XI Congreso Nacional y II Internacional
de Ingeniería Termodinámica

11CNIT-XX-2018 FULLPAPER

COGENERATION VERSUS COMBINED CYCLE TO ENHANCE THE FEASIBILITY OF SMALL GAS TURBINES

Ángel Solanas[1], José Ignacio Linares[1], Eva Arenas[1], Yolanda Moratilla[1]

[1]Comillas Pontifical University, Alberto Aguilera 25, 28015-Madrid, Spain, Phone: 34-91-5422800, Fax: 34-91-5596569
e-mail: linares@comillas.edu

ABSTRACT

Small gas turbines (up to 40 MWe) are used in combined heat and power (cogeneration) industrial applications as an efficient way to produce both electricity and useful heat. However, due to both the high costs of fuel and the relative large investment required even for a small machine, such devices do not reach their economic feasibility, being necessary the use of incentives, as feed-in tariff systems.

In this work, an organic Rankine cycle (ORC) is proposed as a way to recover the waste heat from the flue gases of the turbine, resulting in a gas turbine/ORC combined cycle. Although the electric efficiency is improved, being increased from 38.4% in CHP gas turbine to 46.3% in combined cycle configuration, the levelised cost of electricity (LCOE) increases from 80.4 €/MWhe to 100 €/MWhe, both well above the pool market electricity price (around 72 €/MWhe, once it is levelised). In order to obtain a lower value of LCOE, different arrangements have been tested, coming up with two possible solutions. Both of them use a supercritical ORC and recover the condensation heat for cogeneration. One of the solutions (GT/RORC/HRX) uses a recuperator, in such a way that the flue gases of the gas turbine leave the heat recovery gas generator (HRGG) at high temperature, enabling a new heat recovery for cogeneration. The other solution (GT/ORC) does not include a recuperator, so flue gases leave the HRGG at 123ºC, not allowing a further heat recovery from them.

The value of LCOE in the GT/RORC/HRX configuration is 63.8 €/MWhe, whereas in the GT/ORC is 60.5 €/MWhe, both well below the pool price. In order to select the best option, the exergy of the recovered heat has been evaluated in both configurations, resulting 12 MW in the GT/RORC/HRX arrangement and 13.25 MW in the GT/ORC. The difference is due to the higher temperature of the organic fluid (316ºC) at the inlet of the condenser in the second configuration compared to the first one (99ºC), being the condensing temperature the same (85ºC) in both arrangements.

In conclusion, the conversion of all the heat recovered from the flue gases of the gas turbine into electricity is not enough to enhance the economic feasibility of the turbine. On the other hand, the use of all the recovered heat as useful heat in a pure cogeneration scheme does not allow the turbine to reach the feasibility, neither. The optimal solution is a hybrid one where an ORC is used to convert the heat from the flue gases into electricity and the useful heat is the heat released in the condenser. Using such arrangement, the overall electricity production increases from 37.8 MW in the simple cogeneration gas turbine (baseline) to 47.7 MW and the recovered heat decreases from 46.5 MW to 37 MW.

Keywords: *ORC; Gas Turbines; CHP; Cogeneration; LCOE*

1. Introduction

Small gas turbines (10 to 40 MWe) can be used in power-only applications for island operation or in cogeneration (CHP) configuration, recovering the waste heat contained in the flue gases. In both situations the cost is very high, well above the pool market electricity price, so any kind of subsidies are required [1]. One way forward to enhance the profitability would be the conversion of the waste thermal energy into electricity coupling a bottoming cycle to the flue gases stream, that is, transforming the gas turbine into a combined cycle. The classical Rankine cycle working with steam presents some disadvantages, as the vacuum pressure in the condenser, the required split of the turbine due to the high enthalpy drop, the necessity of superheating the steam entering to the turbine to avoid a high moisture in the last stages of the turbine and the high temperature required in the thermal source [2].

Organic Rankine cycles (ORCs) have emerged as an alternative to the steam Rankine cycles in low temperature and low size applications [3]. The use of a dry organic fluid (usually natural hydrocarbons) allows to avoid the superheating at the turbine inlet because the fluid always leaves it as superheated vapour. Other important advantages of the ORCs are the possibility to condensate at pressures over the atmosphere at ambient temperature (depending on the fluid), the reduced enthalpy drop in the turbine, which entails to one-stage turbines and the low value of the evaporation enthalpy compared with water, which allows to use a simple heat exchanger as boiler.

ORCs have been proposed for waste heat recovery applications, when the thermal source temperature is moderate (300ºC) or even low (100ºC). So, their use as bottoming cycles in cogeneration schemes is usual [3], but they can be also employed in topping cycles, for instance fuelled with biomass and recovering the thermal heat in the condenser [4]. Power-only applications in renewable energies are also possible, as in small concentrated solar plants [5] or geothermal power plants [6, 7].

In this paper an ORC is coupled to a small gas turbine of 40 MWe to convert the waste heat of the flue gases into electricity. The objective is to reduce the generation cost, so that no subsidies are required. Supercritical ORC cycle working with benzene is proposed, analysing recuperative and non-recuperative layouts. The resulting combined cycle is analysed mainly in cogeneration scheme, although a power-only assessment is also carried out.

2. Methodology

All the simulations have considered a small gas turbine of 40 MWe referenced by National Renewable Laboratory of USA [1]. It contains a gas turbine to move the compressor and a power turbine to move the electric generator. Based on the actual performances given in [1], two baseline cases have been obtained: GT0 layout and CHP layout. The former is a power-only application and the latter a combined heat and power (CHP) one. A technical model has been solved in order to obtain the main parameters of the turbine. This model has been implemented in Engineering Equation Solver (EES) [8] considering ideal gas behaviour for air and complete combustion with methane (ideal gas model also considered for flue gases). Figure 1 shows the main parameters for the GT0 model, resulting in an electrical efficiency (referred to higher heating value, HHV) of 40.66%. Taking into account those parameters , a new model has been built (CHP layout), with a heat recovery boiler (HRB) outlet temperature of 120ºC. A relative pressure drop of 3% and a minimum approach temperature difference (pinch point, PP) of 35 ºC in the HRB have been assumed. Figure 2 shows the main parameters of this second model. The power is reduced to 37.78 MWe due to the pressure drop in the HRB and a heat recovery of 46.49 MWth is obtained. The new electrical efficiency is 38.41% (referred to HHV).

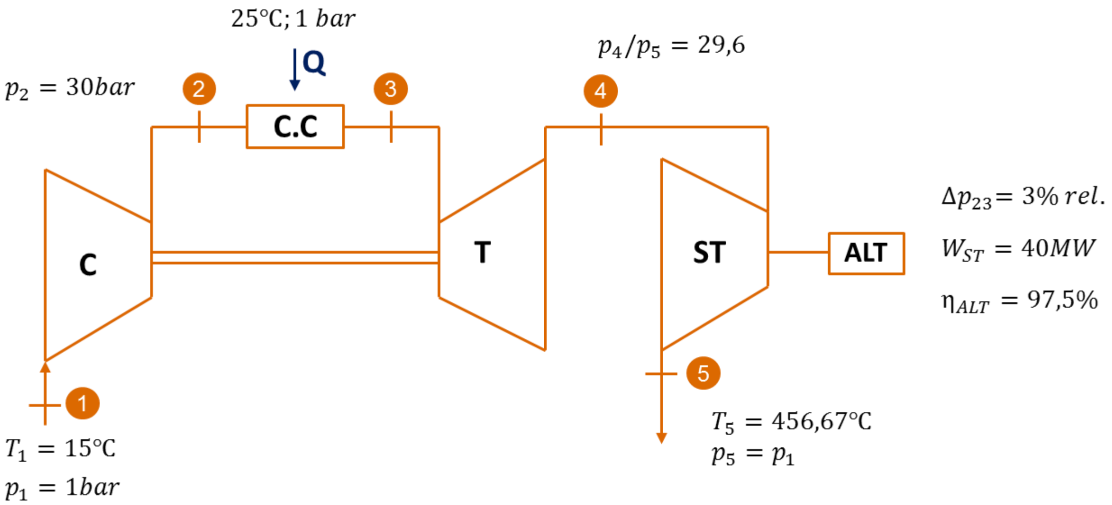

Fig. 1. Small gas turbine considered in the analysis. GT0 layout.

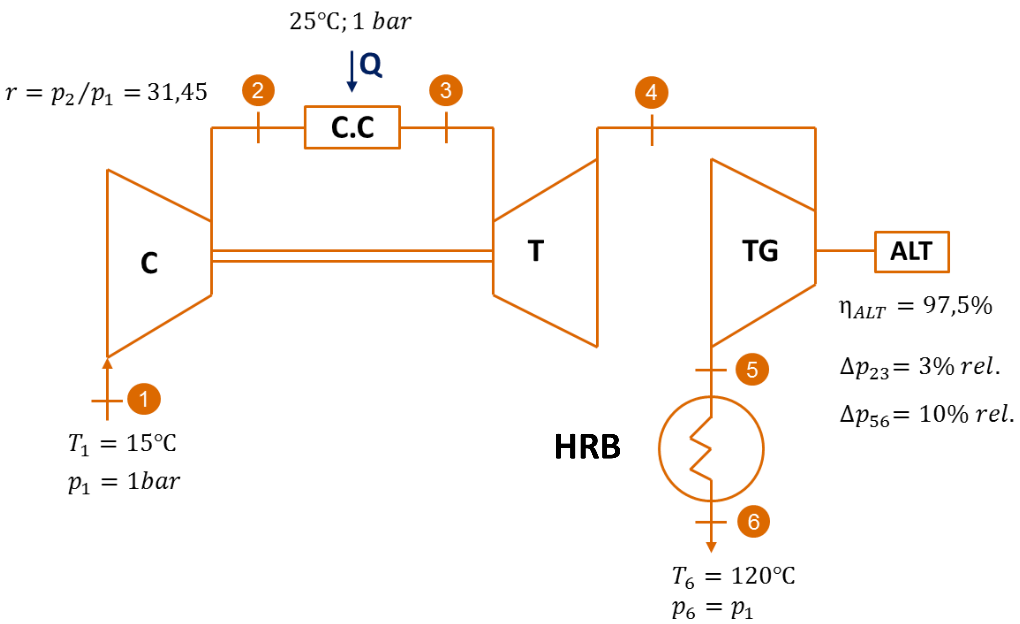

Fig. 2. Small gas turbine with heat recovery boiler to operate in CHP mode. CHP layout.

The Organic Rankine Cycle considered is a supercritical layout using benzene as working fluid. The selection of benzene is due to the high temperature limitations in the turbine inlet (450ºC) and pressure above atmospheric value in the condenser for a condensation temperature of 85ºC (1.18 bar), required for heat recovery applications. The use of an organic fluid allows to operate in supercritical conditions at a moderate pressure (65 bar). Such supercritical pressure entails to close profiles of temperatures in the HRB, reducing the exergy destruction in the recovery process. Two types of layouts for ORC have been considered: recuperated (CC-R) and non-recuperated (CC-NR) one, depending on the desired heat recovery gas generator (HRGG) outlet temperature. So, CC-NR is used when the flue gases leaving the HRGG are not going to be used to recover heat, whereas CC-R is used if a HRB is connected downstream the HRGG. A pinch point of 10ºC has been assumed for the recuperator of the ORC. In both cases, a heat recovery process is carried out in the condenser of the ORC for CHP applications.

Figure 3 shows the main parameters of the combined cycle using non-recuperated ORC (CC-NR layout) and Figure 4 the combined cycle using recuperated ORC (CC-R layout).

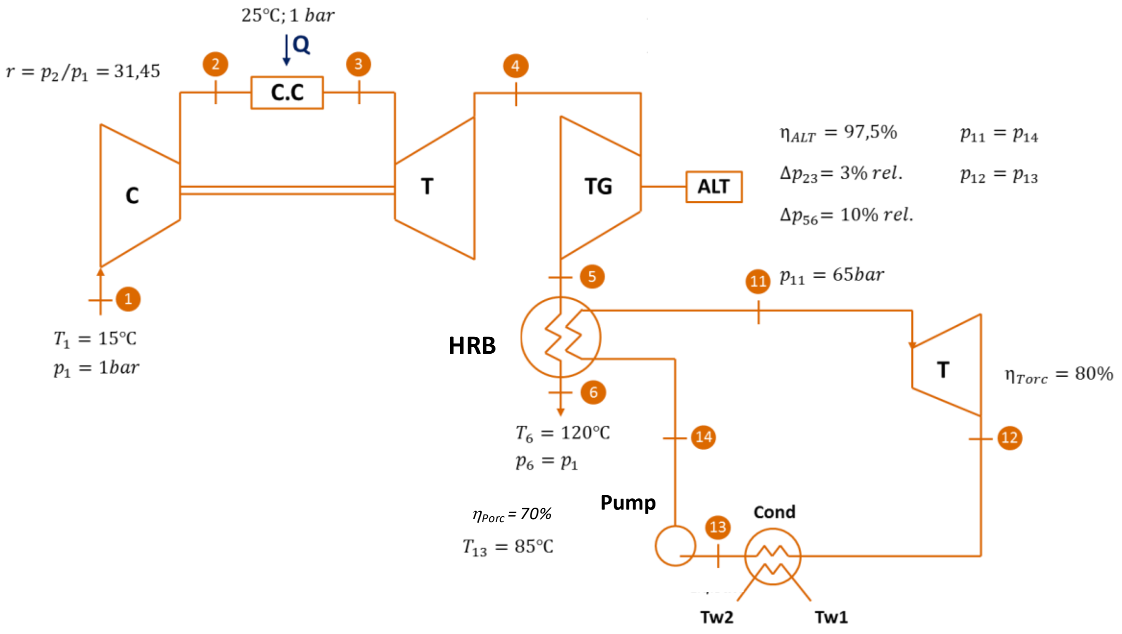

Fig. 3. Small gas turbine in combined cycle with non-recuperated ORC. Heat production for CHP is obtained from the ORC condenser. CC-NR layout.

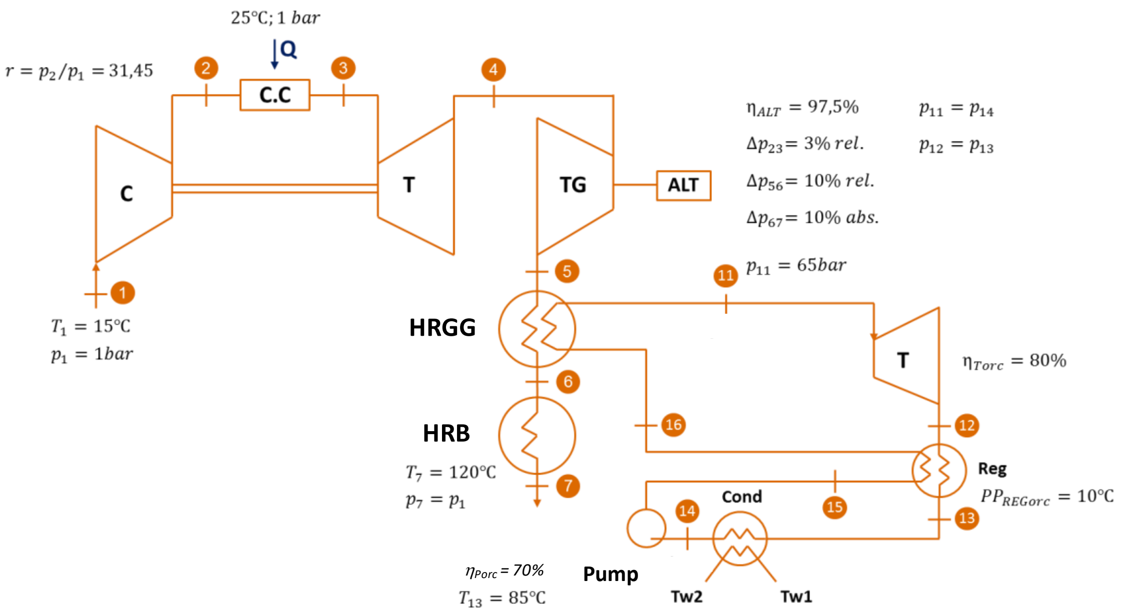

Fig. 4. Small gas turbine in combined cycle with recuperated ORC. Heat production for CHP is obtained from both the ORC condenser and the heat recovering boiler. CC-R layout.

The economic model is based on the levelised electricity cost (LCOE), defined by Equation 1 [9], where CAPEX is the capital expenditure (Eq. 4), OPEX the operation expenditure, CRF is the capital recovery factor (Eq. 2) and AF is the accumulation factor (Eq. 3). The different OPEX are obtained from the item tariff (T), as prescribed in Eq. 5 for the fuel ($OPEX_F$), in Eq. 6 for the operation and maintenance ($OPEX_{OM}$) and in Eq. 7 for the CO_2 emissions tax ($OPEX_{CO2}$). $OPEX_F$ and $OPEX_{CO2}$ take into account the saving due to the avoided fuel or CO_2 emission due to the thermal energy recovered in one year (V). This fuel avoided is calculated from a reference efficiency (η_{Vref}) of 90% (LHV). To obtain the levelised cost, a life span (N) of 15 years, 5,500 hours of yearly operation and 10% of weighted average capital cost (WACC) have been considered. The nominal escalation rate (r) for the fuel, electricity and CO_2 is 5% and for operation and maintenance 2.5%. An exchange conversion of 1.06 €/$ has been assumed. OPEX and CAPEX are referred to the annual electricity production (E).

$$LCOE = CAPEX + \sum_i \; OPEX_i \cdot AF_i \cdot CRF \tag{1}$$

$$CRF = \frac{WACC \cdot (1+WACC)^N}{(1+WACC)^N - 1} \tag{2}$$

$$AF = \frac{k \cdot (1-k^N)}{1-k} \quad ; \quad k = \frac{1+r_i}{1+WACC} \tag{3}$$

$$CAPEX = \left(\frac{INVESTMENT}{E}\right) \cdot CRF \tag{4}$$

$$OPEX_F = T_F \cdot \left(\frac{E_{GT}}{\eta_{GT}} - \frac{V}{\eta_{Vref} \cdot \left(\frac{LHV}{HHV}\right)}\right) \cdot \left(\frac{1}{E}\right) \tag{5}$$

$$OPEX_{OM} = \frac{T_{OM\_ORC} \cdot E_{ORC} + T_{OM\_GT} \cdot E_{GT}}{E} \tag{6}$$

$$OPEX_{CO2} = T_{CO2} \cdot \left(\frac{E_{GT}}{\eta_{GT \cdot HHV}} - \frac{V}{\eta_{V \cdot LHV}}\right) \cdot \left(\frac{44}{16}\right) \cdot \left(\frac{1}{E}\right) \tag{7}$$

The investment for the gas turbine is 592 $/kWe [1] referred to 2003, being the projection factor 541.7/402 (the ratio of Chemical Purchase Cost Index, CEPCI, at 2018 and 2003 [10]). The investment for the ORC plant is 7,760 €/kW (referred to 2018) [11]. The tariff for fuel is 25.4 €/MWh-th [12], for operation and maintenance of the gas turbine is 4.2 $/MWhe (2003) [1] and for operation and maintenance of the ORC plant 2.4 €/MWhe (2018) [13] and for CO_2 emissions is 25 €/ton CO_2 [14]. The lower heating value (LHV) of the natural gas has been assumed as 50.157 MJ/kg, and the ratio of higher to lower heating value (HHV/LHV) as 1.11 [15]. The average price of the electricity in the pool market has been taken as 52.24 €/MWhe [16].

3. Results and Discussion

Table 1 shows the power performances of the different layouts. The inclusion of only one heat recovery boiler (CHP layout) reduces the power due to the back-pressure in the turbine outlet. Regarding the addition of the ORC, the non-recuperated layout (CC-NR) produces more power due to the better utilisation of the waste heat. Table 2 shows the detailed thermal performances, giving Table 3 a summary of them. The largest thermal efficiency, production and exergy are obtained in CHP layout, which produces the lowest amount of electricity. The use of the non-recuperated ORC is a trade-off between electricity and heat recovered, producing the maximum power with the minimum heat recovery. However, the value (exergy) of such layout is the maximum. In a more useful consideration, CHP and CC-R produce the thermal power in sensible way (CHP) or in a mix of sensible and latent, being higher the sensible part.

Table 1. Power performances of the analysed layouts.

Layout	Efficiency (HHV) [%]	GT [MWe]	ORC [MWe]	Plant [MWe]
GT0	40.7	40.0	0.0	40.0
CHP	38.4	37.8	0.0	37.8
CC-NR	47.5	38.8	8.99	47.7
CC-R	44.6	36.7	8.12	44.8

Table 2. Thermal power performances of the analysed layouts.

Layout	Efficiency (HHV) [%]	GT heat recovery boiler (HRB)		ORC condenser (COND)	
		Thermal power [MWth]	Energy quality	Thermal Power [MWth]	Energy quality
GT0	0.0	0.0	--	0.0	--
CHP	47.3	46.5	473ºC / 120ºC sensible	0.0	--
CC-NR	36.9	0.0	--	37.0	316ºC / 85ºC latent
CC-R	40.3	23.6	303ºC / 120ºC sensible	16.9	99ºC / 85ºC latent

Table 3. Summary of thermal power performances of the analysed layouts.

Layout	Efficiency (HHV) [%]	Thermal power (overall) [MWth]	Thermal exergy (overall) [MWth]
GT0	0.0	0.0	0.0
CHP	47.3	47.3	22.6
CC-NR	36.9	37.0	13.25
CC-R	40.3	40.5	12.0

Table 4 shows the breakdown of levelised costs. In order to obtain a fair comparison, the electricity pool market price has been also levelised, moving from 52.24 €/MWhe to 72.45 €/MWhe. Any LCOE higher than this value would require feed-in-tariff or any other subsidy to be feasible. It is seen that the power-only layout (GT0) exhibits the highest cost, larger than the market price. The inclusion of a conventional recovery boiler (CHP layout) reduces the cost more than 1/3, but it still remains over the market. It is with the inclusion of an ORC when a reduction higher than 1/2 is reached regarding the power-only layout, being lower than the market price. Both ORC layouts produce a similar overall LCOE (lower in CC-NR). The cost breakdown is similar for the OPEX, being the difference in the CAPEX, which is lower in the CC-NR. That is, a sooner payback would be expected.

Table 4.Levelised costs breakdown of the analysed layouts.

Layout	CAPEX [€/MWhe]	Fuel [€/MWhe]	Operation & Maintenance [€/MWhe]	CO_2 [€/MWhe]	Overall [€/MWhe]
GT0	18.13	95.30	6.32	16.82	136.57
CHP	22.76	48.35	6.32	8.47	85.89
CC-NR	19.69	33.08	5.66	5.80	64.22
CC-R	23.55	32.53	5.68	5.68	67.45

It is noticeable that performing only heat recovery (layout CHP) is not enough to reduce the LCOE below the market price. It can be also checked that only increasing the electricity production with the ORC (without heat recovery) is not also enough. So, if the heat recovery is supressed in the CC-NR layout, the LCOE reaches 103.83 €/MWhe, higher than CHP but lower than GT0, and in any case still above the market price.

4. Conclusions

The enhancing of a small gas turbine (40 MWe) by addition of an ORC has been analysed. The power-only gas turbine is not economically feasible, with a LCOE of 136.6 €/MWh, clearly far from the levelised pool market electricity price (72.45 €/MWhe). The simple waste heat recuperation reduces the cost to 85.9 €/MWh, but is not still profitable. With the addition of an ORC to convert all the available waste heat in the flue gases into electricity, a cost of 103.83 €/MWhe is reached, still higher than the pool price. Only with the recovery of the waste heat from the ORC condenser, a cost clearly lower than the pool market price is reached (64.2 €/MWhe). So, the conversion into a combined cycle of the baseline gas turbine should be complemented by the heat recovery from the bottom cycle.

Regarding the typology of the ORC, benzene (or any other natural hydrocarbon) is required due to the high temperature of the flue gases that exit the gas turbine. Such working fluids present a condensation pressure below the atmosphere at ambient temperature, so a high (around 100ºC) condensation temperature is required in order to prevent air incoming. As a consequence, the high temperature of the flue gases stream entails to a bottom cycle which is a cogeneration combined plant indeed, with a back-pressure turbine and recovering the waste heat from the condenser. This recovery has revealed as a key factor for the economic feasibility. Supercritical pressure in the evaporator of the ORC has been chosen to reduce the exergy destruction in the heat recovery gas generator and recuperative and non-recuperative layouts have been investigated. As in a conventional combined cycle, the non-recuperated version produces better results due to the complete recovery of the available waste energy. In any case, both non-recuperated and recuperated obtain similar performances, depending the choice on the quality of the recuperated thermal energy (latent in non-recuperated and a mainly sensible in recuperated layout).

REFERENCES

[1] "Gas-Fired Distributed. Energy Resource. Technology Characterizations", National Renewable Energy Laboratory (NREL), Noviembre 2003.

[2] B.Vanslambrouck et al., "Turn waste heat into electricity by using an Organic Rankine Cycle", 2nd European Conference on Polygeneration, 30th Match-1st April, 2011, Tarragona, Spain.

[3] I.Vankeirsbilck et al., "Efficiency comparison between the steam cycle and the organic Rankine cycle for small scale power generation", 2nd European Conference on Polygeneration, 30th March-1st April, 2011, Tarragona, Spain.

[4] Uris, M.; Linares, J.I.;, Arenas, E. *Size optimization of a biomass-fired cogeneration plant CHP/CCHP (Combined heat and power/Combined heat, cooling and power) based on Organic Rankine Cycle for a district network in Spain*. Journal Energy, 2015, vol. 88, pp. 935-945.

[5] Pei, G.; Li, J.; Ji, J. *Analysis of low temperature solar thermal electric generation using regenerative Organic Rankine Cycle*. Journal Applied Thermal Engineering, 2010, vol. 30, pp. 998-1004.

[6] Bronicki, L.Y. *Organic Rankine Cycle Power plant for waste heat recovery*, ORMAT International Inc., 2000, USA.

[7] *Turboden ORC plants for Industrial Heat Recovery. The proven way to address environmental sustainability*. Mitsubishi Heavy Industries Ltd., May 2014.

[8] Klein, S.A.; Nellis, G.F. Mastering EES (58th edition). F-Chart Software, 2018

[9] Bejan, A.; Tsatsaronis, G.; Moran, M. Thermal Design & Optimization, John Wiley & Sons, Inc., New York, 1996.

[10] www.chemengoonline.com

[11] Quoilin, S. et al., *Techno-economic survey of Organic Rankine Cycle (ORC) systems*. Journal Renewable and Sustainable Energy Reviews, vol. 22, 2013, pp. 168-186.

[12] "Gas prices for non-household consumers - bi-annual data (from 2007 onwards)", Eurostat.

[13] "Technical and economical experiences with large ORC systems using industrial waste heat streams of cement plants", Hochschule Luzern-Technik & Architektur Horw, 6th November 2015.

[14] https://markets.businessinsider.com/commodities/co2-emissionsrechte

[15] Guo, B.; Ghalambor, A. Natural Gas Engineering Handbook, Gulf Publishing Company, 2005

[16] www.omie.es