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TECHNO-ECONOMIC ANALYSIS OF THE POTENTIAL FOR ADDITIONAL ELECTRICITY GENERATION USING LOW-GRADE WASTE HEAT RECOVERY IN GAS TURBINES

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Abstract. *The search for more efficient processes has become a global necessity, due to the growing energy demand and the scarcity of nonrenewable energy sources. Combined cycle power plants are examples of how it is possible to increase the thermal efficiency of an electricity generation process. Despite this, there are heat dissipation points in these plants causing decrease in efficiency, especially in gas turbines. As examples, one can mention the heat exchangers used for cooling the air extracted from the compressor for further cooling of the turbine vanes. In this way, this paper presents a technical economic evaluation of the potential for additional electricity generating through the utilization of an Organic Rankine Cycle (ORC) powered by these low-grade heat dissipation streams of a gas turbine system. First, Siemens SGT6-5000F gas turbine was modeled using GateCycle™ software. Then, the spots having the potential for waste heat recovery were identified and analyzed. After that, it was incorporated an ORC in the system. Finally, an economic evaluation was carried out. The results show that it is possible to recover the low-grade heat and generate more electricity while maintaining the same fuel consumption, thus increasing the efficiency and contributing to mitigate the environmental impacts of these systems. The costs associated to changes needed to modify the system are relative small in comparison with the advantages obtained with the additional power generated.*

Keywords: *efficiency, gas turbine, low-grade energy recovery, organic Rankine cycle, waste heat recovery.*

1. INTRODUCTION

The burning of fossil fuels, considered one of the main causes of global warming, grows every year. In 2007, the Intergovernmental Panel on Climate Change (IPCC), created by the United Nations (UN), wrote and published three reports. At last report, the Panel makes clear that although human being is responsible for the environmental impacts of burning fossil fuels, it can also solve this problem (IPCC, 2007). One of the possibilities to reduce these impacts is to improve the efficiency of industrial processes and electricity generation.

Combined cycle and cogeneration plants are examples of how it is possible to increase the thermal efficiency of a process. Operating separately the gas and steam turbines reach efficiencies around 35 to 40%. The combination of these two systems to generate electricity from only one fuel achieves efficiencies up to 60% (Lora and Nascimento, 2004). Despite this, combined cycle power plants have heat dissipation points throughout the process, which cause reduction their efficiency.

Organic Rankine Cycles (ORC) are a technology to produce electricity from energy (heat) sources of low quality (grade), i.e., from low temperature and pressure mass flows (Schuster et al., 2008). When the hot source comes from the residual heat utilization, temperatures are not very high. Thus, it is more efficient to convert thermal energy into electric energy by using an organic fluid instead of water, mainly due to the difference between the specific heat of the organic fluid and the specific heat of water (Karellas and Schuster, 2008).

Some of the advantages of using ORC systems are: better use of energy resources, system size reduction, reduction of pollutant emissions and the possibility of reducing the cost of energy generated (Desai and Bandyopadhyay, 2009).

The purpose of this work is to realize a technical and economic evaluation of the potential for electricity generation through the low-grade waste heat recovery from low temperature streams in gas turbines commonly used in combined cycle power plants. As a case of study, it will be analyzed the gas turbine Siemens SGT6-5000F (formerly named W501F).

2. SIEMENS SGT6-5000F GAS TURBINE

Siemens Corporation introduced the first unit in the W501 series (former name of SGT6-5000F turbine) in 1968. Since that time, new technologies were incorporated in the turbine. New cooling methods have been developed and new materials, as well as improvements in the compressor construction (Siemens, 2008). The SGT6-5000F series was officially introduced in 1993. Current models can produce 208 MW with 38.4% of efficiency in simple cycle and over 300 MW in combined cycle. Operating with natural gas, NOx emissions are less than 9 ppm (Kovac, 2008).

The SGT6-5000F gas turbine consists of an axial flow compressor with 16 stages, a combustion chamber with 16 burners, and a 4-stage reaction turbine (PFC Energia, 2002).

This gas turbine is ideally suited for simple cycle, combined cycle and heat recovery applications, including plants with integrated gasification and cogeneration. In combined cycles, the system efficiency reaches 57% (Siemens, 2008).

A gas turbine is a well stabilished turbomachinery, with internal combustion, that operates according to Brayton cycle. Atmospheric air is conducted to the inlet (suction) of the compressor where it is compressed and forced into the interior of the combustion chambers. The fuel is mixed with the compressed air and burned, releasing the chemical energy that is converted into mechanical work rotation in the turbine (expander). Part of this energy is used to drive the compressor, and the remaining part is used to power a load (PFC Energia, 2002).

3. ORGANIC RANKINE CYCLE

The Organic Rankine Cycle, in a last instance, is a Rankine cycle in which an organic working fluid is used instead of traditional water vapour. In recent years, the ORC has become popular in the power generation processes due to the fact of allowing the heat recovery at low temperatures (Schuster et al., 2009). The ORC's are normally used to generate electricity through low-grade heat recovery, with temperature sources as low as 80 °C (Mohamed et al., 2010).

Although studied since the 1980s, ORC’s did not become popular until the current concern about the scarcity of fossil fuels and the environmental problems associated with these fuels utilization. ORC uses an organic working fluid. It offers advantages over the conventional Rankine cycle with water, because it uses low or medium temperature heat sources with a relative high efficiency (Tchanche et al., 2011). Additional advantages of Organic Rankine Cycle are: adaptability for different types of heat sources, technology well developed, low complexity, ability to use on a small scale, distributed generation, low investment and maintenance costs and market availability (Tchanche et al., 2014).

Fluids in ORC systems, can be classified into three groups, based on the saturated vapor curve on a T-s diagram: (i) dry fluids, such as n-pentane, benzene and toluene, with a positive slope; (ii) wet fluids, such as water and ammonia, with negative slope; and (iii) isentropic fluids, such as trichlorofluoromethane (R11), and dichlorodifluoromethane (R12) without slope (the steam saturation curve for this type of fluid is nearly vertical in T-s diagram) (Desai and Bandyopadhyay, 2009). Fig. 1 shows the saturation curve for the three types of fluids. Dry fluids are most suitable for use in ORC’s that use low-grade heat sources.

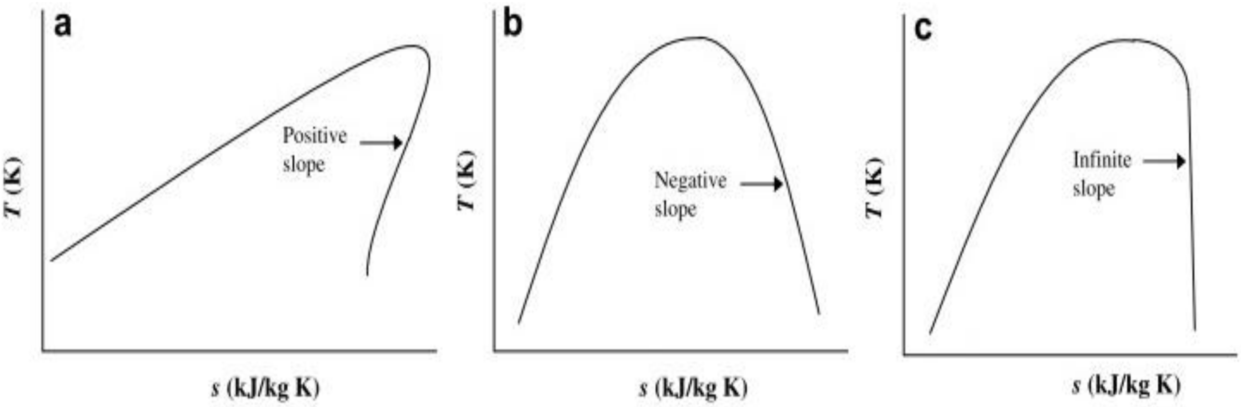

Figure 1. Typical saturation curves on T–s diagram for (a) a dry fluid (b) a wet fluid and (c) an isentropic fluid

Using ORC it is possible to recover heat from different sources, such as: solar and geothermal, biomass, industrial waste heat, etc. This is proven by the large number of systems installed in plants in the US, Canada, Italy, Austria, Germany, Holland, Sweden and other countries (Tchanche et al., 2011).

An ORC is basically constituted of a generator, an expander, a feed pump, an evaporator, a condenser, a recuperator and a control system. There are projects for kW of power up to a few MW. On the market there is a wide range of systems in terms of size, expansion technology and working temperatures and pressures (Tchanche et al., 2014).

The low-grade heat recovery is a complex task. Several aspects must be taken into account. The selection of the working fluid should be careful analyzed, taking into account the ODP (ozone depletion potential), GWP (global warming potential), flammability and toxicity of the fluid, and the resulting cycle efficiency (Meinel et al., 2014).

The heat transfer from the source may be performed in two ways: (i) waste heat stream heating directly and the organic fluid through a heat exchanger or (ii) using an intermediate fluid (oil), that is integrated to the system to avoid the risk of contact between the waste heat stream and a flammable organic fluid (Tchanche et al., 2011). These two configurations can be seen in figure 2.

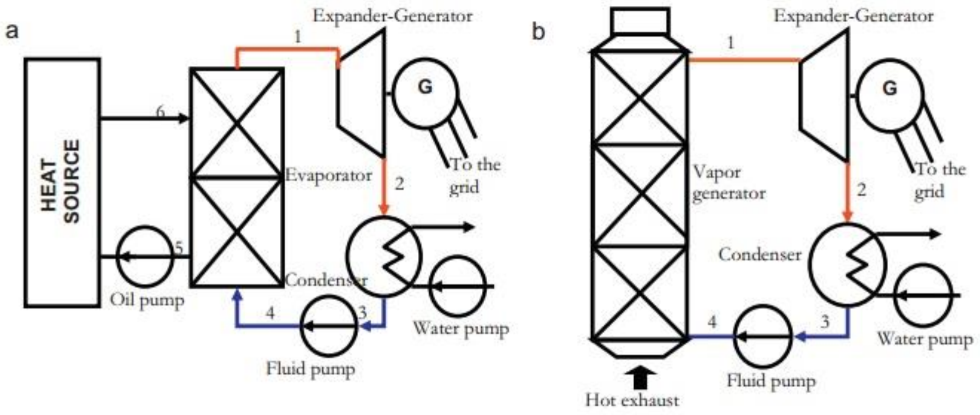

Figure 2. Rankine cycles configurations in waste heat recovery: (a) organic fluid directly receives heat from the hot source and (b) an oil circuit heat is utilized (Tchanche et al., 2011)

4. TURBINE MODELING

Siemens SGT6-5000F turbine was modeled through GateCycle™ software. The model was built using data from a gas turbine installed at Uruguaiana Power Plant, a combined cycle located in southern Brazil. The system was modeled in accordance to data shown on Table 1. The obtained model is shown in Figure 3.

Table 1. Data for turbine modeling

COMPRESSOR	Inlet	Mass flow rate (kg/s)	449
		Temperature (°C)	15
		Pressure (kPa)	101.325
	Bleed 01 (stage 6)	Mass flow rate (kg/s)	2.404
		Pressure (kPa)	393
	Bleed 02 (stage 10)	Mass flow rate (kg/s)	5.824
		Pressure (kPa)	765.32
	Bleed 03 (stage 13)	Mass flow rate (kg/s)	19.464
		Pressure (kPa)	1151.42
	Bleed 04 Rotor Cooling (stage 16)	Mass flow rate (kg/s)	38.165
		Pressure (kPa)	1657.22
		Temperature (°C)	411
COMBUSTION CHAMBER	Fuel Inlet (Natural Gas)	Pressure (kPa)	2757.90
		Temperature (°C)	135
	Air Inlet	Pressure (kPa)	1657.22
		Temperature (°C)	411
	Outlet	Combustion Efficiency (%)	98
		Gas Oulet Temperature (°C)	1382.5
TURBINE (EXPANDER)	Rotor Cooling	Air Temperature (°C)	200
	Outlet	Oulet Pressure (kPa)	101.325
		Outlet Temperature (°C)	609
		Generator Efficiency (%)	98

The model developed allows the calculation of the system net power, overall efficiency and other parameters. The main results obtained are shown in Table 2. In the W501F turbine, part of the air that enters in the compressor is extracted to promote cooling of the expander components (nozzle and blades). There are four bleeds in different stages. Bleed 04 is used to cool the turbine rotor. However, when this air leave the compressor, it is not at the proper temperature to achieve blade cooling. Thus, a heat exchanger is required to remove part of the energy of this stream, reducing its temperature to 200 °C, before it reentry into the turbine (PFC Energia, 2002).

The heat exchanger normally used is of the type or air/water or air/air, which contains a fan that promotes the system air cooling. Air enters at 411 °C and comes out at 200 °C. Usually, the energy (waste heat) removed from the system by the heat exchanger is not used. Therefore, this is a point of potential integration of an organic Rankine cycle. Another important point is the turbine output. Exhaust gas leave at a temperature of 609 ºC, but this flow will not be considered here, since it is on under a high temperature, being more suitable to be recovered on a traditional steam cycle, through heat recovery steam generator. So, the position considered here is in the cooling air heat exchanger.

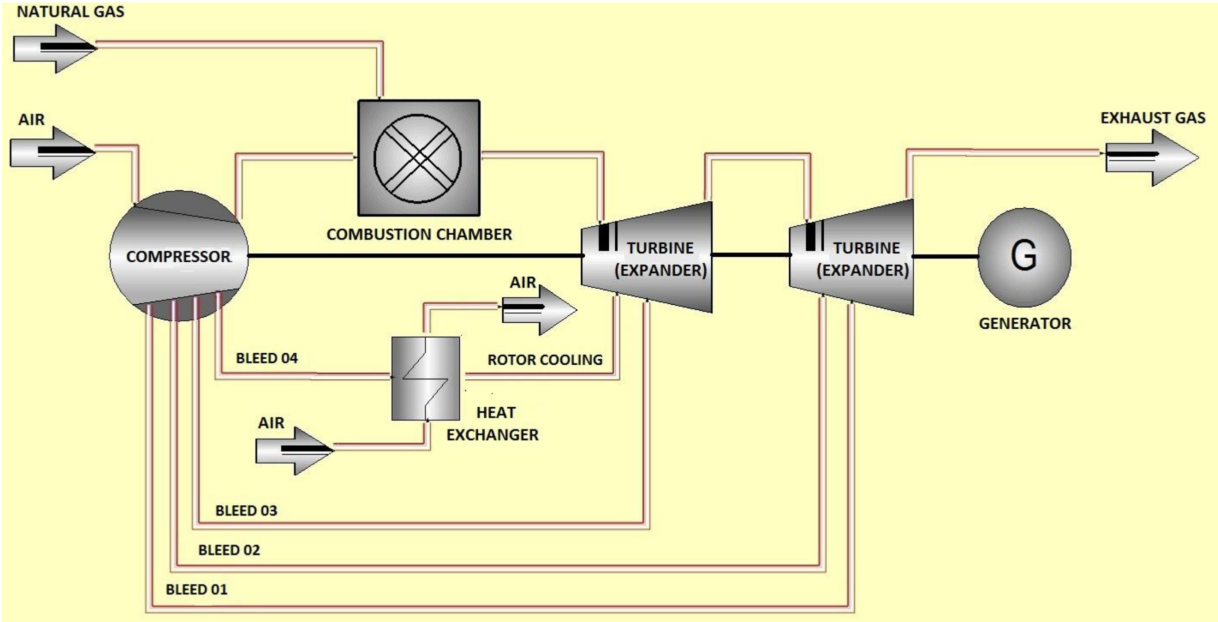

Figure 3. Turbine model (Expander was divided into two parts due to the restrictions of GateCycle)

Table 2. Information obtained from the turbine

Compressor Power (MW)	181.335
Expander Power (MW)	361.695
Net Power Generated (MW)	173.127
Fuel Consuption (kg/s)	10.505
Rejected Energy - Heat Exchanger (MW)	8.477
System Efficiency (%)	34.73

5. WORKING FLUID SELECTION

The first step in the ORC design is to select the fluid. The selection should be made according to available parameters (Karellas and Schuster, 2008). The organic fluid used in a ORC is of fundamental importance, since it affects the efficiency of the system, the size of the components, stability, security and influences the environmental impacts (Bao and Zhao, 2013).

Therefore, most of the work focuses on the appropriate fluid selection. Thermal efficiency is usually adequate as the main criterion for evaluating different fluids (Long et al., 2014).This work used this criterion for choosing the working fluid. As previously told, the energy is recovered from the air at the exit of the fourth bleed of the compressor, which is at 411 °C. Table 3 shows some recommended fluids, identified by previous studies, in accordance with the heat source temperature mentioned.

Table 3. Recommended fluids (Bao and Zhao, 2013)

Working Fluid	Source Temperature	Reference
Benzene	470 °C	(Vaja and Gambarotta, 2010)
Toluene	250 – 500 °C	(Siddiqi and Atakan, 2012)
Dodecane	250 – 500 °C	(Siddiqi and Atakan, 2012)

Table 4 shows the practical limits of temperature and pressure for the main fluids that can be used in the ORC. The fluids were placed in order according to the highest possible evaporating temperature.

It is preferable to adopt the maximum pressure evaporation and the minimum condensing pressure. However, there are always restrictions in practice (Rayegan and Tao, 2011).

Some previous works recommend 2.0 MPa for the fluid evaporation pressure, while others recommend 2.5 MPa. There are still those who prefer to work near critical pressure, adopting the limit point in which the fluid in the saturated vapor condition will not suffer condensation in expander. This criterion is the same adopted for the fluids in Table 4. Regarding the condensing pressure, there are recommendations to adopt at least 5 kPa. However, it is always preferable to work with values equal or above atmospheric pressure to prevent the air entering in the system (Bao and Zhao, 2013).

Table 4. Practical limits of the ORC for preselected working fluids (Rayegan and Tao, 2011)

Fluid	Maximum T_{eva} (°C)	Maximum P_{eva} (MPa)	Minimum P_{cond} (kPa)	Minimum T_{cond} (°C)
Dodecane	381	1.723	5.1	121
Decane	337	1.896	5.1	85
Nonane	314	2.059	5	65
Toluene	307	3.576	5.1	31
Octane	287	2.2	5	44
Benzene	274	4.067	12.7	25
Cyclohexane	272	3.665	13	25
Heptane	258	2.41	6.1	25
Hexane	226	2.68	20.2	25
Isohexane	216	2.682	28.2	25
Acetone	213	3.379	30.7	25
Pentane	186	2.865	68.3	25
Isopentane	177	2.887	91.8	25

6. THECNICAL ANALYSIS

For the analysis presented in this work, it was considered a simple ORC system (pump, evaporator, condenser and expander). All the fluids of Tab. 4 were analyzed. It was adopted that the organic fluid should leave the evaporator as saturated vapor. As all the selected fluids are dry type, there are no condensation problems inside the expander. It were not considered pressure losses. The effectivities of the condenser and evaporator was considered 80% and the adopted isentropic efficiency of the pump and expander were 90% and 70%, respectively. For the electrical generator, the efficiency used was 95%. ORC simple scheme and the temperature-entropy diagram of the cycle are shown in Figure 4.

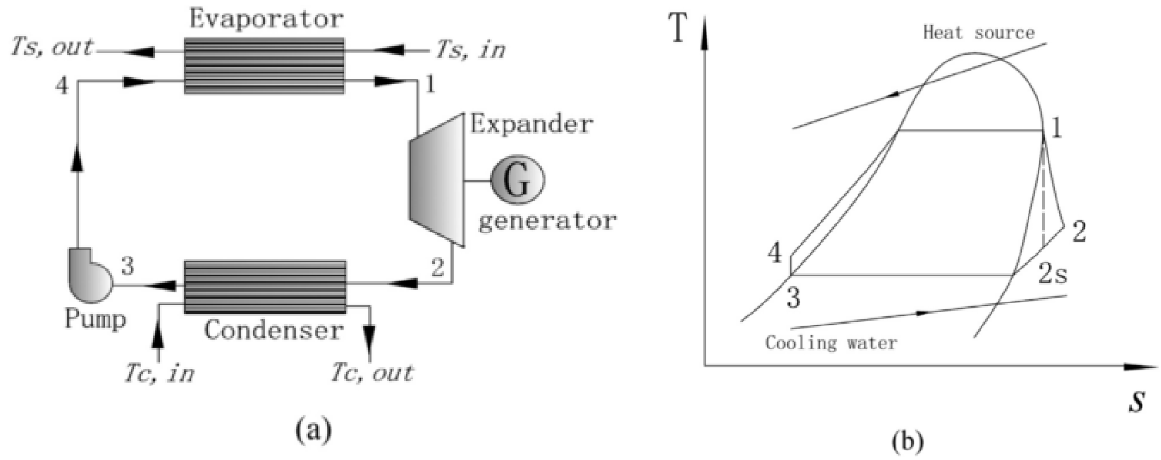

Figure 4. Schematic diagram of a typical ORC (a) and T-S diagram (b) (Long and Bao, 2014).

The determination of the working fluid properties it was used “Coolprop”, which is a library of thermophysical properties for various fluids (Bell et al., 2014). It was performed two analyzes regarding the working fluids. In the first analysis it was considered the minimum condensing pressure of each fluid, found in Tab. 4. In the second analysis the condensation pressure was considered equal to atmospheric pressure at sea level (101,325 kPa). In both cases, calculations were made for different evaporating pressures. It was calculated the ORC efficiency, the net power generated, the final efficiency of the system, among other factors. Figure 5 shows the cycle efficiency obtained for both analyzes.

In the first analysis (Fig. 5a), toluene appears as the fluid with higher efficiency for evaporation pressures until 3.6 MPa. Above this pressure, toluene reach the critical temperature and benzene is more efficient. After these fluids, cyclohexane and acetone appears with good values of efficiency. In the second analysis (Fig. 5b), the condensing pressure was considered the same for all fluids. Efficiencies are smaller in this case. Benzene is the fluid with higher efficiency for any evaporation pressure. Acetone appears immediately in second. Taking into account the recommendations to the evaporation pressure limits, the results were grouped into six groups in Tab. 5.

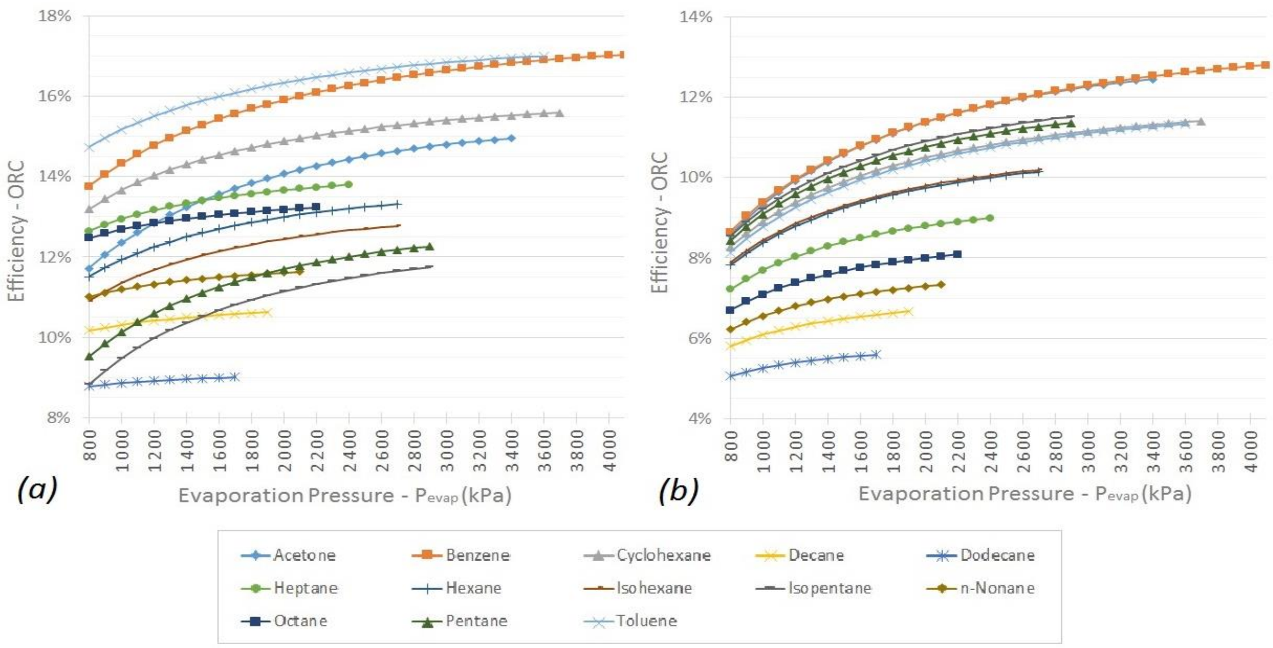

Figure 5. Efficiency of the ORC fluid for different evaporation pressures: (a) for minimum condensing pressure and (b) for condensing pressure equal to atmospheric.

Table 5. Working fluid with higher efficiencies for different condensation and evaporation pressures

Pcond (kPa)	**Pevap (MPa)**	**Fluids**	**Efficiency**	**Net Power (kW)**	**Increase in Overall Efficiency**
Minimum	Maximum	Benzene	17.0 %	1443	0.29 %
Minimum	2.5	Toluene	16.6 %	1410	0.28 %
Minimum	2.0	Toluene	16.3 %	1385	0.28 %
101.3	Maximum	Benzene	12.8 %	1084	0.22 %
101.3	2.5	Benzene	11.9 %	1010	0.20 %
101.3	2.0	Benzene	11.4 %	965	0.19 %

Table 5 shows that for different pressure conditions there are a more suitable fluid according to the performance criterion. In the first analysis (higher pressure ratio), benzene and toluene reaches 17% of efficiency. It means a reduction of 0.83% in fuel consumption. It also means a reduction in the emission of 14 tons of CO_2 per day.

For evaporation pressures of 2.0 and 2.5 MPa, toluene is more efficient, it reaches 16.3 and 16.6% of efficiency, respectively. In the second analysis, benzene is the fluid with higher efficiency in the three cases analyzed. The efficiencies in this case are between 12.8 and 11.4%.

7. ECONOMIC ANALYSIS

For economic analysis, equipment costs were calculated taking into account the situations presented in Tab. 5. Costs of heat exchangers (evaporator and condenser) depend on the equipment's heat transfer area (m²), as shown on Tab. 6. This area calculation was based on the method of logarithmic average temperatures (Rodriguez, 2014). To calculate the cost of pump and expander it was used their respective power (kW) (Tab. 6). For the auxiliary equipment (piping and other accessories), it was estimated a cost of 5% relative to the total amount of the four main components of the system (Tab. 6). In this way, for the situations presented in Tab. 5, taking into account only the best fluid, the total cost was calculated, as shown on Tab. 7.

Table 6. Equipment Costs (Rodriguez, 2014)

<table>
<tr><th>Equipament</th><th>Cost (US$)</th></tr>
<tr><td>Evaporator</td><td rowspan="2">$717.36\,(\text{Area})^{0.8}$</td></tr>
<tr><td>Condenser</td></tr>
<tr><td>Expander</td><td>$5374.1(\text{Power})^{0.7}$</td></tr>
<tr><td>Pump</td><td>$1366.4(\text{Power})^{0.8}$</td></tr>
</table>

Table 7. Total Costs of Equipments for Different Situations

Situations	Pcond (kPa)	Pevap (MPa)	Fluid	Equipment Costs (Thousands of dollars)
1	Minimum	Maximum	Benzene	1100
2	Minimum	2.5	Toluene	1061
3	Minimum	2,0	Toluene	1048
4	101.3	Maximum	Benzene	923
5	101.3	2.5	Benzene	871
6	101.3	2.0	Benzene	848

Then the Levelized Cost of Energy (LCOE) was calculated. It is defined as the value of the investment over the lifetime of the plant divided by the cumulative amount of energy generated by this investment (Pawel , 2014).

In practice, the LCOE is an indicator of economic viability. It can be calculated from Equations (1) and (2):

$$LCOE = \frac{I_a + O\&M_a}{E_a} \quad (1)$$

$$I_a = \frac{i(1+i)^L}{(1+i)^L - 1} I_{total} \quad (2)$$

In Equation 1, I_a corresponds to the annual investment, $O\&M_a$ represents the annual cost of operation and maintenance and E_a corresponds to the annual energy generated. In Equation 2, I_{total} is the total investment (equipment and installation), i is the discount rate and L is the useful life of the system (years) (Rodriguez, 2014).

To calculate the LCOE, total investment (I_{total}) was considered equal to the cost of the equipment (Tab. 7) with a increase of 10% related to installation costs. The cost of operation and maintenance was considered 5% of the equipment costs. The lifetime (L) was considered 20 years and the operation time, 6000 hours per year. Different discount rates were considered for the scenarios presented in Tab. 7. The results can be seen in Figure 6.

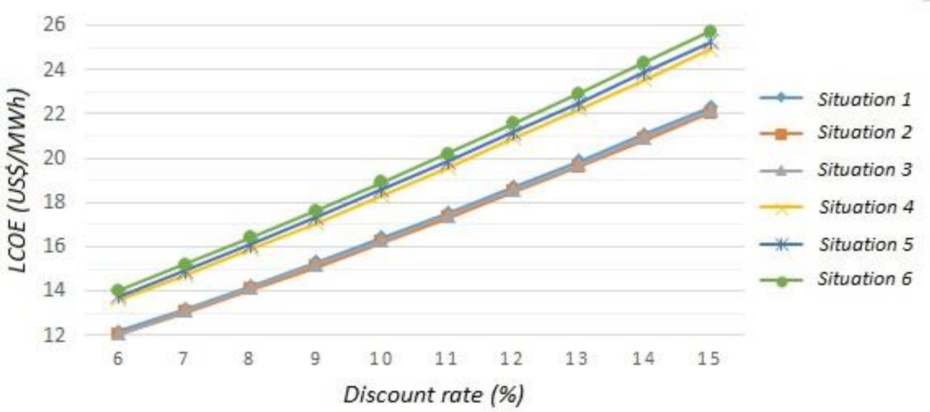

Figure 6. LCOE for different situations

The results show that when using the maximum pressure ratio the LCOE is lower. Among the three situations that represent this case, the cost is almost the same. For a discount rate of 12% for example, the cost is around 18.5 US$/kWh. However, when using condensing pressure equal to atmospheric, the LCOE increases. However, in both cases, the LCOE is lower in comparison with other systems. Rodriguez (2014), for example, showed for a geothermal ORC, LCOE around 200 US$/MWh. However, economic viability depends mainly on the electricity price.

8. CONCLUSIONS

This work shows a technical and economic evaluation of the potential for additional electricity generation using organic Rankine cycle in a gas turbine system. Thirteen working fluids were analyzed according to the criterion of efficiency. The results show that it is possible to recover up to 17.0 % of the low-grade waste heat using benzene as the working fluid, promoting an increase of 1.44 MW in power generated by the system and 0.29% increase in overall efficiency at a cost of 18.5 US$/kWh for an interested rate of 12%. Furthermore, the integration of ORC can promotes a reduction of 0.83% in fuel consumption. It also means a reduction in the emission of 14 tons of CO_2 per day.

It is important to emphasize that was analyzed only the basic ORC system. There are other configurations of ORC and Kalina cycle that must be analyzed. Probably, these configurations will reach higher efficiencies. Furthermore, there are other points in combined cycle where others organic cycles can be integrated. Therefore, this paper shows that the ORC technology is adequate to produce additional electricity using low-grade waste heat with high efficiencies and low costs.

9. ACKNOWLEDGEMENTS

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11. RESPONSIBILITY NOTICE