of its primary energy sources.

The concept of exergy was introduced in the LCA as an indicator of the energy content quality of resources. In the life cycle of a product, process or service, one can estimate the "removal" of exergy from nature no longer be available for future exploration (Ehtiwesh et al. 2016). According to Silva et al. (2018), the exergy methods in LCA can help reduce the use of natural resources, the environmental pollution and the discharge of waste.

The exergy embedded into a product system's corresponds to the minimum work required for its production or to the maximum amount of work made available when bringing its components to the most common state in the natural environment (Bösch et al. 2007). As the natural environment is not in thermodynamic equilibrium, the method considers "reference species" for all elements that represent the most stable compounds naturally found.

The more exergy is embedded into a product, the greater the impact associated with its use. From the point of view of the reversibility, the embedded exergy is irreversible.

To date, we have found that the state of the art of exergetic life cycle analysis consists of a limited number of publications conducted through distinct and non-consensual approaches. This number narrows further with regard to the analysis of thermodynamic cycles. Cornelissen and Hirs (2002) began this discussion by estimating depletion of natural resources, irreversibility and removal of exergy in a case study of treatment of wood residues in the Netherlands.

Portha et al. (2010) conducted a coupled exergy analysis with carbon footprint of a petrochemical process in France. Boateng and Lee (2014) assessed an ethanol refinery in Malaysia based on exergy analysis, carbon footprint and TSI. Penchah et al. (2016) studied the production of agglomerated wood panels in Iran and identified hotspots in each subcategory of the embedded exergy.

Zhang et al. (2018) assessed energy and exergy efficiencies as well as carbon footprint of industrial coal boilers in China. Morosuk et al. (2016) studied a steam compression refrigeration machine through exergetic analysis and LCA. According to the authors, the cumulative exergy contribution of fuel production should be considered in analysis, but the one from equipment and machinery can be neglected. Ehtiwesh et al. (2016) in their exergetic and environmental study on solar panels corroborate with the conclusion that the main sources of cumulative exergy are fuels.

As we have observed, this subject is yet to be further explored. Thus, this work aims to assess the exergetic life cycle comprising both the embedded and the operational dimensions of thermodynamic systems by investigating Rankine and Organic Rankine cycles using different operational parameters and commonly found inputs.

## 2. MATERIALS AND METHODS

### 2.1 Embedded exergy

An exergetic life cycle scheme of a thermodynamic system is shown in Fig. 1. The system boundaries of this study cover both the production phase, measured by the embedded exergy, and the use phase, quantified by the operational exergy. Finally, the end-of-life phase represents recycling and final disposal activities.

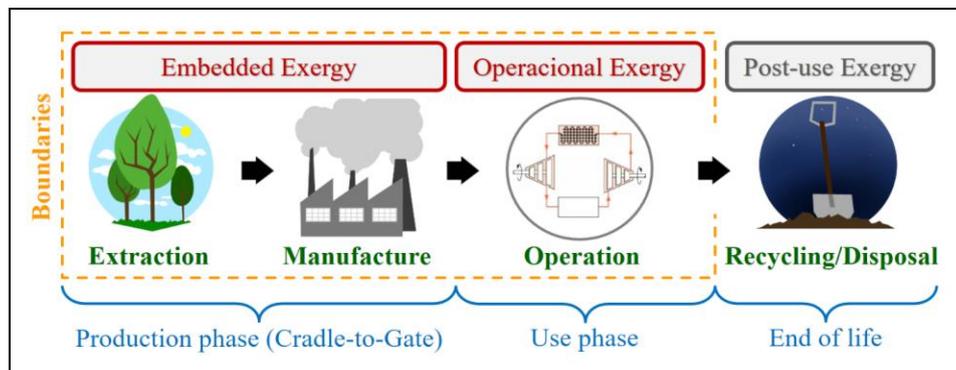


Figure 1. Exergetic life cycle of thermodynamic systems

For the embedded exergy estimation, an LCA was performed based on the ISO 14040 (2006a) and ISO 14044 (2006b). Within the LCA framework, the Cumulative Exergy Demand (CExD) characterization model was applied. It includes both the energy carrying materials (such as fuels) and the non-energy materials (such as metals) (Ehtiwesh et al. 2016).

This model accounts for the exergy stored in the products in the form of chemical, kinetic, hydro-potential, nuclear, solar-radiative and thermal exergy (Bösch et al. 2007). In terms of resource sources, it is divided into ten subcategories: fossil, nuclear, primary, minerals and metals as non-renewables; and kinetic, solar, potential, biomass and water as renewables; all expressed in  $\text{MJ}_{\text{equivalent}}$ . The analysis performed covered extraction of raw materials and manufacture of products. Transport scenarios from gate to use phase were not modeled. The software SimaPro 8.4, Ecoinvent v3.4 database and CExD v1.05 method with educational licenses were used.

### 2.2 Operational exergy

For the operational exergy calculation, the Rankine cycle was assessed. It consists of a steam power cycle in which the working fluid, often water, passes through the components with no irreversibility. Therefore, the processes occurring in the turbine and the pump are isentropic. This cycle is the most used for electricity generation. The main difference of an Organic Rankine cycle is the working fluid, which is a refrigerant instead of water. The simulations were conducted using Rankine cycles both alone and coupled with an Organic Rankine cycle, which exploits the exhaust gases from the first one (Fig. 2). The analysis was based on the thermodynamic basic principles, as shown in Eq. 1.

The following premises were adopted: environment conditions of 25 °C and 1 atm; condenser inlet conditions of 25 °C, 50% of relative humidity; condenser outlet is saturated and dry air flows at 100 kg/s; surface exergy of heat exchanger represents a negligible portion of the overall exergy loss (Zhang et al. 2018); perfect insulation of heat exchanger and fluid conduits; turbine and pump efficiency of 75% (these parameters were set to assess the impacts of fuels); leakage of working fluid after the pump and the turbine.

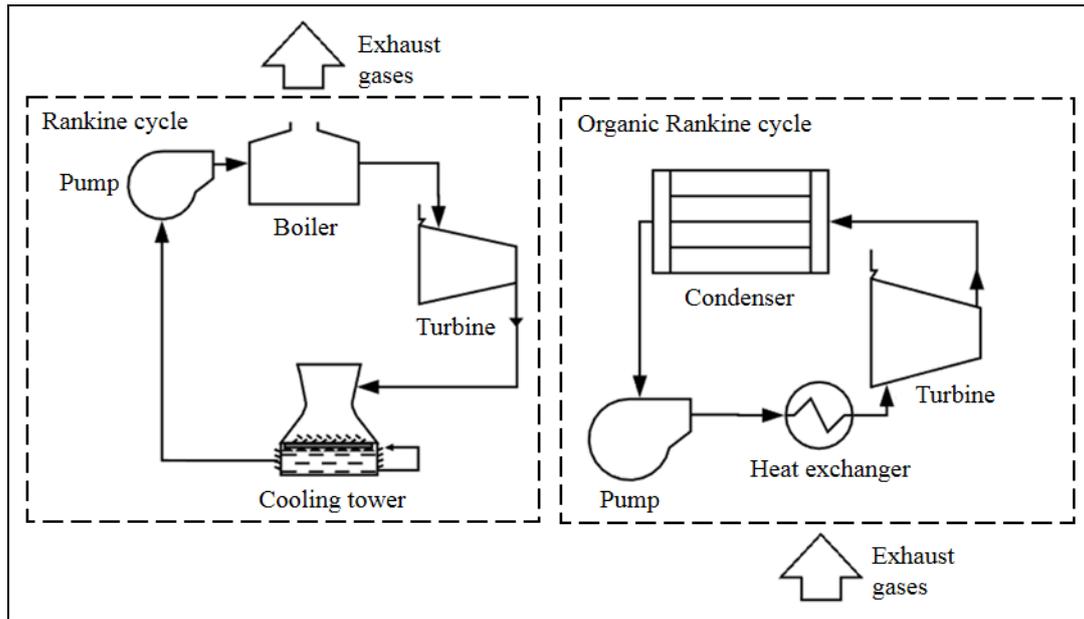


Figure 2. Rankine and Organic Rankine cycles

$$Ex_{flow} = m_{steam}((h_{flow} - h_o) - T_o(S_{flow} - S_o)) \quad (1)$$

Where  $Ex$  = exergy,  $m$  = mass flow,  $h$  = enthalpy,  $T$  = temperature, and  $S$  = entropy.

The boiler models exergy flowchart are shown in Fig. 3. They yield Eq. 2, Eq. 3, Eq. 4 and Eq. 5. As mentioned in the premises statement, the heat output state depends on the amount of heat to be removed from the working fluid, as in Eq. 6. The condenser is considered as a cooling tower as shown in Fig. 4, thus the water consumed is the difference between the inlet and outlet air absolute humidities as in Eq. 7. Both energy and exergy efficiencies depend on the fuel characteristic and boiler performance, as in Eq. 8 and Eq. 9. The fuels studied were lignite coal, kerosene, biogas and ethanol. The boilers efficiencies are shown in Tab. 1.

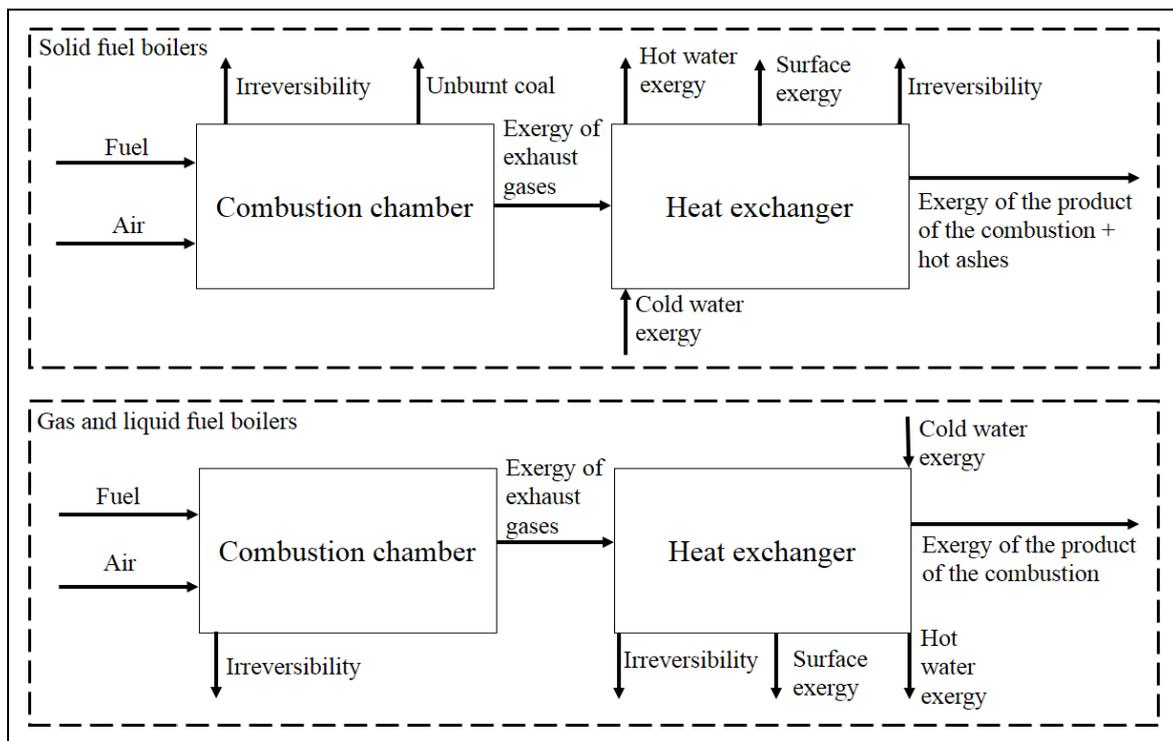


Figure 3. Boilers exergy flowchart

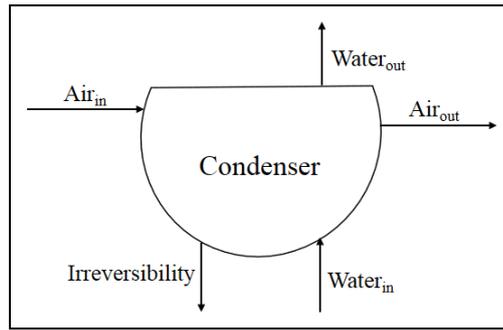


Figure 4. Condenser flowchart

$$EX_{Fuel} + EX_{Air} = EX_{Exhaust} + EX_{Unburnt\ coal} + I \quad (2)$$

$$EX_{Fuel} + EX_{Air} = EX_{Exhaust} + I \quad (3)$$

$$EX_{Exhaust} + EX_{Cold\ water} = EX_{Hot\ water} + EX_{Hot\ ash} + EX_{Product\ of\ combustion} + EX_{Surface} + I \quad (4)$$

$$EX_{Exhaust} + EX_{Cold\ water} = EX_{Hot\ water} + EX_{Product\ of\ combustion} + EX_{Surface} + I \quad (5)$$

$$Q = m(h_{(t,100\%rh)} - h_{(25^{\circ}C, 50\%rh)}) \quad (6)$$

$$EX_{Air(in)} + EX_{Water(in)} = EX_{Air(out)} + EX_{Water(out)} + I \quad (7)$$

$$\eta_{En} = (W_{Turbine} - W_{Pump})/Q_{Boiler} \quad (8)$$

$$\eta_{Ex} = (W_{Turbine} - W_{Pump})/EX_{(in)} \quad (9)$$

Where  $Ex_i$  = exergy of component  $i$ ,  $I$  = irreversibility,  $Q$  = heat,  $m$  = mass flow,  $h$  = enthalpy,  $t$  = temperature,  $rh$  = relative humidity,  $\eta$  = efficiency, and  $W$  = work.

Table 1. Boiler efficiencies per fuel

Boiler fuel	Type of fuel	Efficiency	Reference
Lignite coal	Solid	68%	(Zhang et al. 2018)
Kerosene	Liquid	72%	(Saidur et al. 2010)
Biogas	Gas	68%	(Pambudi et al. 2017)
Ethanol	Liquid	63%	(Martin and Boateng, 2014)

### 2.3 Thermodynamic Sustainability Index

The Thermodynamic Sustainability Index (TSI) measures the ratio of input exergy and destroyed exergy during fossil fuel combustion (Eq. 10). This index can be used to infer about environmental impacts since the exergy efficiency can be associated with the emission of gases like CO<sub>2</sub>, SO<sub>2</sub>, NO<sub>x</sub> during the combustion of such fuels (Rosen et al. 2008). Nevertheless, this study expands this estimation for all fuels evaluated. A high TSI means great exergy efficiency as well as low atmospheric emissions, i.e. the higher the TSI the more thermodynamically sustainable is the fossil fuel system. According to Portha et al. (2010), the TSI starts to rise significantly above about 80% of exergetic efficiency.

$$TSI = EX_{(in)}/EX_{(Destroyed)} \quad (10)$$

### 2.4 Proposed scenarios and simulations

The scenarios were proposed in two different configurations, either Rankine cycle alone or coupled with Organic Rankine cycle. The first four setups were Rankine cycles alone, with four different fuels as well as ultrapure water as working fluid and regular industrial water in the condenser. The last four setups were coupled Rankine with Organic Rankine cycles, where the exhaust gases from the boiler of the Rankine cycle were used as the heat source of the Organic one. Such cases used two different fuels as well as two different organic working fluids (refrigerants). The premises of the regular Rankine cycle remained the same. The data from the eight simulated scenarios were compiled in Tab. 2.

The setups acronyms include the type of cycle, the fuel and the refrigerant, respectively. The inputs with the restitution function refer to the periodic refill due to the losses of water by evaporation through the boiler and by a simulated leakage of the working fluid. The only output flow considered here is the very result of the thermodynamic cycle, i.e. the useful energy generated in its functional unit: 1.0 MJ produced.

Table 2. Inventory of inputs per scenario to produce 1.0 MJ

Type	Input	Function	Scenario								Unit
			Rankine				Rankine + Organic R.				
			RL	RK	RB	RE	OEA	OER <sub>a</sub>	OBA	OBR <sub>a</sub>	
<b>Pump drive</b>	Electricity	Consumption	26,3	26,3	26,3	26,3	26,6	26,6	26,6	26,6	kJ
	Lignite	Consumption	0,62								kg
<b>Heater fuel</b>	Kerosene	Consumption		0,129							kg
	Biogas	Consumption			0,22				0,21	0,21	m <sup>3</sup>
	Ethanol	Consumption				0,21	0,22	0,22			kg
<b>Condenser cooling</b>	Water	Restitution	1,3	1,3	1,3	1,3	1,2	1,2	1,2	1,2	kg
<b>Rankine working fluid</b>	Ultrapure	Restitution	0,038	0,038	0,038	0,038	0,036	0,036	0,036	0,036	kg
	Water	Restitution									kg
<b>Organic Rankine working fluid</b>	Ammonia	Restitution					0,036		0,036		kg
	R134a	Restitution						0,037		0,037	kg

\*Acronyms: R: Rankine, O: Organic Rankine, L: Lignite, K: Kerosene, B: Biogas, E: Ethanol, A: Ammonia, R<sub>a</sub>: R134a

### 3. RESULTS AND DISCUSSION

Different configurations were simulated in order to understand how the choice of both material and energy inputs or a parameter variation affect a thermodynamic system operational performance as well as its life cycle exergetic efficiency. One configuration may raise the cycle output and, nevertheless, increase the embedded exergy, or vice versa. Knowing the exergetic footprint may be useful for designing and making decisions from a broader perspective.

The embedded exergy of a product provides two main information: the absolute value of exergy destruction and the share of renewable sources. This indicator has been divided into a set of renewable and non-renewable subcategories that reflect the quality of a product's content. Hence, it can be used as an indicator of its environmental profile. That is to say, the lower the exergy removal from nature and the lower the proportion of non-renewable sources, the higher is the exergo-environmental performance.

#### 3.1 Embedded exergy

The results were calculated as a ratio with the functional unit, i.e. MJ<sub>equivalent</sub> of embedded exergy per 1.0 MJ produced in the cycle. The inputs with the greatest embedded exergy were the fuels above all, followed by the refrigerants (Tab. 3, Fig. 5). All Rankine scenarios together with OEA, the fuels stood out as hotspots in both the magnitude and the renewable content criteria (Fig. 6). The OEA embedded exergy was an order of magnitude higher than RB, mainly due to the fuel, but also to the refrigerant. In the organic cycles OER and OBA, the refrigerants contributed considerably. In OBR<sub>a</sub>, the refrigerant stood out as a hotspot.

Table 3. Scenarios embedded exergy

Scenario	CExD (MJ)	Magnitude per input							Source quality			
		BW (MJ)	CW (MJ)	El (MJ)	F (MJ)	R (MJ)	Hotspots	Rank. (1-8)	Renew.	Non-renew.	Hotspots	Rank. (1-8)
<b>RL</b>	6,73	0,09	0,00	0,07	6,57		L	3	1,5%	98,5%	L	8
<b>RK</b>	7,60	0,09	0,00	0,07	7,44		K	4	1,7%	98,3%	K	7
<b>RB</b>	2,31	0,09	0,00	0,07	2,15		B	1	25,3%	74,7%	B	4
<b>RE</b>	20,70	0,09	0,00	0,07	20,6		E	6	93,0%	7,0%	E	1
<b>OEA</b>	23,68	0,09	0,00	0,07	21,6	1,98	E	7	85,7%	14,3%	E	2
<b>OER<sub>a</sub></b>	27,64	0,09	0,00	0,07	21,3	6,28	E, R <sub>a</sub>	8	73,2%	26,8%	R <sub>a</sub>	3
<b>OBA</b>	4,19	0,09	0,00	0,07	2,05	1,98	B, A	2	16,0%	84,0%	B, A	5
<b>OBR<sub>a</sub></b>	8,49	0,09	0,00	0,07	2,05	6,28	R <sub>a</sub>	5	11,0%	89,0%	R <sub>a</sub>	6

\*Acronyms: BW: Boiler Water, CW: Cycle Water, El: Electricity, F: Fuel, R: Refrigerant, L: Lignite, K: Kerosene, B: Biogas, E: Ethanol, A: Ammonia, R<sub>a</sub>: R134a

The setup with the greatest embedded exergy was the Organic with ethanol and R134a (OER). Water for the condenser cooling, water as working fluid and electricity contributions were not significant neither hotspots in any of the cases. The most renewable setup was the Rankine cycle with ethanol (RE). The RL and the RK setups were the least renewable ones. Assuming the same weight for both criteria, the best scenario was the Rankine cycle with biogas (RB), even with the predominance of non-renewable sources. The worst result was shared by four scenarios, with RL, RK and OBR<sub>a</sub> being attributed to the quality of the sources, and OER to the absolute value of the impact.

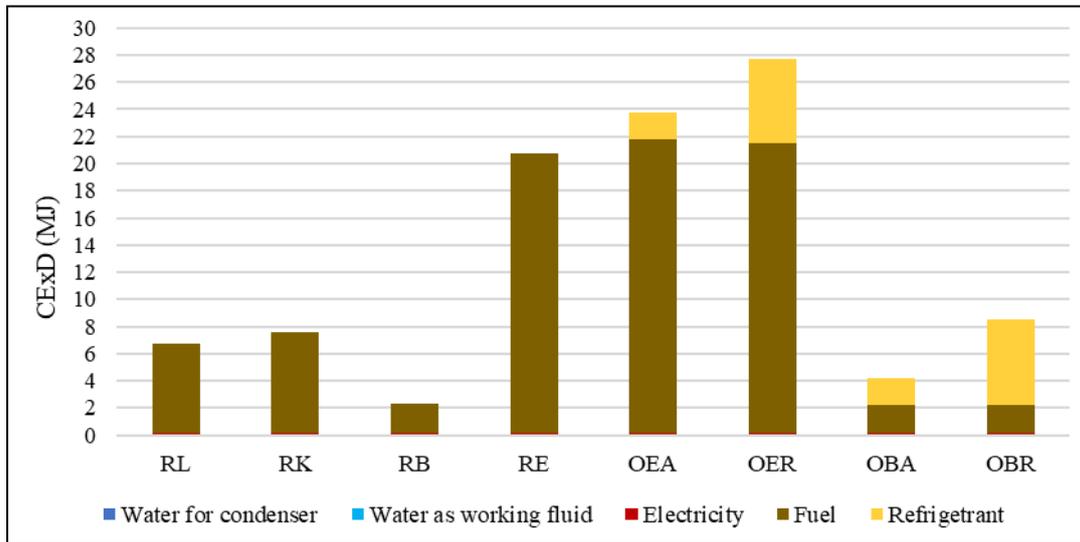


Figure 5. Magnitude of embedded exergy

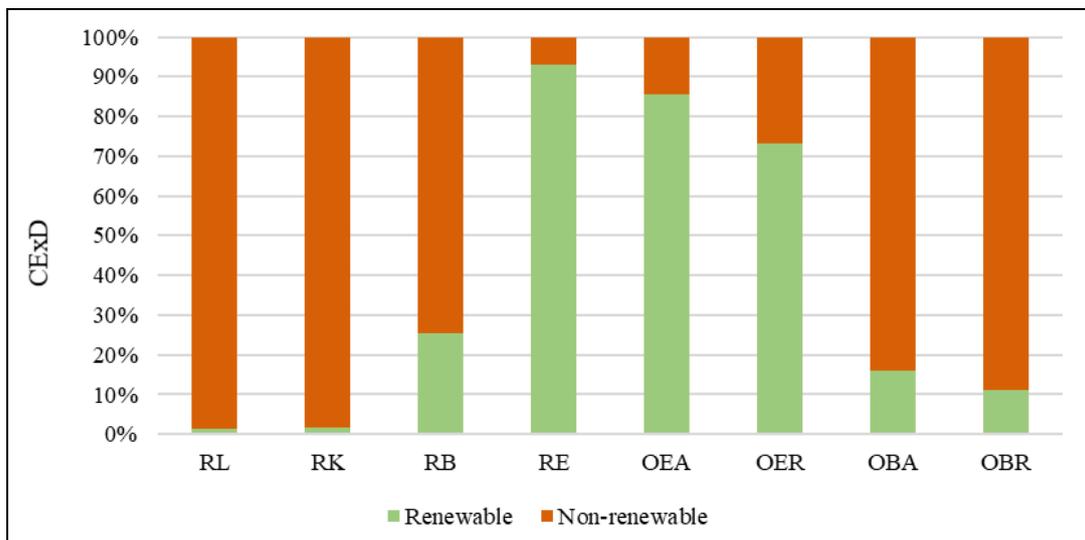


Figure 6. Quality of sources of embedded exergy

### 3.2 Operational exergy

The cases with the highest operational energetic and exergetic efficiencies were the ones that used ethanol with or without refrigerant (RE, OER and OER) (Tab. 4, Fig. 7). This is a consequence of the of the boiler characteristic. The exergetic efficiency was higher than the energetic one in all setups simulated. This can be explained by the fact that the lower heating values were greater than the exergy inputs. As for the fuels exergy calculation, impurity as well as ash concentration played an important role. The differences associated to low quality solid fuels were even more expressive. Lignite presents high ash content lowering its exergy significantly.

The higher exergy destructions were found both in the boiler and in the condenser. During the heat transfer within the boiler, these losses can be associated primarily to its low energetic efficiency, but also to the radiation loss and the hot gases exhaustion. In turn, the condenser lost exergy mainly by restoring the liquid state of the turbine's outlet fluid to be, then, compressed by the pump. Although the losses were significant, they do not rely exclusively on the

condenser performance. The exergy destroyed in the boiler of the Organic Rankine cycles was lower than that of the steam cycles. Although it benefits from the energy released by the boiler exhaust of the Rankine cycle, the Organic one naturally presents low efficiency, compensating the effects.

### 3.3 Thermodynamic Sustainability Index

The ratios between the input and the destroyed exergies of the thermal systems assessed are close to 1, which yield low TSI (Tab. 4). The cases with higher indexes were those with ethanol and refrigerants (OEA and OER), since a significant part of the hot gases loss is used by the organic cycle. The RE setup showed the smaller TSI due to the low loss in the boiler, which makes the losses in the condenser significant compared to the input exergy. The reduction in the boiler losses when coupling the organic cycle was significant, since the input exergy is low.

Table 4. Operational exergetic and energetic efficiencies and TSI

Scenario	Input exergy (kW)	Total losses		Performance		
		Exergy destruction of boiler (kW)	Exergy destruction of condenser (kW)	Energetic efficiency	Exergetic efficiency	TSI
<b>RL</b>	6.244	2.247	3.267	13,0%	14,8 %	1,13
<b>RK</b>	5.270	1.275	3.267	15,0%	16,5%	1,16
<b>RB</b>	6.547	2.549	3.267	13,7%	14,1%	1,13
<b>RE</b>	5.327	1.329	3.267	17,2%	17,3%	1,07
<b>OEA</b>	5.327	743	3.652	17,4%	17,6%	1,21
<b>OER<sub>a</sub></b>	5.326	544	3.652	17,6%	17,7%	1,27
<b>OBA</b>	6.547	1.967	3.652	13,9%	14,3%	1,17
<b>OBR<sub>a</sub></b>	6.547	1.764	3.652	14,0%	14,4%	1,20

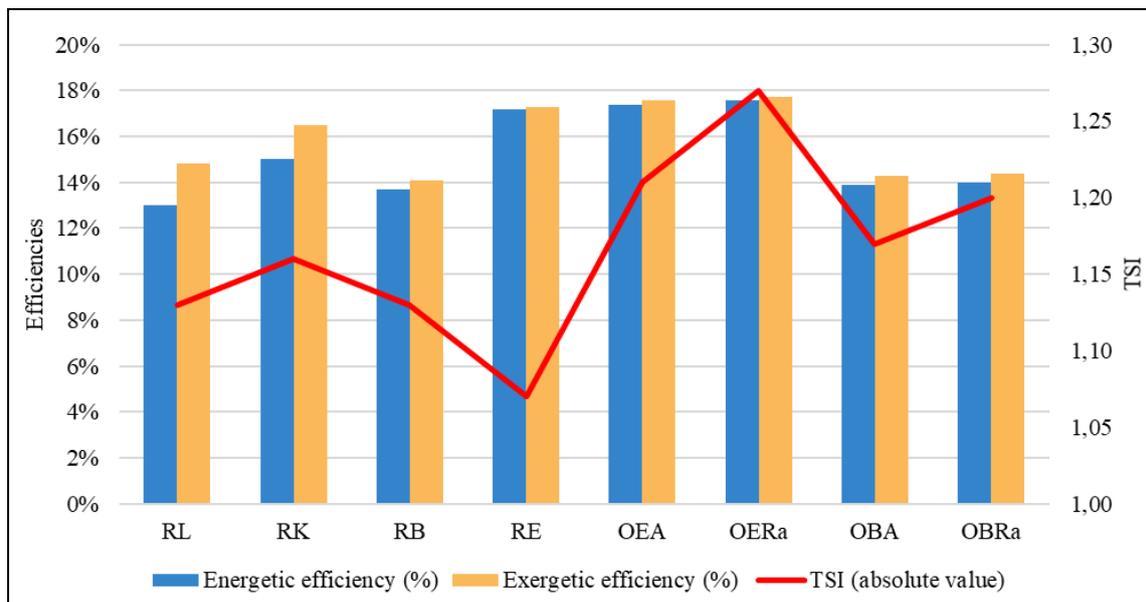


Figure 7. Operational exergetic and energetic efficiencies and TSI

### 3.4 Coupled embedded and operational exergies

From the operational exergy perspective, the OER<sub>a</sub> case presented both the greatest exergetic efficiency and the highest TSI (Tab. 4, Fig. 7). The RE was the scenario with the lowest TSI. Both setups were simulated with ethanol as the fuel and presented low losses in the boiler. The major differences were the use of ammonia as working fluid of the organic cycle and the use of the exhaust as the heat source. By better exploiting the exhaust exergy losses of the boiler of the Rankine steam water cycle, the OER<sub>a</sub> presented a 19% higher TSI than the RE.

Although the RE case yielded the lowest TSI, it outperformed in terms of renewable sources in its exergy profile (Fig. 6). This shows that for fuels with high renewable content, the TSI output does not necessarily mean a low environmental performance. The RB scenario had the lowest operational exergy efficiency, yet it was the one with the

highest score considering both the magnitude and quality of the embedded exergy. These results highlight the importance of assessing the thermal systems life cycle to enhance the understanding of their exergetic performance.

#### 4. CONCLUSION

This study aimed to assess how the choice of material and energetic inputs can affect the exergetic performance of thermodynamic systems life cycles. Results highlight that the substitution of an input or the variation in a design parameter can, for instance, enhance the operational efficiency and, nevertheless, increase the embedded exergy or the non-renewable content of inputs, affecting the overall performance, and vice-versa. The exergetic analysis comprising both the operational and the pre-operational phases can support the design and the decision making more consistently and comprehensively in addition to comprise environmental aspects.

The setup with the greatest exergetic efficiency as well as TSI in the operation stage was also the one with the worst performance regarding the exergy embedded during the pre-operational stages. On the other hand, the case with the lowest operational exergetic efficiency outperformed in terms of embedded exergy. Furthermore, it is noteworthy that low TSI does not always imply low environmental performance, especially for fuels with high renewable content.

The application of an organic cycle to exploit the exhaust energies in the cycle operation did not enhance the performance significantly, although they reduced the exergetic losses in the boilers. The inputs with the greatest embedded exergy were the fuels. In the organic cycles, the refrigerants also contributed significantly, standing out in those with fuels of lower impact such as biogas. Non-renewable sources of exergy were predominant. This can be assigned mostly to the fuels with low exergetic quality as well as refrigerants.

Future studies may focus on the analysis of different thermal systems, the use of alternative inputs, the transport scenario modeling, and boundary extension to cover post-operational life-cycle stages such as demobilization, treatment, recycling, and final disposal.

#### 5. REFERENCES

- Bösch, M.E., Hellweg, S., Huijbregts, M.A.J., Frischknecht, R., and GeraldRebitzer, R.G. 2007. "Applying Cumulative Exergy Demand (CExD) Indicators to the Ecoinvent Database." *Int J LCA* 12(3): 181–90.
- Boateng, O.C. and Lee, K.T. 2014. "An Oil Palm-Based Biorefinery Concept for Cellulosic Ethanol and Phytochemicals Production: Sustainability Evaluation Using Exergetic LCA" *Appl. Therm. Eng.* 62(1): 90–104.
- Cornelissen, R.L. and Hirs, G.G. 2002. "The Value of the Exergetic Life Cycle Assessment besides the LCA." *Energy Convers. Manag.* 43(9–12): 1417–24.
- Ehtiwesh, I.A.S., Coelho, M.C., and Sousa, A.C.M. 2016. "Exergetic and Environmental Life Cycle Assessment Analysis of Concentrated Solar Power Plants." *Renew. Sustain. Energy Rev.* 56: 145–55.
- International Organization for Standardization (ISO). 2006a. "ISO 14040:2006 - Environmental Management, Life Cycle Assessment, Principles and Framework."
- International Organization for Standardization (ISO). 2006b. "ISO 14044:2006- Environmental Management - Life Cycle Assessment - Requirements and Guidelines."
- Martin, J.A. and Boateng, A.A. 2014. "Combustion Performance of Pyrolysis Oil/Ethanol Blends in a Residential-Scale Oil-Fired Boiler." *Fuel* 133: 34–44.
- Morosuk, T., Tsatsaronis, G., and Koroneos, C. 2016. "Environmental Impact Reduction Using Exergy-Based Methods." *J. Clean. Prod.* 118(x): 118–23.
- Pambudi, N.A., Laurensia, R., Wijayanto, D.S., Perdana, V.L., Fasola, M., Imran, M., Saw, L.H., and Handogo, R. 2017. "Exergy Analysis of Boiler Process Powered by Biogas Fuel in Ethanol Production Plant: A Preliminary Analysis." *Energy Procedia* 142: 216–23.
- Penchah, K.H., Sharifi, M., Mousazadeh, H., Hosseinabadi, Z.H., and Pelesaraei, N.A. 2016. "Gate to Gate Life Cycle Assessment of Flat Pressed Particleboard Production in Islamic Republic of Iran." *J. Clean. Prod.* 112: 343–50.
- Portha, J.F., Louret, S., Pons, M.N., and Jaubert, J.N. 2010. "Estimation of the Environmental Impact of a Petrochemical Process Using Coupled LCA and Exergy Analysis." *Resour. Conserv. Recycl.* 54(5): 291–98.
- Rocco, M.V., Colombo, E., and Sciubba, E. 2014. "Advances in Exergy Analysis: A Novel Assessment of the Extended Exergy Accounting Method." *Appl. Energy* 113: 1405–20.
- Rosen, M.A., Dincer, I., and Kanoglu, M. 2008. "Role of Exergy in Increasing Efficiency and Sustainability and Reducing Environmental Impact." *Energy Policy* 36(1): 128–37.
- Saidur, R., Ahamed, J. U., and Masjuki, H. H. 2010. "Energy, Exergy and Economic Analysis of Industrial Boilers." *Energy Policy* 38(5): 2188–97.
- Silva, S.R., Niquini, G.R., Turetta, L.F., and Andréa, O.S. 2018. "Aplicação da Propriedade Termodinâmica Exergia na Avaliação de Processos de Produção de Etanol Lignocelulósico : Uma Revisão" *Rev. Virtual Quim.* 10(5).
- Zhang, Q., Yi, H., Yu, Z., Gao, J., Wang, X., Lin, H., and Shen, B. 2018. "Energy-Exergy Analysis and Energy Efficiency Improvement of Coal-Fired Industrial Boilers Based on Thermal Test Data." *Appl. Therm. Eng.* 144(February): 614–27.