

# ORGANIC RANKINE CYCLE FOR WASTE HEAT RECOVERY ENERGY FROM INTERNAL COMBUSTION ENGINES (TECHNICAL AND ECONOMIC ANALYSES)

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**Abstract.** *Due the low complexity the Organic Rankine Cycle (ORC) can be considered one of the best options for the waste heat recovery at a low and medium temperatures. A technical and economic study was conducted in this work, in order to increase the efficiency in the electricity production and, thus, reduce fuel consumption and polluting gas emissions in an Internal Combustion Engine (ICE). To do this, a set of ORC have been suggested, it plant contains: an evaporator, a pump, a superheater and a condenser with the water supply made by the urban net of water. The simulation occurred on software HYSYS version 8.6 of ASPEN<sup>®</sup>tech, the simulated system is able to increase the electricity production in almost 20% and the First Law efficiency of the ORC plant in almost 6%, when the working fluid was toluene. The economic analysis, based on CEPCI (Engineering Chemical Cost Plant Index) model, showed the financial return of the ORC system implementation may occur in six years. With this, it is noted the ORC system, despite being an appropriate technological solution to recover the waste heat present in ICE's exhaust gas, it still needs incentives from government for a wide application of the system, which financially support the investor.*

**Keywords:** *Organic Rankine Cycle, exhaust gas, internal combustion engine, technical analysis, economic analysis*

## 1. INTRODUCTION

The ORC is the most used solution, among the possibilities of technologies facing rise the energy efficiency (Wei, 2007). It may reduce the pollution gases as, sulphur dioxide, without performance losses in electricity production. Beyond, there is a higher energy production for the same amount of pollutants (Quoilin, 2009 and Quoilin, 2013). Tchanche et al. (2011) showed that ORC has been considered to be the main procedure to convert heat from low-temperature sources into electric power. There are many possibilities of ORC heat sources, such as: biomass, solar and geothermal energy, and heat from ICEs exhaust gases. Biomass is the most used source, followed by heat recovery (Meinel, 2014).

Heat released in the ICE exhaust gas from thermal power plants correspond to more than half of the calorific power provided to them. This number is equivalent to approximately 55% of the heat which is possible to be removed from the fuel (Roy, 2010 and Carcasci, 2014). Such wasted energy decreases equipment efficiency. Pollutants are released along with this reject ( $\text{CO}_2$ ,  $\text{SO}_x$ ,  $\text{NO}_x$ , etc.), which are harmful to the environment. The heat released is classified among three gas temperature categories: low (at most 230 °C), average (230 °C to 650 °C), and high (up to 650 °C). Since ORC have a low system complexity, it can be considered as one of the best options for employment of low and medium temperature tailings, such as in the case of ICEs' exhaust gas.

Previous studies employed R245fa as a working fluid on primary ORC (ORC P) and R123 on secondary ORC (ORC S) (Zhang, 2013). Simulations were done according to rotation speeds between 1,000 and 4,000 rpm, and 100% loads up to the minimum indicated for system stability. With this, 7.8% yield was obtained for ORC P and 8.89% for ORC S. At the ideal operational point, specific fuel consumption was reduced from 212 g/kWh to 185 g/kWh. Finally, an increase between 14 and 16% in energy production was found, but it could reach up to 43% for low engine loads and high speed rotation.

Authors from Yang et al. (2014) performed the simulation with another internal combustion diesel engine and used only R245fa as a working fluid, for both ORC P and ORC S. Operating range varied from 900 to 1,900 rpm and the load reached 247 kW. Primary and secondary ORC systems produced 10 kW and 17.85 kW of energy at the ideal operational point, respectively. Heat recovery efficiency was 5.4% for the integrated system. A 13% fuel economy was also observed, and it might increase if the engine operates under medium and high loading conditions.

In this paper, an economic and technical case study was carried out in an ORC plant that uses the heat from an ICE exhaust gases as energy source. For such, was chosen an engine that dropped gas in average temperature and an ORC set was suggested. This work must show the deployment cost of these systems, the financial return time, how much more energy would be possible to produce and if such a system could be deployed in deserted areas or even difficult access to water.

## 2. SIMULATED ORC SYSTEM

In order to increase the power generation plant efficiency, the ORC systems suggested in this study (Fig. 1) include a superheater and basic ORC components (evaporator, condenser, expansion device, and pump). In addition, implemen-

tation of a regenerator would increase ORC efficiency by so little that investment on such device would not be worthy (Cayer, 2010).

It is worth mentioning that point 2, showed on Fig. 1 represents the working fluid evaporating temperature. Also, the "Pinch Point" is indicated (lowest temperature difference between chains of MCI exhaust gas and the organic cycle).

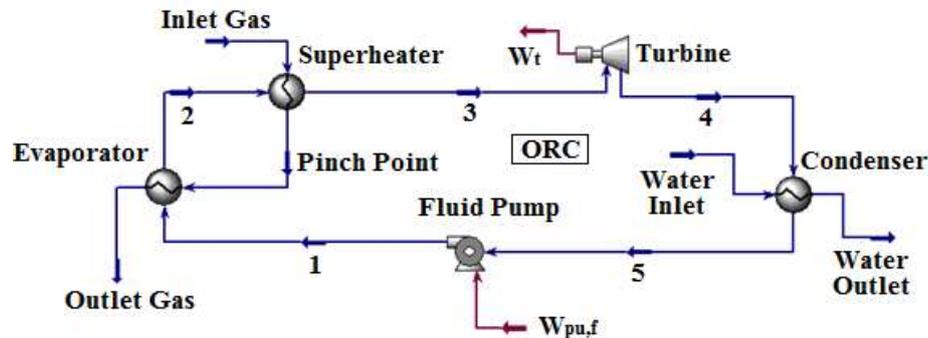


Figure 1 – Sketch of the analyzed ORC system.

### 3. TECHNICAL SIMULATION

Some considerations and parameters have allowed the performance of computer simulations in order to maintain an evaluation standard among working fluids of interest. Such considerations are presented on Tab. 1.

Table 1 – Features and main of the ORC system considerations made for technical analysis.

Gases released to the environment as saturated steam	
Non-condensing turbine expansion	
Liquid compression (only)	
Cooling water temperature variation in condenser	5 °C
Ambient pressure ( $P_0$ )	1 atm
Ambient temperature ( $T_0$ )	25 °C
Turbine and pump isentropic efficiency	80%
Pinch Point	10 °C
Simulation minimum condensing temperature	40 °C
Fully developed flow within the ORC system	
irreversibility's inside the pipes and connections despised	
Variations in potential and kinetic energies unappreciated	
No Pressure drop inside the equipment	
No water mass loss in the condensing water cooling system	
Thermodynamic properties are calculated based on the PRSV state equations	

For flow measurement, which is common to all seven fluids analyzed, as well as their respective evaporation pressure, an optimization analyses should be done where simulation characteristics are maintained. Since this type of optimization calculation is not intended by this study, in order to maintain simulation parameters (steam expansion and sole liquid compression, gas released into the environment at the saturation point, maximum pinch point, etc.) without having done the optimization aforementioned, the flow for each evaporator and pressure of each working fluid was varied, which allowed the organic cycle to work accordingly.

#### 3.1 The engine and working fluids

A heavy duty stationary internal combustion diesel engine was chosen for simulation. Such machine is manufactured by CATERPILLAR<sup>®</sup> (2008) (Tab. 2).

Table 2 – Features of MCI used as reference for this paper.

Model	Diesel Engine CATERPILLAR C32 ATAAC
Power	830 kW
Rotation speed	1,800 rpm
Consume (at a full load)	223.7 L/h
Exhaust gas temperature	473.2 °C
Exhaust gas mass flow	5.172 kg/h

Diesel B S-500 Petrobras (2004) was the fuel employed in the engine. It is a hydrocarbon with a short chemical formula,  $C_{12}H_{26}$  (dodecane), with approximately 0.15 mol of nitrogen and 0.0027 mol of sulphur per compound mole. The diesel combustion process occurs with 20% excess air (ideal air was adopted). Tab. 3 describes the exhaust gas with a percentage by molecule mass. It is observed that particulate matter released does not have power generation potential, and therefore it is not included into gas percentage mass distribution.

Table 3 – ICE exhaust gas characteristics used as reference for this paper (at full load operation).

Component	[%]
O <sub>2</sub>	3.54
N <sub>2</sub>	72.75
CO <sub>2</sub>	16.43
H <sub>2</sub> O	7.28

Main characteristics to determine an organic compound for the ORC system, which can describe an ideal working fluid:

- Isentropic or dried fluids (saturated curve from T diagrams is null or positive);
- Low specific and latent vaporization heats;
- Average or high values for critical pressure and temperature;
- Low viscosity and high thermal conductivity;
- Good thermal and chemical stability at high temperatures;
- Non-corrosive, non-flammable, and non-toxic;
- Low environmental impact and costs;
- High availability;
- Availability in ASPEN<sup>®</sup> HYSYS 8.6 version, software used to assist in the technical analysis of the proposed systems.

Thus, Tab. 4 presents selected organic fluids with their respective pressure and temperature limits, according to Bao et al. (2013).

Table 4 – Working fluids for the ORC system analyzed in the present work, with their respective limits of temperature and pressure (Bao and Zhao, 2013 – modified).

Organic fluid	Maximum evaporation pressure [kPa]	Maximum evaporation temperature [°C]	Minimum condensing pressure [kPa]	Minimum condensing temperature [°C]
Acetone	3,300	213	30.7	25
Benzene	4,000	274	12.7	25
Cyclohexane	3,600	272	13	25
Heptane	2,400	258	6.1	25
Hexane	2,600	226	20.2	25
Octane	2,200	287	5.0	44
Toluene	3,500	307	5.1	31

### 3.2 First Law analysis

According to studies from Long et al. (2014) and Song et al. (2014), the performance of a first law efficiency analyses provided the yield of a working fluid for an ORC system. From this concept, the first law efficiency calculation for an ORC system, according to previous studies identified on Roy et al. (2010) and Long et al. (2014), which employed the operational concept showed on Fig. 2, followed Eqs, (1) to (6):

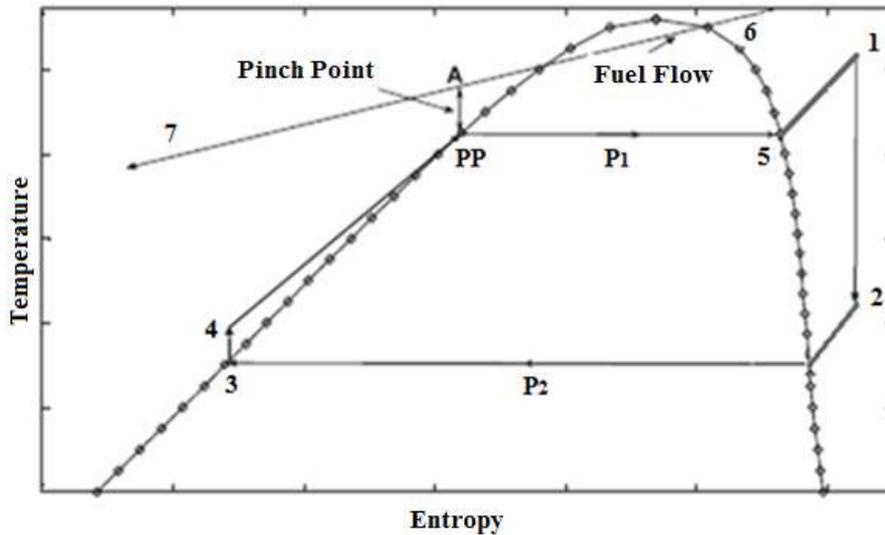


Figure 2 – T-s graphic of ORC system (Roy et al., 2010 – modified).

Expansion in the turbine takes place in process 1 – 2 and the power produced is given by Eq. (1).

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

Working fluid condensation occurs in process 2 – 3, in which the energy discarded is calculated in Eq. (2).

$$\dot{Q}_{\text{cond}} = \dot{m}_f(h_2 - h_3) \quad (2)$$

Working fluid is pumped in process 3 – 4 and the pump employed consumes part of the energy produced by the turbine (Eq. (3)).

$$\dot{W}_{\text{pu},f} = \dot{m}_f(h_4 - h_3) \quad (3)$$

Residual energy from the ICE exhaust gas is recovered in Process 4 – 5 (Eq. (4)). The working fluid then evaporates as a consequence.

When the fluid is later at the saturated steam point, it enters the superheater in order to be brought to a superheated steam state, also taking advantage from the energy produced by engine exhaust gases (Eq. (5)). It is worth mentioning that the first "contact" between the working fluid and the rejected ICE heat happens in the superheater.

$$\dot{Q}_{\text{evap}} = -\dot{m}_f(h_4 - h_5) \quad (4)$$

$$\dot{Q}_{\text{sup}} = -\dot{m}_f(h_5 - h_1) \quad (5)$$

Thus, the first law efficiency can be calculated using Eq. (6). The condensate pump term ( $\dot{W}_{\text{pu},w}$ ) may or may not exist, depending on ORC settings.

$$\eta_1 = \frac{\dot{W}_{\text{net}}}{\Delta \dot{E}_{\text{gas}}} = \frac{\dot{W}_t - \dot{W}_{\text{pu},f}}{\dot{E}_{\text{gas},i} - \dot{E}_{\text{gas},o}} \quad (6)$$

### 3.3 Technical study results

A technical analyses dealt with main issues that characterized the deployment of ORC system. These aspects were: useful energy produced and First efficiency. Then, the economic analyses will determine the feasibility of the suggested system.

#### 3.3.1. Net power produced

Net power is given by the difference between the power produced by the turbine and the one consumed at the pump (Eq. (7)). It refers to how much electricity will be produced if the system is deployed according to each model.

$$\dot{W}_{net} = \dot{W}_t - \dot{W}_{pu,f} \quad (7)$$

Figure 3 graph shows the electric energy generated by simulated working fluids in each evaporation pressure condition of the ORC system. A rapid growth in the cycle performance is noticed when pressures are still low. Then, a mild growth curve happened when the pressures approached the maximum.

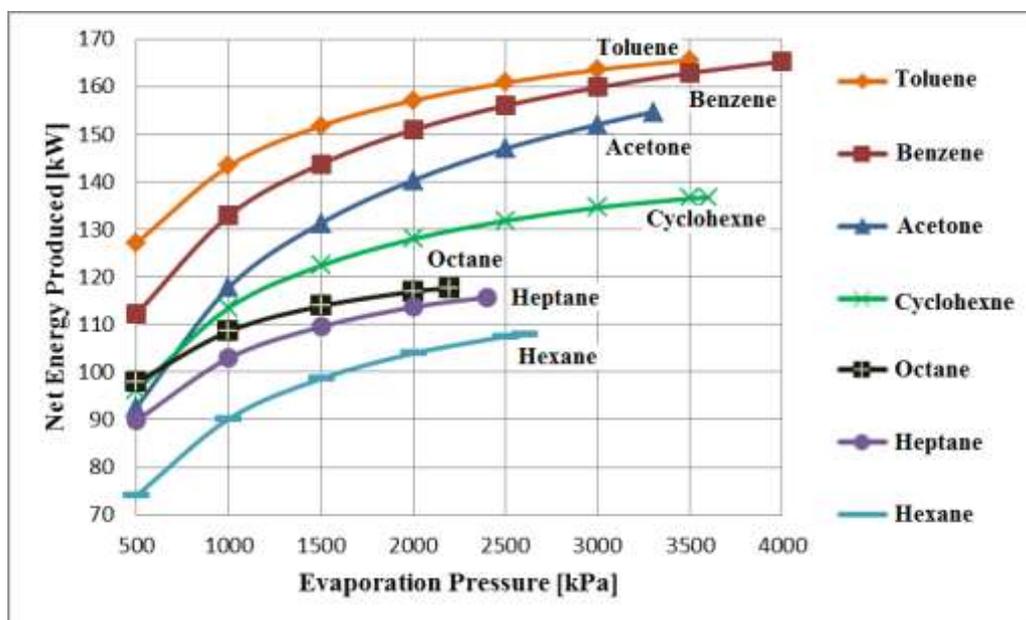


Figure 3 – Graph of the net energy produced by evaporating pressure of the ORC systems.

Produced electric energy values reached approximately 165 kW. Toluene, benzene, and acetone are fluids capable of producing more energy, respectively. Maximum power produced in simulations happened when toluene was used at 3.500 kPa evaporation pressure (165.27 kW). An 19.91% increase of electricity production for the ICE and ORC combined system was achieved when the engine operated at full load, because there was a greater use of heat produced in the MCI. Under similar simulation conditions, net energy generated in the ORC with cooling tower was equivalent to 162.03 kW. Note that this difference is so small, about 3.5 kW for all simulated cases, this difference was so small that it would not be a great loss takes the technical results from both ORC systems proposed as the same.

#### 3.3.2. First Law efficiency

Figure 4 shows a chart that represents First Law efficiencies for simulated systems. The calculation for this issue was carried out according to Eq. (6), which presents the ratio between the net power produced and the total energy available from engine exhaust gases. The chart includes values for First Law efficiency between 2.5 and 6%. Toluene, benzene, and acetone were the most efficient fluids among those analyzed. It was observed that the organic cycle efficiency was low, which is due to the heat source being in the average temperature range, in addition to a great loss caused by system irreversibilities. However, as already shown, production gain is high with employment of this system.

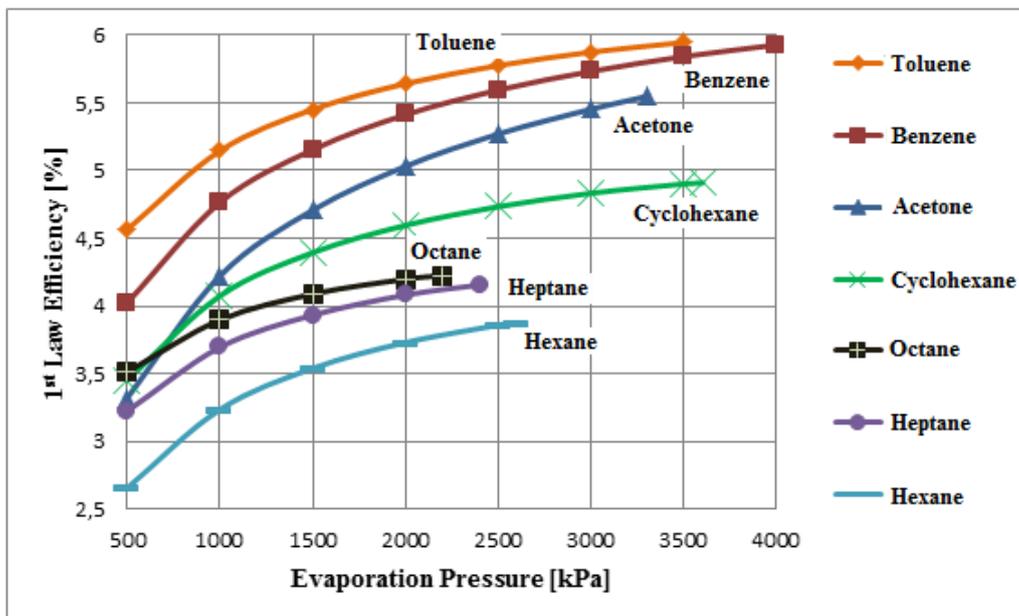


Figure 4 – Graph of the First Law efficiency by the evaporation pressure of the ORC systems.

#### 4. ECONOMIC SIMULATION

This section presented economic feasibility information to implement the ORC systems proposed. Such analysis was based on the CEPCI economic model and supported by studies performed on Cayer et al. (2010), Tian et al. (2012), Chew et al. (2014), Le et al. (2014), Mignard (2014), Shu et al. (2014), and Toffolo et al. (2014), as well as reference Book Turton et al. (2008). The economic study showed the equipment initial investment needed to deploy the system, the electricity production cost, and the capital return.

##### 4.1. CEPCI (Chemical Engineering Plant Cost Index)

CEPCI is a dimensionless index used to update the cost estimate for a physicochemical process plant deployment from one year to the next. Created in 1963, it has since been used by engineers, technicians, and managers to evaluate the deployment of an energy unit or the economic potential of processing industries. With that, it makes long-term plans, budgets, and contracts Vatauvuk (2002).

With technology advancements and new market trends, CEPCI needs a periodic review. This index is actually composed of four main sub-indexes, which represent factors that generate costs. These are indispensable factors that must be taken into consideration for a chemical plant economic feasibility analysis:

CEPCI as well as any other index are tools which help company managers to make plans. When there is little time to evaluate deployment of a chemical plant or the goal is to deploy the system later on, CEPCI helps considerably, since it consists of quick calculations easy to understand. In addition, it is a good representation of the reality within a certain period of time (approximately five years). However, if there is enough time for a decision and the actual equipment costs are available, as well as cost generators for other factors, it is better to choose a direct analysis. Results obtained will be an accurate reflection of reality, and not approximate values (Vatauvuk, 2002).

##### 4.2. Investment cost, EPC (Electricity Production Cost) and Payback (investment repayment time)

Investment costs or equipment purchase price were calculated by Eq. (8).

$$C_{BM} = C_p^0 \cdot F_{BM} \quad (8)$$

“ $C_p^0$ ” is the cost of the equipment built with carbon steel, which operates in ambient temperature and pressure conditions, and it is obtained from equipment capacity or size parameters, depending on the device type (Eqs. (1) to (5)). “ $F_{BM}$ ” is the bare module cost factor, a parameter that takes into account the material from which the equipment was manufactured. Finally, “ $C_{BM}$ ” is the equipment total investment cost, which takes into account all the aspects from the device.

In order to obtain “C<sub>p</sub><sup>0</sup>”, constants “K” were used, which are obtained by correlations between the equipment type and its capacity or size, as well as the device capacity or size (Tab. 5). Equations (9) to (14) show, respectively, how “C<sub>p</sub><sup>0</sup>” was calculated for: turbine, pumps, evaporator, superheater, condenser, and cooling tower.

$$\log C_{p,t}^0 = K_1 + K_2 \cdot \log(W_t) + K_3 \cdot [\log(W_t)]^2 \quad (9)$$

$$\log C_{p,pu}^0 = K_1 + K_2 \cdot \log(W_{pu}) + K_3 \cdot [\log(W_{pu})]^2 \quad (10)$$

$$\log C_{p,evap}^0 = K_1 + K_2 \cdot \log(A_{evap}) + K_3 \cdot [\log(A_{evap})]^2 \quad (11)$$

$$\log C_{p,evap}^0 = K_1 + K_2 \cdot \log(A_{evap}) + K_3 \cdot [\log(A_{evap})]^2 \quad (12)$$

$$\log C_{p,sup}^0 = K_1 + K_2 \cdot \log(A_{sup}) + K_3 \cdot [\log(A_{sup})]^2 \quad (13)$$

$$\log C_{p,cond}^0 = K_1 + K_2 \cdot \log(A_{cond}) + K_3 \cdot [\log(A_{cond})]^2 \quad (14)$$

Table 5 – “K’s” Coefficients regarding the size or capacity and the equipment type (Turton et al., 2008).

Equipment	K <sub>1</sub>	K <sub>2</sub>	K <sub>3</sub>	Capacity / Size	Model
Turbine	2.2476	1.4965	0.1618	100 – 1,500 [W]	Radial
Condenser	2.7652	0.7282	0.0783	10 – 100 [m <sup>2</sup> ]	Shell and tube (multiple tubes)
Fluid pump	3.8696	0.3161	0.1220	0.1 – 200 [W]	Reciprocating
Evaporator	5.2366	-0.6572	0.3500	10 – 100 [m <sup>2</sup> ]	Shell and tube (shot tube)
Superheater	2.7652	0.7282	0.0783	10 – 100 [m <sup>2</sup> ]	Shell and tube (multiple tubes)

Thus, costs can be calculated for each equipment built with carbon steel which operates in ambient temperature and pressure conditions (C<sub>p</sub><sup>0</sup>). Construction materials are described on Tab. 6 for each one of these devices suggested in Turton et al. (2008), with lower and higher costs.

Table 6 – Each equipment manufacture materials (Turton et al., 2008).

Equipment	Material	
	Lower cost	Higher cost
Turbine	Carbon steel	Nickel
Condenser	Carbon steel	Titanium
Fluid pump	Cast iron	Titanium
Evaporator	Carbon steel	Titanium
Superheater	Carbon steel	Titanium

Calculation of “F<sub>BM</sub>” can be done for heat exchangers and pumps through Eq. (15). Coefficients “B”, “FM”, and “FP” represent the device type constant, the material factor for each equipment, and the pressure factor, respectively. They are different for each equipment (Tab. 7). To the turbine and the evaporator, “F<sub>BM</sub>” is provided directly through Tab. 8, since they do not have classification by pressure.

$$F_{BM} = B_1 + B_2 \cdot F_M \cdot F_P \quad (15)$$

The “FP” coefficient is obtained by Eq. (16) in which “C” represents constants for each equipment that has its classification based on pressure (Tab. 7). For those that do not have this triage (turbine and evaporator), constants “C” are null. “P” is the ORC equipment operation pressure.

$$\log F_P = C_1 + C_2 \cdot \log(P) + C_3 \cdot [\log(P)]^2 \quad (16)$$

Table 7 – Coefficients and constants necessary for the parameters “FP” and “FBM” calculation, both from pumps as the heat exchangers (Turton et al., 2008).

Equipment	Classification by Pressure	Material	C <sub>1</sub>	C <sub>2</sub>	C <sub>3</sub>	B <sub>1</sub>	B <sub>2</sub>	F <sub>M</sub>
Condenser	P < 40 bar	Carbon steel	0	0	0	1.74	1.55	1
Condenser	P < 40 bar	Titanium	0	0	0	1.74	1.55	11.4
Superheating	P < 40 bar	Carbon steel	0	0	0	1.74	1.55	1
Superheating	P < 40 bar	Titanium	0	0	0	1.74	1.55	11.4
Fluid pump	P < 11 bar	Cast iron	0	0	0	1.89	1.35	1
Fluid pump	P < 11 bar	Titanium	0	0	0	1.89	1.35	6.4
Fluid pump	11 < P < 101 bar	Cast iron	-0.245	0.259	-0.014	1.89	1.35	1
Fluid pump	11 < P < 101 bar	Titanium	-0.245	0.259	-0.014	1.89	1.35	6.4

Table 8 – “FBM” parameter for: turbine and evaporator (Turton et al., 2008).

Equipment	Material	F <sub>BM</sub>
Turbine	Carbon steel	2.2
Turbine	Nickel	11.6
Evaporator	Carbon steel	3
Evaporator	Titanium	14.5

Values for all coefficients (K, B, C, F<sub>M</sub>, and F<sub>BM</sub>) were established on 2001 CEPCI based model (CEPCI<sub>2001</sub> = 397) (Turton et al., 2008). Thus, there was a need to convert these results to current times. As CEPCI calculation is done with one year delay, the results obtained for economic analysis in this study were related to September 2014 (CEPCI<sub>Sep/2014</sub> = 575.4) (Chemical Engineering site, 2015).

In the first place, the total investment cost for the ORC plant construction in the year of 2001 was retrieved (Cost<sub>2001</sub>). To do this, all costs from purchasing each equipment were added up (Eq. (17)).

$$\text{Cost}_{2001} = C_{\text{BM,t}} + C_{\text{BM,evap}} + C_{\text{BM,sup}} + C_{\text{BM,cond}} + C_{\text{BM,pu,f}} + C_{\text{BM,tow}} \quad (17)$$

In order to update the 2001 total plant investment cost to September 2014, the value was just multiplied by the ratio between the respective CEPCI from each period, as shown on Eq. (18).

$$\text{Cost}_{\text{Sep/2014}} = \text{Cost}_{2001} \cdot \left[ \frac{\text{Cost}_{\text{Sep/2014}}}{\text{Cost}_{2001}} \right] \quad (18)$$

Easiness to convert the cost from one period to another, without loss of precision, is one of the great advantages of this economic model. Furthermore, when adding the annual percentage rate of interest (i) that the investment is subjected to, and also the ORC plant operating time in years (t), the "annuity" can be calculated (Eq. (19)).

$$A = \text{Custo}_{\text{Sep/2014}} \cdot \left\{ i \cdot (1 + i)^t / [(1 + i)^t - i] \right\} \quad (19)$$

Finally, EPC is calculated as shown on Eq. (20), in which "f" represents the operation, maintenance and facility insurance cost, that is 1.65% of the plant total cost according to Yang et al. (2014). "H" is equal to hours per year of system operation. 7,500 h/year was adopted Yang et al. (2014), which includes ORC plant maintenance shutdowns. The calculation also takes into consideration the net energy produced by the ORC.

$$\text{EPC} = \left[ (A + f \cdot \text{Cost}_{\text{Sep/2014}}) / (W_{\text{net}} \cdot H) \right] \quad (20)$$

Sales from the electric energy market, in terms of prices, must be assessed in order to find out the time period in which the investments will be repaid from the proposed ORC systems. This study took Brazil's Southeast region as an

example. According to ANEEL (2015), the average electricity selling price for industries to ANEEL was 0.38726 R\$/kWh or 0.10475 \$/kWh for that region (dollar exchange rate for 11/21/2015, 11:20).

Thus, the difference between ANEEL value for electricity selling price and the EPC is the gain obtained by the ORC plant (G) (Eq. (21)). It is worth mentioning that this gain assumes negative values to consider the years in which the ORC system will be in operation until the time that the investment is repaid (payback). From this point on, implementation of one of the ORC systems proposed is assumed as a profit. As the depreciation period gets higher, the financial return becomes faster.

$$G = \text{Price}_{\text{ANEEL}} - \text{EPC} \tag{21}$$

### 4.3. Economic study results

Results focused on the initial investment, the EPC and the payback, these for the ORC with toluene as working fluid and several evaporation pressures that make the plant able to operate.

The invested capital, electricity production cost, and payback were presented for the September 2014 period. The CEPCI based economic model can be adopted without major errors during a five year period (Vatavuk, 2002). Thus, results presented in this section can be used for economic feasibility analysis of an electrical energy production ORC plant, ICE based, with deployment scheduled until September 2019.

An analysis of the capital invested in the ORC equipment purchase that operates with toluene was taken as an illustration. Values were between R\$ 1,812,259.89 and R\$ 10,234,870.83, as shown on Tab. 9.

Figure 5 shows the EPC in R\$/kWh, as a function of the ORC plant useful lifetime or amortization period ( $t = 1$  to 20 years). It was calculated for each toluene evaporation pressure proposed. These graphs represent calculations made for an 12% interest rate, but EPC for 8, 10, 14, and 16% were also simulated, in which EPC had a continuous increase, on average, 1.85% to one interest rate to the other, when " $t = 1$  year" and up to 12.5% for " $t = 20$  years".

Payback is presented on Fig. 6. Graphs were set in function of the gain regarding the sale of electricity produced (Eq. (21)) and the ORC plant operation lifetime, stipulated in 20 years. These graphs represent calculations made for an 12% interest rate, but also was simulated for 8, 10, 14, and 16% payback, from a value of " $i$ " to another, respectively. The payback increased steadily during 4.5 months for toluene. It is worth mentioning that when a graph based on a certain working fluid, evaporation pressure, ORC setting, and interest rate, reaches the horizontal axis, that point represents the time when the ORC system investment is repaid. From that point on, a profit gained with the plant implementation is observed. Figure 7, unlike Fig. 6, shows the gain on the electricity produced sale based on the amortization period for different interest rates analyzed, in which the evaporation pressure is equivalent to 2,000 kPa.

Table 9 – Investment cost for the ORC plant.

Working fluid	Evaporation Pressure [kPa]	Net Power [kW]	Shipper ORC setting [R\$]	Expensive ORC setting [R\$]
Toluene	500	127.12	1,812,259.89	9,160,262.50
	1,000	143.28	1,851,502.93	9,344,628.86
	1,500	151.77	1,927,972.67	9,789,384.38
	2,000	157.07	1,955,161.77	9,928,735.38
	2,500	160.80	1,977,956.89	10,045,701.25
	3,000	163.55	1,997,688.27	10,147,156.99
	3,500	165.54	2,014,690.08	10,234,870.83

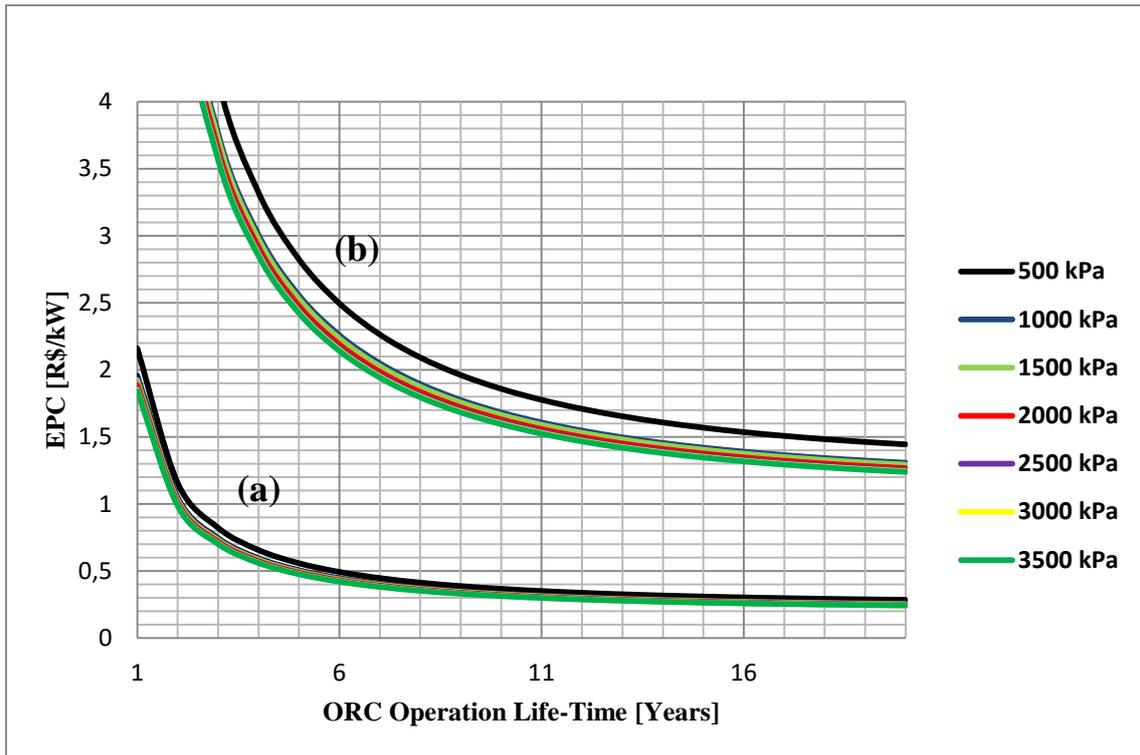


Figure 5 – Graph of EPC for the ORC plant with toluene as the working fluid ( $i = 12\%$ ) for (a) lower-cost ORC plant setting and (b) higher cost ORC plant setting.

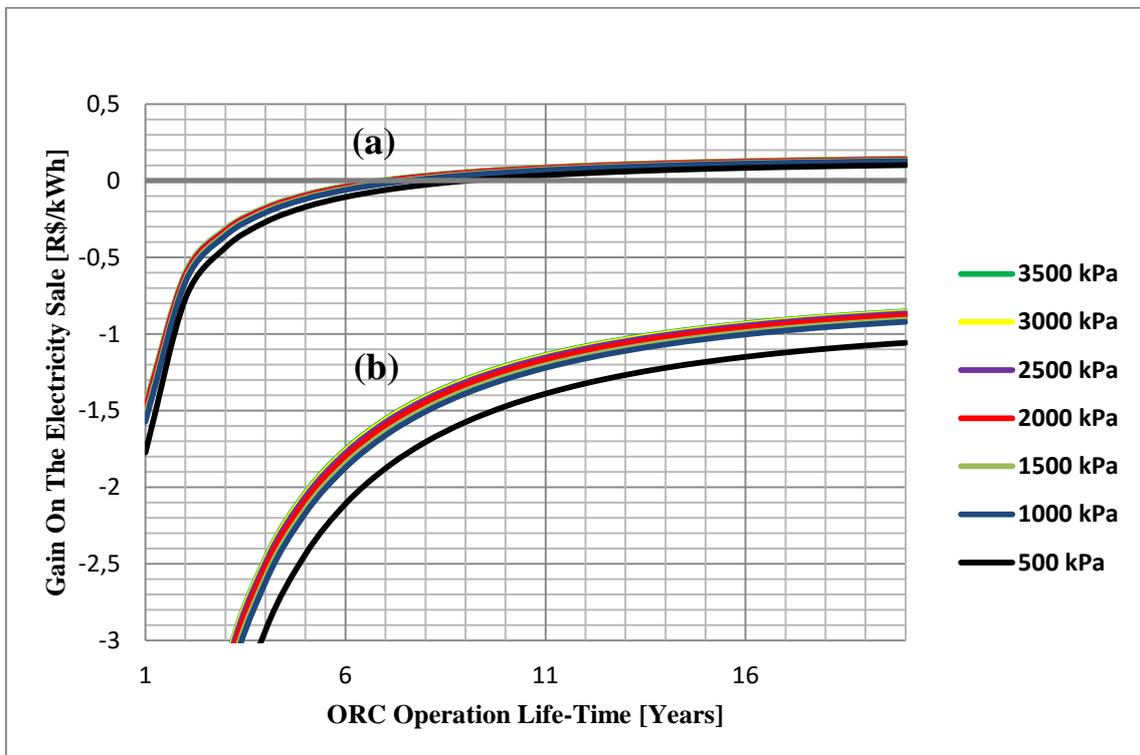


Figure 6 – Graph of payback for the ORC plant with toluene as the working fluid ( $i = 12\%$ ) for (a) lower-cost ORC plant setting and (b) higher cost ORC plant setting.

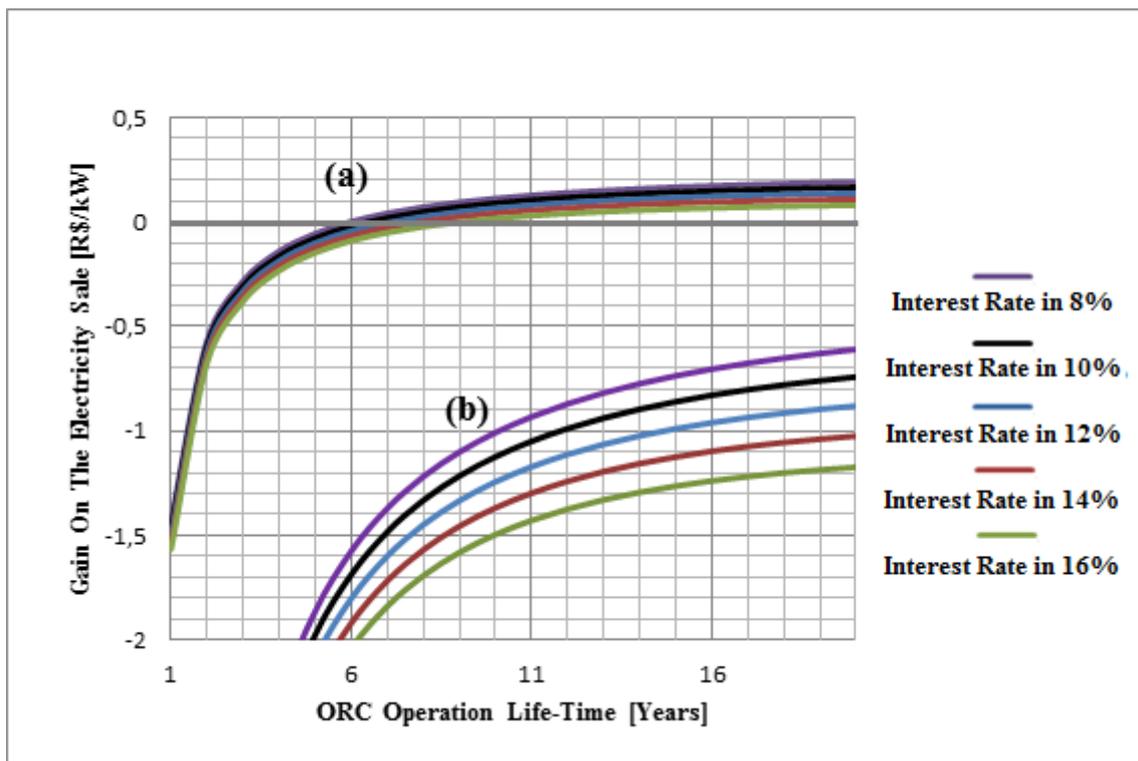


Figure 7 – Graph of payback for the ORC plant with toluene as the working fluid ( $P_{evap} = 2,000$  kPa) for (a) lower-cost ORC plant setting and (b) higher cost ORC plant setting.

## 5. CONCLUSIONS

The ORC systems suggested, with or without a cooling tower, provided similar results according to the technical analyses, despite the initial cost being greater for the system with a cooling tower due to equipment investment. When there is difficulty regarding water access, this configuration type has proved to be almost as efficient as the other one. It was possible to generalize the results for both systems proposed in this study.

Working fluids with best results were toluene, benzene, and acetone, respectively. These fluids presented greater energy production values, as well as First and Second Law efficiencies among the simulated working fluids. More satisfactory results for all fluids were obtained when the evaporation pressure approached the maximum (Tab. 10).

Finally, the set of ORC plant proposed, despite the investment price is no problem, the project is able to increase the company energy production in almost 20%.

Table 10 – Best technical results obtained for all fluids on suggested ORC systems.

Fluid – Evaporation pressure [kPa]	Net Power [kW]	1 <sup>st</sup> Law efficiency [%]
Acetone – 3,000	152.03	5.46
Benzene – 4,000	165.27	5.94
Cyclohexane – 3,500	136.46	4.90
Heptane – 2,000	113.65	4.08
Hexane – 2,500	107.46	3.86
Octane – 2,000	116.91	4.20
Toluene – 3,500	165.54	5.95

The CEPCI based economic model is quite useful for strategic analysis by company managers. This method produces data in accordance with the market reality and it is a powerful tool to evaluate chemical plant economic feasibility, such as the ORC. Three parameters were evaluated in the economic simulations during this study: investment cost, cost of electricity produced, and payback. For the last two parameters as the evaporation pressure was higher, analysis

results were minor. As with regards to the investment cost, as evaporation pressure increased, plant cost also increased due to the need of technologically advanced equipment to produce more power, which is consequently more expensive.

Generally, not only for toluene, ORC systems assembled with the most expensive equipment returned results which prevented their implementation (plant investment costs were between 8.7 and 10.3 million Reais). With this, EPC values were also very high and made the financial return just come after 20 years of plant operation. Thus, an option for cheaper equipment should be made whenever possible, within the resistance and safety project specifications.

As an example, the economic analysis carried out in this study showed that the ORC system, assembled with the lowest possible cost, can have a payback in six years, for the specific case of toluene as working fluid,  $P_{\text{evap}} = 3,500$  kPa and 12% annual interest rate. Such system has an investment cost of R\$ 2,014,690.08. Thus, it is noticed that the ORC system may not be advantageous only for electric power trade, since financial return would not be achieved soon.

However, technological advances related to a system that reduces pollutant emissions, as well as increase considerably the electrical production system efficiency, can bring marketing gains to the company, besides increasing the investors interest on this type of technology.

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