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EMERGY ANALYSIS OF AN ORGANIC RANKINE CYCLE (ORC) USING DIFFERENT WORKING FLUIDS

Anelize Terroni Teixeira
Santiago del Rio Oliveira
São Paulo State University (UNESP), School of Engineering, Bauru
anelizetteixeira@gmail.com
santiago.oliveira@unesp.br

Abstract. *Emergy analysis has been used in recent years to measure environmental and economic impacts associated a production of some form of energy or product. A traditional emergy analysis is divided in three phases. First, all materials required to manufacture the working fluid and cycle equipment are measured in terms of unit and transformity; Second, the necessary inputs to operate the thermodynamic cycle like electricity and waste heat are considered, and third, the inputs necessary to transport all components of system. In this paper, results of an emergy analysis in three different organic fluids were compared to determine the performance of an ORC and to rank it in a scale of short, medium and long-term sustainability, according to EIS (Emergy Index of Sustainability). As such, EES (engineering equation solver) was used to get the thermodynamics parameters for each ORC working fluid; all inputs used along the three phases of emergy analyses had been added to obtain the EIS. R134a and NH3 were classified as sustainable on medium term. R227ea was classified by sustainable in long term. These results show that ORC system is less sustainable in comparison to renewable power plants, but more sustainable than fossil fuel power plants.*

Keywords: *emergy, organic Rankine cycle, life cycle.*

1. INTRODUCTION

Since the end of the past century, the search from others fluids to substitute the CFC's started, and the space for organic fluids grown up, especially for applications on waste heat power generation when the temperature oscillates between 100 ºC and 350 ºC, in what is known as medium and low temperatures for Rankine cycles. In that case, is necessary study the different types of organic work fluid to choose the fluid with best properties for the desired cycle application. The organic Rankine cycle (ORC) is commonly used to generate electrical energy and can been adapted in different kinds of industry. An ideal ORC is composed by a turbine, pump, evaporator and condenser.

(Banks et al., 1998) made an analysis of an organic fluid R227ea manufacturing, concluding that the process of manufacturing contributes to the environmental impact due to the products derived from chemical process. This study leads from a life cycle analysis when is necessary to compute the different environmental impacts from the manufacture the inputs necessary to build and to operate a power plant system.

A kind of life cycle analysis is the study of emergy. Recently, the concept of emergy has been used in thermodynamics analysis, since before it was usually used just in biological analysis from the impacts in biosphere. (Campbell et al., 2014) used the emergy to analyzed the impacts of the pre-industrial age (before 1850) in a global scale. (Yang et al., 2011) used the emergy to analyze the different feedstock to produced ethanol and assess with them feedstock in order to founding a more sustainable fuel. The unit of emergy is (seJ) – emJoules and there are several ways to obtain the emergy values. (Aghbashlo and Rosen, 2018) used a thermodynamic cycle with cogeneration based on gas and turbine to obtain emergy values for system components to evaluate the long-term sustainability and link the feature between energetic, financial and ecological parameters for the system described.

(Merlin and Boileau, 2017) used the emergy analyzis to determine the sustainability of two small biogas plant in a long term, and with the data obtained to estimate better conversion system to improve the energetic efficiency and decrease the environmental impact, making the biogas plant more sustainable. (Sha and Hurme, 2012) compared the emergy from biomass and coal to produce heat and power. The results showed that biomass from cogeneration is 3,3 more efficient than coal in emergy terms, and the emergetic inputs was 77% less for biomass regarding coal. In the search for equilibrium between energy production, lower costs and smaller environmental impacts (Hajabdollahi et al., 2013) looking for a balance with that three points in an ORC to use waste heat from a diesel engine. For the best cycle performance, the authors get four organic fluids, being them R245fa, R134a R22 and R123 to reach an optimized model. In terms of thermodynamic and economic, R123 obtained better results.

To perform an emergy analysis, according to (Liang et al., 2016) it's necessary to divide all materials components of determined system under analysis in each emergy type index being them: renewable environmental resources (*R*), non-renewable environmental resources (*N*), renewable purchased inputs (*Fr*), non-renewable purchased inputs (*Fn*) and products (*P*). Combinations of these indices given others indices which are used to measure the environmental impacts being them: Yield (*Y*) is the total needed emergy; Emergy Yield Ratio (*EYR*) is the ability of the system exploit and make local resources available by investing in outside resources; Transformity (*Tr*) represents the emergy consumption per unit, Environmental Load Ratio (*ELR*) measure the environmental load by the system; Environmental Investment Ratio (*EIR*) measure the emergy level utilization that is invested and Emergy Index of Sustainability (*EIS*) measure the sustainability of a product, process or a service.

The EIS is divided in three categories: If *EIS* < 1 the process is not sustainable in the long term, if 1 < *EIS* < 5 the process is sustainable to economic for mediums periods and if *EIS* > 5 the process is sustainable in a long term. In this work, the results of an emergy analysis were compared in terms of different organic fluids in order to determine the performance of an ORC and to rank the ORC in a scale of short, medium and long-term sustainability using the *EIS* index.

2. ENERGY AND EMERGY ANALYSIS

2.1 Energy analysis

In this work, an organic Rankine cycle was modeled based in an ideal cycle composed of a set of evaporator, condenser, pump and turbine. A physical model of this type of cycle can be seen in Fig. 1:

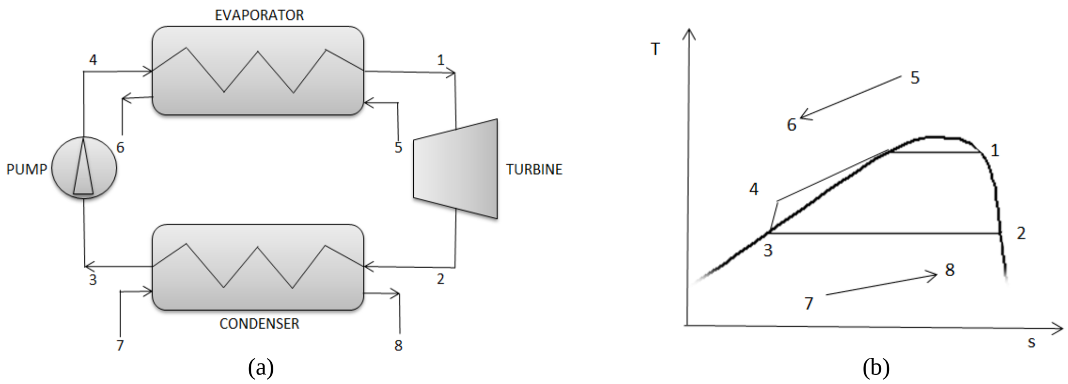


Figure 1. (a) Ideal ORC model. (b) *T-s* diagram for an ideal ORC.

The thermodynamic analysis was based on the following considerations: variations of kinetic energy and potential energy are neglected; the cycle operates in steady state; heat losses for the environment are neglected; pressure drop in heat exchangers and pipes are neglected and thermal resistance of working fluid in heat exchanger was neglected. The thermodynamic model for the cycle is based on the first law of thermodynamics for open systems together with the mass conservation equation. The energy transfer per unit mass in each of the four processes can be written as:

$$\dot{W}_t / \dot{m} = h_1 - h_2 \quad (1)$$

$$\dot{Q}_c / \dot{m} = h_2 - h_3 \quad (2)$$

$$\dot{W}_p / \dot{m} = h_4 - h_3 \quad (3)$$

$$\dot{Q}_e / \dot{m} = h_1 - h_4 \quad (4)$$

where $\dot{W}_t$ is the power produced by the turbine, $\dot{Q}_c$ is the heat rate rejected in the condenser, $\dot{W}_p$ is the power consumed by the pump, $\dot{Q}_e$ is the heat rate absorbed by the evaporator, h is the specific enthalpy and $\dot{m}$ is the mass flow rate of the working fluid.

2.2 Mass of cycle componentes

To perform the emergy analysis, it is necessary to calculate the mass of the cycle components to measure the environmental impact to build the power plant. The evaporator and condenser masses $m_{e/c}$ can be calculated by the following equation (Zhang et al., 2018):

$$m_{e/c} = \rho_{e/c} A_{e/c} \delta_{e/c} \tag{5}$$

where ρ is the specific mass of the construction material, A is the heat exchanger area and δ is the material thickness.

The heat exchanger area can be obtained using the LMTD method, that is:

$$A_{e/c} = \frac{\dot{Q}_{e/c}}{U_{e/c} \Delta T_{lm,e/c}} \tag{6}$$

where U is the global heat transfer coefficient and $\Delta T_{lm,e/c}$ is the log mean temperature difference of heat exchangers.

For turbine and pump masses, $m_{t,p}$, (Zhang et al., 2018) suggests the following expression:

$$m_{t,p} = \alpha \dot{W}_{t,p} \tag{7}$$

where α is the necessary mass per (kW) and $\dot{W}_{t,p}$ is the power generated or consumed in the cycle.

The total working fluid mass m_{wf} can be calculated using the following equation (Zhang et al., 2018):

$$m_{t,p} = L_{wf} + \beta \dot{W}_t \tag{8}$$

where β is an index that represents the working fluid mass consumption in the turbine (kg/kW) and L_{wf} represents the loss of working fluid in the cycle (%).

2.3 Emergy analysis and life cycle

The emergy analysis is realized using the definition of Transformity (*Tr*) to determinate the total emergy of the system. The Transformity (*Tr*) values were obtained by different authors through specific studies for each inputs, including (Zhang et al., 2018) and (Banks et al., 1998). According to (Odum, 1996), to initialize an emergy analyze is necessary to define the environmental window of your system. To model the environmental window is required to determine the boundary for all ORC inputs (*N*, *R*, *Fr* and *Fn*) in each phase of life cycle system until to obtain the final product (in this study, electricity by a ORC system). The model of environmental window of ORC system can be visualized in Fig. 2:

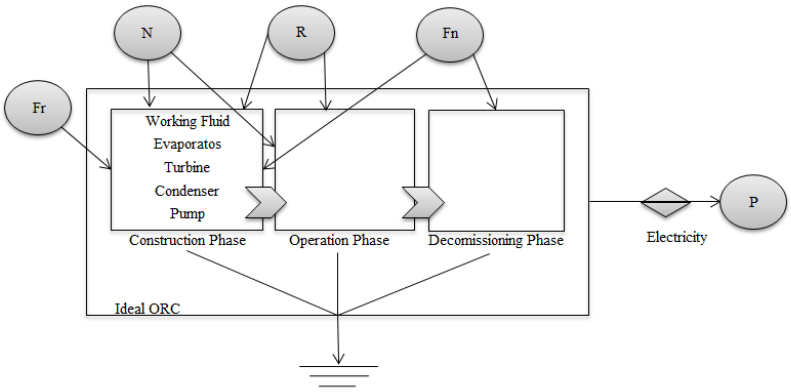


Figure 2. Environmental window for and ideal ORC.

The environmental window show that the boundary conditions of ORC system include three processes to obtained electricity, being them: construction, operation and decommissioning phase. In construction phase is considered all necessary inputs to manufacture the ORC components and the working fluid used in the cycle. In operation phase, are accounted all inputs necessary to keep running the system like the waste heat (the labor energy it was not considered due the difficult to measure that effort). In decommissioning phase, the energy used in transport, to bring the ORC components and working fluid from the local of manufacture to the power plant, was measured. It was considered that all ORC components were manufactured in steel ($\rho = 7930$ kg/m^3). After setting the environmental window and insert all inputs on the life cycle analysis, it is possible to determine and calculate the emergy indexes. These indexes can be seen in Tab. 1, as shown by (Liang et al., 2016):

Table 1. Emergy indexes.

INDEX NAME	SYMBOL	FORMULA
Renewable environmental resources	*R*	
Non-renewable environmental resources	*N*	
Renewable purchased inputs	*Fr*	
Non-renewable purchased inputs	*Fn*	
Product	*P*	
Transformity	*Tr*	
Emergy yield ratio	*EYR*	*Y/(Fr+Fn)*
Environmental load ratio	*ELR*	*(Fn+N)/(Fr+R)*
Environmental investment ratio	*EIR*	*(Fr+Fn)/(R+N)*
Emergy index of sustainability	*EIS*	*EYR/ELR*

With these indexes, is possible to calculate the *EIS* index for different working fluids ORC cycle and compare the environmental sustainability for each cycle, selecting then the most sustainable.

2.4 Thermodynamic conditions

According to (Ding et al., 2018) the conditions used in the thermodynamic cycle were listed in the Tab. 2:

Table 2. Calculation parameters.

PARAMETERS	VALUE
Temperature of the waste heat gas T_h (°C)	120
Mass rate of the waste heat gas $\dot{m}_h$ (kg/s)	1
Pinch temperature difference in evaporator ΔT_e (°C)	10
Pinch temperature difference in condenser ΔT_c (°C)	5
Annual power plant operation hours t (hour)	7000
Power plant operation time n (year)	20

The software EES (engineering equation solver) was used to calculated the parameters for the working fluid. According to (Ding et al., 2018) the global heat transfer coefficient for the evaporator is 50 W/(m².K) and for the condenser is 70 W/(m².K). Still from (Ding et al., 2018), the mass of working fluid (β) is 5.57 kg for 1kW generated by the turbine; the steel ($\rho = 7930$ kg/m³) plate thickness for the evaporator and condenser is 0.002 m; the steel mass required from pump and turbine (α) is 14 kg/kW and 31.22 kg/kW respectively; the loss mass of working fluid in the cycle (L_{wf}) is 10% from the total mass of the cycle. The evaporator and condenser were modelled as shell and tube heat exchangers with cross flow.

3. RESULTS AND DISCUSSION

3.1 Thermodynamic data

Using three different working fluids (R134a, R227ea, NH3), it was possible to obtain the data shown in Tabs. 3 to 5 for the thermodynamic analysis of each state for ORC cycle introduced in Fig. 1:

Table 3. Thermodynamic data for R134a.

ORC STATE	p (bar)	T (ºC)	$\dot{m}$ (kg/s)	h (kJ/kg)
1	7.706	30	0.25	93.58
2	32.47	31.45	0.25	95.66
3	32.47	90	0.25	277.1
4	7.706	30	1	251.9
5	1.013	120	1	394.3
6	1.013	80	1	353.9
7	1.013	20	6.5	293.5
8	1.013	25	6.5	298.4

Table 4. Thermodynamic data for R227ea.

ORC STATE	p (bar)	T (ºC)	$\dot{m}$ (kg/s)	h (kJ/kg)
1	5.265	30	0.25	54.55
2	2306	31.06	0.25	55.87
3	23.06	90	0.25	188.2
4	5.265	38.62	1	170.9
5	1.013	120	1	394.3
6	1.013	80	1	353.9
7	1.013	20	6.5	293.5
8	1.013	25	6.5	298.4

Table 5. Thermodynamic data for NH3.

ORC STATE	p (bar)	T (ºC)	$\dot{m}$ (kg/s)	h (kJ/kg)
1	11.67	30	0.25	341.8
2	51.16	31.09	0.25	348.4
3	51.16	90	0.25	1459.0
4	11.67	30	1	1292.0
5	1.013	120	1	394.3
6	1.013	80	1	353.9
7	1.013	20	6.5	293.5
8	1.013	25	6.5	298.4

The mass flow rate of the ORC system was determined for an average from four working fluids used by (Ding et al., 2018), with purpose to obtaining cycles with the same mass flow rate and to compare them in a more equivalent way. For mass and thermal components cycle calculus (evaporator, turbine, condenser and pump), using Eqs. (1) to (4), and the amount of the working fluid necessary to operate the cycle, using Eqs. (5) to (8), it was possible to obtain the Tabs. 6 to 8, what are results to R134a, R227ea and NH3 respectively:

Table 6. Area, mass and energy rate for an ORC using R134a as a working fluid.

EQUIPMENT	Evaporator	Turbine	Condenser	Pump	R134a	Total
AREA (m²)	16.82	-	109.74	-	-	126.56
MASS (kg)	266.71	196.69	1740.46	7.28	38.60	2249.74
ENERGY RATE (kW)	45.36	6.30	39.58	0.52	-	5.78

Table 7. Area, mass and energy rate for an ORC using R227ea as a working fluid.

EQUIPMENT	Evaporator	Turbine	Condenser	Pump	R134a	Total
AREA (m²)	12.21	-	49.65	-	-	61.86
MASS (kg)	193.68	135.03	787.45	4.62	26.50	1147.28
ENERGY RATE (kW)	33.08	4.33	29.09	0.33	-	4.00

Table 8. Area, mass and energy rate for an ORC using NH3 as a working fluid.

EQUIPMENT	Evaporator	Turbine	Condenser	Pump	R134a	Total
AREA (m²)	102.52	-	658.63	-	-	761.15
MASS (kg)	1626.03	1303.44	10445.85	23.10	255.80	13654.22
ENERGY RATE (kW)	277.65	41.75	237.55	1.65	-	40.10

3.2 Emergy data

To calculate the EIS index, it's necessary to obtain the emergy index for all component of ORC system (in the three phases: operation, construction and decommioning), according the environmental window model, and sum the results to obtain the desired emergy indexes. Performing this analysis for different working fluid (R134a, R227ea and NH3), it's possible to compare the environmental sustainability between these three working fluids and rank them. (Zhang et al., 2018) introduced that emergy accounting. With the emergetic data obtained by them, will be used adapted to specific mass of all components (condenser, evaporator, pump and turbine, according Tabs. 6 to 8 for each working fluid). That total account can be seen in Tab. 9 for the R134a.

The calculus from Tab. 9 take into account the proportion of all system mass and working fluid (R134a) component. To calculate R227ea and NH3 some adjustments are required. The construction phase for ORC components is calculated for mass proportion, so to the R227ea and NH3 it will be necessary to apply the mass proportion and construction phase for working fluid has different component according to the composition of each working fluid. The operation phase also has the adjustments for mass proportion. The decommissioning phase has the same value for each working fluid. For R227ea and NH3 respectively, the construction phase can be seen in Tab. 10 and Tab.11. The components to construction phase for NH3 it is given by (Bicer et al., 2016) and R227ea for (Banks et al., 1998). Transformity (*Tr*) value for some components of R227ea is giving by (Ma, 2013) and (Paoli et al., 2008).

Table 10. Emergy indexes to ORC cycle construction phase for R227ea.

Construction phase – Working fluid							
Component (unit)	*R*	*N*	*FR*	*FN*	*P*	*Tr* (sej/unit)	Emergy (sej)
H_2O (t)	2.12E+00					6.64E+11	1.40E+12
HF (t)		2.38E-02				9.89E+08	2.35E+07
CL_2 (t)		1.10E-01				1.60E+15	1.77E+14
Coal electricity (J)				1.25E+09		1.17E+05	1.46E+14
Heat (J)				2.27E+09		6.07E+04	1.38E+14
R227ea (t)					2.65E-02	1.74E+16	4.62E+14

Table 11. Emergy indexes to ORC cycle construction phase for NH3.

Construction phase – Working fluid							
Components (unit)	*R*	*N*	*FR*	*FN*	*P*	*Tr* (sej/ unit)	Emergy (sej)
H_2O (t)	4.07E-01					6.64E+11	2.70E+11
N_2 (t)			2.11E-01			4.05E+16	8.53E+15
Coal electricity (J)				1.01E+07		1.17E+05	1.19E+12
NH3 (t)					2.56E-01	3.33E+16	8.53E+15

Table 9. Emergy indexes to ORC cycle for R134a.

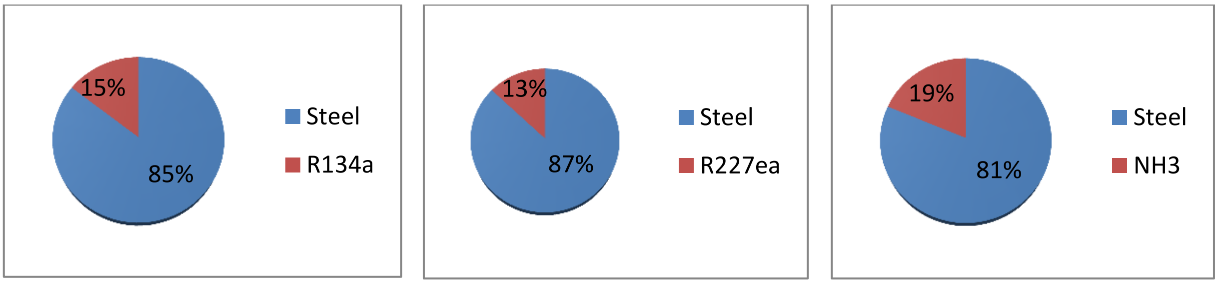
Components (unit)	*R*	*N*	*FR*	*FN*	*P*	*Tr* (sej/ unit)	Emergy (sej)
Construction phase – ORC components							
Air (t)(1)	2.57E-01					5.16E+13	1.33E+13
Limestone (t)(1)	5.59E-02					1.00E+15	5.59E+13
Aluminium mine (t)(1)	1.90E-02					1.00E+15	1.9E+13
Vanadict Titanomagnetite (t)(1)	2.79E-01					4.24E+15	1.18E+15
Ilmenite (t)(1)	6.48E-03					1.86E+16	1.21E+14
Iron Ore (t)(1)	4.65E-01					8.55E+14	3.97E+14
Fresh Water (t)(1)			5.63E+00			6.64E+11	3.74E+12
Hydraulic electricity (t)(1)			3.00E+09			8.00E+04	2.4E+14
Semi coke (t)(1)				5.52E+09		1.06E+04	5.85E+13
Coke (t)(1)				1.26E+10		1.06E+04	1.33E+14
Silica (t)(1)				4.45E-01		1.20E+14	5.34E+13
Fluorite (t)(1)				1.85E-04		2.71E+15	5.01E+11
Cymrite (t)(1)				1.15E-01		1.00E+15	1.15E+14
Steel cuttings (t)(1)				1.74E-02		4.24E+15	7.37E+13
Cutting slag (t)(1)				5.89E-03		4.24E+15	2.5E+13
Oxidized scale (t)(1)				1.03E-02		8.55E+14	8.82E+12
Aluminum (t)(1)				1.34E-02		3.58E+15	4.81E+13
Powdered iron (t)(1)				5.75E-01		8.55E+14	4.92E+14
Bentonite (t)(1)				6.64E-03		1.00E+15	6.64E+12
Coal (t)(1)				5.94E+09		3.98E+04	2.36E+14
Iron ingot (t)(1)				5.75E-03		8.55E+14	4.92E+12
Ferrosilicon (t)(1)				1.69E-04		4.88E+14	8.27E+10
Ferroalloy (t)(1)				5.53E-04		8.55E+14	4.73E+11
Machinery Buildings ($)(1)				3.99E+01		5.20E+12	2.07E+14
Service e Labor ($)(1)				5.05E+02		5.20E+12	2.63E+15
Steel (t)					2.21E+00	2.77E+15	6.12E+15
Construction phase – Working fluid							
Water (t)(2)	9.65E-01					6.64E+11	6.41E+11
Fluorspar (t)(2)		1.51E-02				2.72E+15	4.09E+13
Crude oil (J)(2)		5.79E-03				5.40E+04	3.126.608
Natural gas (J)(2)		6.56E-03				4.80E+04	3.149.768
Limestone (t)(2)		8.11E-03				1.00E+15	8.11E+12
Sulphur (t)(2)		6.18E-03				8.60E+14	5.31E+12
Sodium Chloride (t)(2)		1.20E-01				1.00E+15	1.2E+14
Nitrogen (t)(2)			1.93E-02			4.05E+16	7.82E+14
Coal electricity (J)(3)				1.67E+08		1.17E+05	1.95E+13
Heat (J)(3)				1.08E+09		6.07E+04	6.56E+13
R134a (t)					3.86E-02	2.70E+16(4)	1.04E+15
Operation phase							
Absorbing of heat released(J) (9)	1.99E+13					9.63E+02	1.92E+16
Waste heat (J) (5)		2.29E+13				4.46E+04	1.02E+18
Decommioning phase							
Diesel for transportation (J) (6)					1.09E+09	6.60E+04	7.20E+13
RESULT							
ELETRICITY (J) (7)					2.91E+12	3.59E+05(8)	

(1) Corresponds to the mass quantity necessary to produce the total mass of ORC components (in this case 2211.74 kg of steel, for R134a as working fluid). The data base was obtained by (Zhang et al., 2018).
(2) Corresponds to the mass quantity necessary to produce the total mass of working fluid (in this case 38.60 kg of R134a). The data base was obtained by (Zhang et al., 2018).
(3) Corresponds to the energy quantity necessary to produce the total working fluid used in ORC system (in this case, 38.60 kg of R134a). The data base was obtained by (Zhang et al., 2018).
(4) Corresponds to the (*Tr*) calculus for working fluid. The data base was obtained by (Zhang et al., 2018).

(5) Corresponds to the calculus of waste heat which will be used to generate electricity by the ORC system throughout its useful life. In this case 20 years, 7000 hours per years in relation to $\dot{Q}_e$ (Waste heat = $\tau n \dot{Q}_e$).The data base was obtained by (Zhang et al., 2018).
(6) Corresponds to the calculus of "Diesel for transportation" from decommioning phase. It is considerate an average distance of 200km and average diesel consumed 2423 (MJ/(kt.km)), to calculate the amount of fuel consumed from manufacturing local to installation local of OC components (Diesel for transportation = 200*mass of system*2423 (MJ/(kt.km)). The data base was obtained by (Zhang et al., 2018).
(7) Corresponds to the calculus of all energy (electricity) will be produced by the ORC system throughout its useful life. In this case 20 years, 7000 hours per years in relation to $\dot{W}_{cycle}$ (electricity = $\tau n \dot{W}_{cycle}$). The data base was obtained by (Zhang et al., 2018).
(8) Corresponds to the (*Tr*) calculus for the electricity (Product), using the definition of $Tr = Y/P$. The data base was obtained by (Zhang et al., 2018).
(9) Corresponds to the released energy from condenser by the ORC system throughout its useful life. In this case 20 years, 7000 hours per years in relation to $\dot{Q}_c$ (Waste heat = $\tau n \dot{Q}_c$). The data base was obtained by (Zhang at al., 2018).

4. RESULTS AND DISCUSSION

Using the energy, mass and emergy equations it is possible to calculate the mass and energy necessary to build the power plant for a 20-year operation. Applying the transformity definition it is possible to calculate the emergy for all system input and then the EIS index for the total system. This index is a measure of the cycle sustainability over the years. The amount of all input emergy used in the construction of an ORC power plant system was listed and compared in Fig. 3 to each working fluid. It can be seen that the working fluid represents a considerable part of life cycle sustainability and cannot be negligible.



(a) (b) (c)

Figure 3. Emergy proportion between working fluid and steel system components used to construct the ORC, being (a) R134a as working fluid, (b) R227ea as working fluid and (c) NH3 as working fluid.

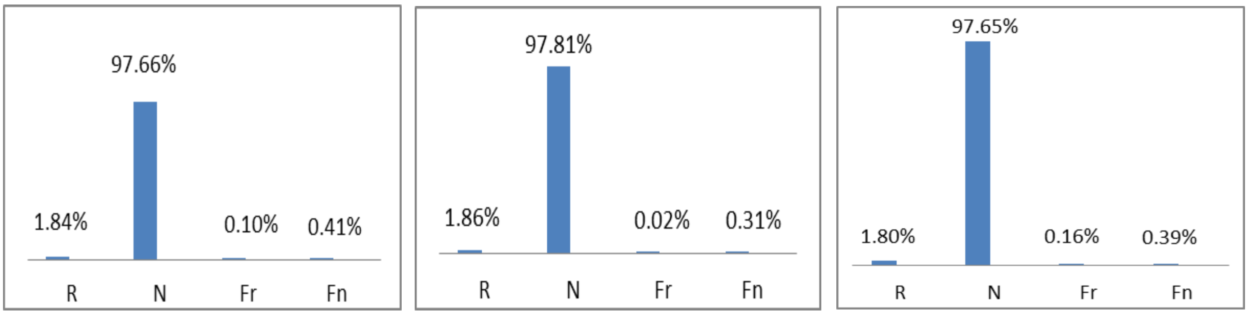
The transformity *Tr* for ORC system with different working fluids can be seen in Tab. 11. Comparing the results presented by (Zhang et al., 2018) between ORC and other power plant system, it's possible to see that *Tr* it's greater. It's possible due to the thermodynamic efficiency of an ORC is modest low then other power plants.

Table 11. Index (*Tr*), (*EYR*), (*ELR*) and (*EIS)* for each work fluid comparing to other six types of power plants (Ding et al., 2018).

	Transformity	*EYR*	*ELR*	*EIS*
ORC R134a	4.31E+05 sej/J	197.81	49.78	3.97
ORC R227ea	4.48E+05 sej/J	290.14	51.32	5.65
ORC NH3	3.17E+05 sej/J	183.91	50.06	3.67
Wind	5.85E+04 sej/J	77.47	0.15	48.3
Geothermal	1.42E+05 sej/J	4.81	0.44	11.05
Hydro	5.87E+04 sej/J	7.65	0.45	16.9
Methane	1.60E+04 sej/J	6.60	11.78	56
Oil	1.87E+05 sej/J	4.21	14.24	0.3
Coal	1.62E+05 sej/J	5.48	10.37	0.53

The EIS from ORC R134a is 3.97, which implies in a system sustainable to the economy for a medium term. For R227ea the EIS is 5.65 that implies in a system sustainable to the economy for a long term. Finally, to NH3 the EIS is 3.67, which implies in a system sustainable to the economy for a medium term. The ORC system had a considered higher EYR in comparison the other six power plants shown in Tab. 11. It means, according to (Liang et al., 2016) that ORC have a greater capacity to exploit and make local resources available by investing in outside resources. The index ELR in Tab. 11 for three ORC working fluid is higher than the six other power plants, shows that the natural resources were extensively explored which limits their use again.

Figure 4 shown the proportion of each input (in percentage) used to build and operate ORC for each working fluid in study. It is evident that non-renewable environmental resources represent an overwhelming plot of total inputs, so this shows that it is necessary efforts to decrease the quantity of these materials to reduce the costs and the environmental impact of ORC system, and with that reduces, increase the EIS, making the ORC a system more and more sustainable in a long term.



(a) (b) (c)

Figure 4. Emergy in percentage to all input used in ORC, (a) using R134a as a working fluid, (b) using R227ea as a working fluid (c), using NH3 as a working fluid.

5. CONCLUSIONS

In this study, the environmental sustainability for an ideal ORC system with three different working fluids was performed. With these results, it's possible to obtain the following results:

a. The emergy analysis is an additional method to select the most appropriate ORC system for certain using.

b. *EIS* index for ORC systems are smaller than renewable power plants, but larger than non-renewable power plant (from petroleum products), as can see in Tab. 11. So, in comparison to petroleum products, ORC system is a better option in terms of environmental sustainability.

c. *EYR* index for ORC system is larger than other types of power plan system (both renewable and non-renewable power plants), as can see in Tab. 11. This show that an ORC system have a better capacity to explore and to make available the local resources by investing in outside resources (Liang et al., 2016).

d. *ELR* index for ORC system is larger than other types of power plan system. When choosing a model system, is important to select a model with lower *ELR*, in order to obtain a lower environmental load.

e. According to dates obtained from Fig. 3, working fluids represents 10 to 20 percent of total inputs in terms of ORC mass. Thus, in an emergy analysis the working fluid can be not disregard.

f. Non-renewable resources represents larger parcel of inputs used in ORC system construction. Reducing the use of this input, less will be the environmental load, consequently reducing the *Tr* value, and increasing the *EIS*, making the system more environmental sustainable.

g. It is important to test different fluids in an ORC emergy analysis to compare the different life cycle indexes, in order to obtain the most optimized system according the desired useful life of power plant.

h. These results show that obtain a good thermodynamic performance does not guarantee a good emergy performance, because how much more components are added to system to obtain a higher power generation, the greater will be the environmental impact due to more resources will be withdrawn from nature, making the ORC system short sustainable in a long term.

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7. RESPONSIBILITY NOTICE

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