ANALYSIS OF THE COGENERATION IMPLEMENTATION POTENTIAL INTO AN EXISTING SATURATED STEAM BOILER INDUSTRIAL PLANT

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Rezumat. Lucrarea prezintă o analiză tehnico-economică referitoare la potenţialul de implementare a unei instalaţii de cogenerare cu turbină cu abur, utilizând un cazan de abur existent în industria petrolieră.În acest sens s-a avut în vedere utilizarea unei turbine cu abur în condensaţie, în două regimuri posibile de operare: cu şi fără prize de presiune, utilizând debitul de abur produs de cazan. În realizarea studiului s-a utilizat programul Engineering Equation Solver (EES), pentru diferite temperaturi de supraîncălzire a aburului (Regim I) şi pentru diferite debite de abur prelevate din turbină (Regim II). Principala concluzie a studiului întreprins este că nu se justifică investiţia în echipamentele aferente unei instalaţii cogenerative cu turbină cu abur, la presiunea de lucru din cazan de 6 bar deoarece perioada de amortizare a investiţiei este mare.

Cuvinte cheie: cogenerare, cazan de abur, turbină cu abur, analiză tehnico-economică.

Abstract. The paper presents a techno-economical analysis concerning the potential implementation of a steam turbine cogeneration plant into an existing saturated steam boiler plant from the oil industry. It was analyzed the use of a condensing steam turbine in two possible operating conditions: with and without extractions, using the production of an existing saturated steam boiler. The study was carried out using the Engineering Equaton Solver (EES) software, for different superheat conditions (Regime I) and for different steam flow extractions (Regime II). The plant performances were determined and a comprehensive economic calculation was performed for the two operating conditions. The main conclusion of the study was that due to the low boiler operating pressure of only 6 bar the investment into cogeneration equipment is not justified, because of the too long payback period.

Keywords: cogeneration, steam boiler, steam turbine, techno-economical analysis.

1. INTRODUCTION

The paper deals with the possibility of implementing a steam turbine cogeneration plant into an existing steam boiler in the oil industry.

Cogeneration is the simultaneous production of heat and power from the same primary energy source in a single system/unit. The two types of steam turbines most widely used are the back pressure and the extraction-condensing one. The choice between backpressure turbine and extraction-condensing turbine depends mainly on the quantities of power and heat, quality of heat, and economic factors [1,2].

The existing steam boiler, produced by Sieta Cluj-Napoca, of VAP 3D type, has the following nominal parameters:

- Thermal load at 100°C:	3942 kW;
- Nominal pressure:	8 bar;
- Nominal steam flow rate :	6t/h;
- Nominal temperature:	175°C;
- Maximum working pressure:	8 bar.

2. FUNCTIONAL DESCRIPTION OF A COGENERATION PLANT AND OF POSSIBLE OPERATION CONDITIONS

The cogeneration potential study has been done under the conditions determined by the measured parameters of the boiler steam output: steam pressure 6 bars and the steam mass flow rate: 1.212 kg/s.

Because the plant comprises two steam boilers which never work simultaneously, one can support the whole technological process, while the second may be used to produce electricity through a Claussius-Rankine cycle.

The most appropriate technological solution for the analised plant is the option of cogeneration with extractions condensing steam turbine. As the available pressure at the steam turbine inlet is very low, expansion in the steam turbine above atmosferic pressure would represent a low potential for producing mechanical power.

The schematic diagram of a condensing steam turbine cogeneration plant and thermodynamic cycle in temperature (T) - entropy (s) diagram is presented in fig.1, [3,4].

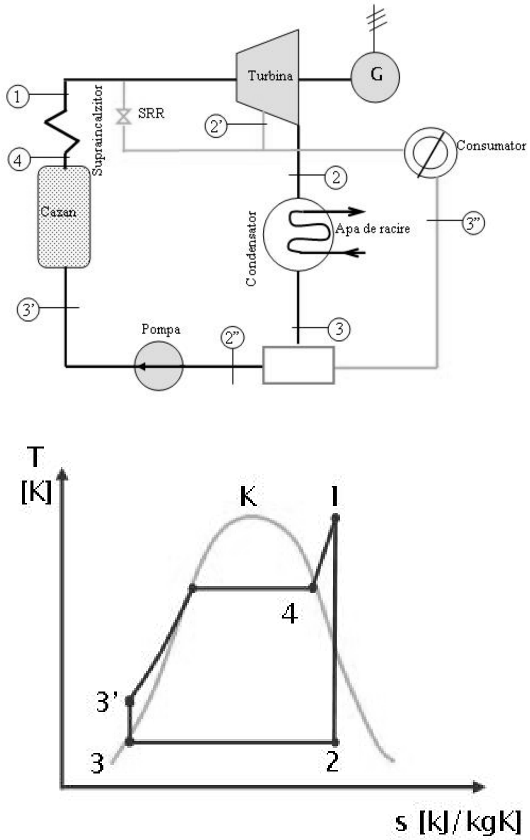


Fig. 1. The schematic diagram of an extraction steam turbine cogeneration plant and thermodynamic cycle in T-s diagram

The existing boiler will ensure the steam evaporation (3'-4) and will produce saturated steam; the boiler must be equipped with a steam superheater (4-1) that will use the methane gas as fuel, in order to realise the superheated steam.

The mechanical energy is developed in a steam turbine, where the steam expands following a theoretical adiabatic process (1-2).

The exhausted steam from the turbine is condensed in a condenser (2-3).

A condensation pump will increase fluid pressure (3-3'), up to the boiler pressure.

In the current operation, the steam boiler provides saturated steam to a pressure of 6 bars and temperature of 160°C. If equipping the boiler with a superheater, it will produce superheated steam. To determine performance indicators for the steam turbine cogeneration plant, the superheated steam temperature is considered to be in the range of 160 ... 500°C.

Two possible operating conditions were considered:

Regime I: The entire flow steam expands in the turbine, to a pressure higher than 0.05 bars (which corresponds to a saturation temperature of 33°C). This operating mode corresponds to a maximum electrical power because the entire available steam is used to produce work.

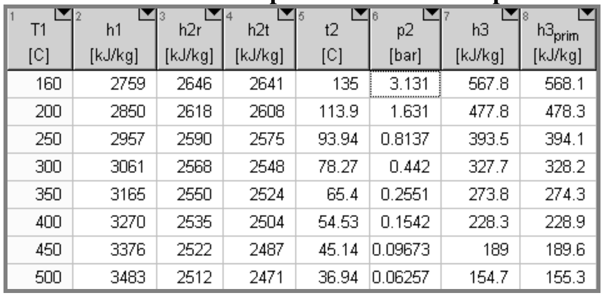
Regime II: Most of the steam flow rate (70-90%) expands in the turbine, producing mechanical work while a part (10-30%) is being extracted to a pressure of 1 bar and used for heating purposes.

3. PERFORMANCE ANALYSIS OF THE THERMODYNAMIC CYCLE FOR THE STEAM TURBINE COGENERATION PLANT

3.1. Regime I

In order to perform the analysis on the potential use of cogeneration, a computer program has been developed by using the application Engineering Equation Solver, (EES). The main parameters of the fluid in the characteristic points in terms of superheated steam temperature are presented below.

Table 1
The values of thermal parameters as function of superheated steam temperature



1 T1 [C]	2 h1 [kJ/kg]	3 h2r [kJ/kg]	4 h2t [kJ/kg]	5 t2 [C]	6 p2 [bar]	7 h3 [kJ/kg]	8 $h3_{prim}$ [kJ/kg]
160	2759	2646	2641	135	3.131	567.8	568.1
200	2850	2618	2608	113.9	1.631	477.8	478.3
250	2957	2590	2575	93.94	0.8137	393.5	394.1
300	3061	2568	2548	78.27	0.442	327.7	328.2
350	3165	2550	2524	65.4	0.2551	273.8	274.3
400	3270	2535	2504	54.53	0.1542	228.3	228.9
450	3376	2522	2487	45.14	0.09673	189	189.6
500	3483	2512	2471	36.94	0.06257	154.7	155.3

Analyzing the values of thermodynamic parameters obtained for the cycle, it turns out that for high values of superheat temperature (250-500) °C the pressure at the end of expand process is lower than barometric pressure, which requires the use of a condensing steam turbine.

Calculation of the energy transfer in the processes

The energy transfer can be calculated for each process, as follows [5]:

- The heat flow absorbed by the working medium in the boiler during the heating process 3 '-4 -1, ($\dot{Q}_{cazan}$) is:

$$\dot{Q}_{cazan} = \dot{m}_a \cdot (h_1 - h_{3'}) \left[\mathrm{kW}\right] \qquad (1)$$

- The heat of condensation, ($\dot{Q}_{cond}$) during isobar process(2-3), is:

$$\dot{Q}_{cond} = \dot{m}_a \cdot (h_2 - h_3)\,[\mathrm{kW}] \tag{2}$$

- The power obtained in the turbine (P_T), considering an irreversible process is:

$$P_T = \dot{m}_a \cdot (h_1 - h_{2r})\,[\mathrm{kW}] \tag{3}$$

- The necessary power for fluid compression (in absolute value) is (P_P) :

$$P_P = \dot{m}_a \cdot (h_{3'} - h_3)\,[\mathrm{kW}] \tag{4}$$

Calculation of the fuel consumption and performance indicators

The required **fuel consumption** ($\dot{V}_{cb}$) is:

$$\dot{V}_{cb} = \frac{\dot{Q}_{cazan}}{\eta_{cazan} \cdot q_i}\left[\frac{m_N^3}{s}\right] \tag{5}$$

where η_{cazan} is the thermal efficiency of boiler and q_i is the fuel lower heating value.

Electrical efficiency (η_e) is the ratio of power produced in the turbine (P_T) and heat developed by combustion ($\dot{Q}_a$):

$$\eta_e = \frac{P_T}{\dot{Q}_a}\,[-] \tag{6}$$

Thermal efficiency (η_t) is the ratio of useful heat ($\dot{Q}_u$) (if heat recovery is possible) and the heat developed by combustion:

$$\eta_t = \frac{\dot{Q}_u}{\dot{Q}_a}\,[-] \tag{7}$$

The total efficiency of the system (η) is the ratio of two useful effects: power (P_T) and useful heat ($\dot{Q}_u$) and the heat developed by combustion ($\dot{Q}_a$):

$$\eta = \frac{P_T + \dot{Q}_u}{\dot{Q}_a}\,[-] \tag{8}$$

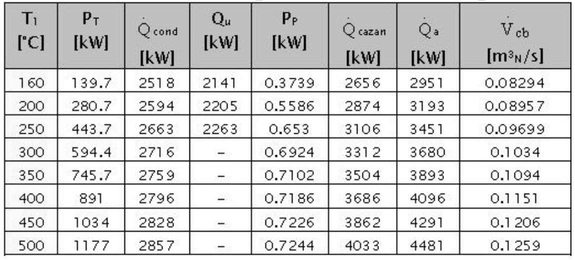
Power to heat ratio (PHR) is an important indicator used in assessing the performance of cogeneration plants:

$$PHR = \frac{P_T}{\dot{Q}_u}\,[-] \tag{9}$$

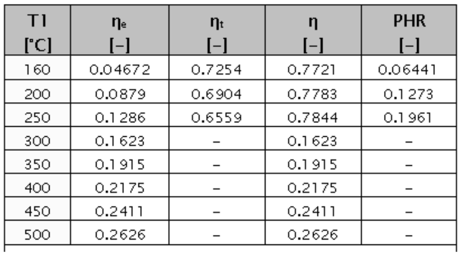
The values obtained by using the computer program, for energy transfer, fuel consumption, electrical efficiency, thermal efficiency, the overall efficiency of the plant and for power to heat ratio in terms of superheated steam temperature are listed in table 2.

Table 2

The values of energy transfer, fuel consumption, efficiencies and power to heat ratio as function of superheated steam temperature



T_1 [°C]	P_T [kW]	$\dot{Q}_{cond}$ [kW]	Q_u [kW]	P_P [kW]	$\dot{Q}_{cazan}$ [kW]	$\dot{Q}_a$ [kW]	$\dot{V}_{cb}$ [m^3_N/s]
160	139.7	2518	2141	0.3739	2656	2951	0.08294
200	280.7	2594	2205	0.5586	2874	3193	0.08957
250	443.7	2663	2263	0.653	3106	3451	0.09699
300	594.4	2716	–	0.6924	3312	3680	0.1034
350	745.7	2759	–	0.7102	3504	3893	0.1094
400	891	2796	–	0.7186	3686	4096	0.1151
450	1034	2828	–	0.7226	3862	4291	0.1206
500	1177	2857	–	0.7244	4033	4481	0.1259



T1 [°C]	η_e [–]	η_t [–]	η [–]	PHR [–]
160	0.04672	0.7254	0.7721	0.06441
200	0.0879	0.6904	0.7783	0.1273
250	0.1286	0.6559	0.7844	0.1961
300	0.1623	–	0.1623	–
350	0.1915	–	0.1915	–
400	0.2175	–	0.2175	–
450	0.2411	–	0.2411	–
500	0.2626	–	0.2626	–

The electric efficiency values are found between 0.04 and 0.26; these values are lower than those commonly found in the literature (0.1-0.2) for this performance indicator [8].

Considering a 85% recovery of condensation heat, the resulting thermal efficiency values are 0.65-0.72. For higher values of the superheat temperature, heat is transferred in the condenser at low temperature, which is not usable and therefore represents a lost heat.

The total efficiency of the plant has high values when heat recovery is possible at the condenser (0.77-0.78). If the heat recovery is not possible (because of the condensation temperature), the only useful effect is the electrical power developed in the turbine; for these conditions, the total efficiency has the same values as the electric efficiency.

The power to heat ratio (PHR) for these conditions has values between 0.064 and 0.196 . The literature values obtained for this indicator are between 0.125-0.33 [8].

3.2. Regime II

This operating mode is characterized by the fact that the main steam flow rate that expands in the turbine represents about 70-90% of the steam flow rate provided by boiler. A part of the steam flow rate is extracted from the turbine to a pressure level of 1 bar. This amount of steam can be used for heating purposes. A superheated steam temperature of 500° C was considered, for a maximum turbine power output.

Thermodynamic parameters for working medium at turbine inlet (1) and outlet (2) and for condenser outlet (3) have the same numerical values as in the operating conditions described above.

For the other cycle points, thermodynamic parameters were determined as following:

- extraction steam pressure was set to 1 bar;
- the enthalpy of extraction steam ($h_{2'r}$) was determined from internal efficiency of the turbine:

$$\eta_{iT} = \frac{l_{Pr}}{l_P} = \frac{h_1 - h_{2'r}}{h_1 - h_{2't}} \tag{10}$$

Graphical representation of theoretical and real-turbine process is shown in the diagram below.

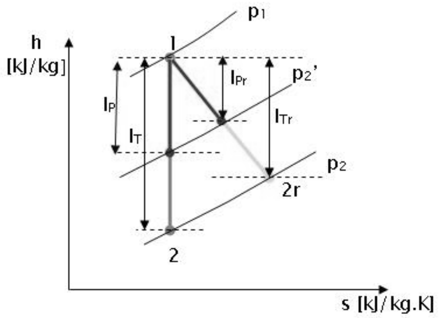


Fig. 2. T-s diagram steam expanding process in turbine

- the heat balance equation was used to determine the enthalpy of mixture ($h_{2''}$) after collecting two amounts of condensate (in the condenser and preheater)

$$\dot{m}_a \cdot h_{2''} = (\dot{m}_a - \dot{m}_p)\cdot h_3 + \dot{m}_p \cdot h_{3''} \tag{11}$$

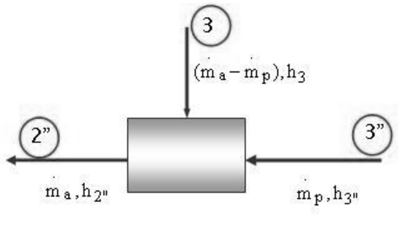


Fig. 3. Schematic representation of the heat balance equation for the mixture

The main thermodynamic parameters in the cycle characteristic points: extraction (2'), condensate (3"), condensate mixture (2") and boiler inlet (3') obtained by using the computer program developed for extraction flow rates between 10-30% of the total flow, are listed below.

Table 3
The values of thermodynamic parameters on the characteristic states of the cycle, function of extraction flow rate

$\dot{m}_p$ [kg/s]	h2r' [kJ/kgK]	h2t' [kJ/kgK]	h2" [kJ/kgK]	h3' [kJ/kgK]	h3" [kJ/kgK]
0.1212	2979	2958	181	181.8	417.4
0.2424			207.2	208.9	
0.3636			233.5	236.5	

The theoretical power obtained in the turbine is:

$$P_T = \dot{m}_a \cdot (h_1 - h_{2'r}) + (\dot{m}_a - \dot{m}_p)\cdot(h_{2'r} - h_{2r})\left[kW\right] \tag{12}$$

and the extraction available heat:

$$\dot{Q}_{priza} = (\dot{m}_p)\cdot(h_{2'r} - h_{3''})\left[kW\right] \tag{13}$$

The values obtained by using the computer program, for energy transfer, fuel consumption and efficiencies are given in tabel 3.

Table 4
The values of energy transfer, fuel consumption, efficiencies and power to heat ratio function of extraction flow rate

$\dot{m}_p$ [kg/s]	P_T [kW]	$\dot{Q}_P$ [kW]	Q_{cond} [kW]	P_P [kW]	$\dot{Q}_{cazan}$ [kW]	$\dot{Q}_a$ [kW]	$\dot{V}_{cb}$ [m^3_N/s]
0.1212	1120	310.5	2571	1.051	4001	4445	0.1249
0.2424	1060	621	2285	2.036	3968	4409	0.1239
0.3636	1007	931.4	2000	3.693	3935	4372	0.1229

$\dot{m}_p$ [kg/s]	η_e [–]	η_t [–]	η [–]	PHR [–]
0.1212	0.252	0.06984	0.3219	3.608
0.2424	0.2413	0.1408	0.3821	1.713
0.3636	0.2303	0.2131	0.4434	1.081

With increasing extraction steam flow, the turbine power is reduced from 1120 to 1007 kW. The electric efficiency values of 0.252...0.2303 are commonly found in the literature for this performance indicator.

4. ECONOMIC ANALYSIS

In order to implement a cogeneration system, the following investments should be made: steam turbine, generator, condenser, steam superheater, a circulating pump and a cooling tower.

The speciality literature indicates the following investment and operating and maintenance costs, for steam turbine cogeneration plants:

Investement costs

- 800-1000 \$/kWe [6];
- 200-1000 \$/kWe [7];
- 1500 \$/kWe for electric power of 1 MWe [8].

If the investment costs do not involve the purchase of the steam boiler, the following specific cost is recomanded: 400-800 \$/kWe [8].

Operating and maintenance costs

- 0.004 \$/kWhe, [6];
- Up to 0.002 \$/kWhe [7];
- Between 2.3 and 1.5 \$/MWhe [8]

In accordance with mentioned bibliographical resources, the most appropriate investment cost is 1,500 \$/kWe, that means 1180 €/ kWh.

Regime I

For a maximum turbine power of 1177 kW an investemnt cost (a first cost) of approximately 1.4 million € results.

The electrical energy that could be produced annually by the steam turbine cogeneration plant depends on the turbine power output, P_T, utilisation factor τ, and on the annual hours n_h:

$$E_{el} = P_T \cdot \tau \cdot n_h = 8{,}248{,}416 \text{ kWh / y} \qquad (14)$$

Annual operating time of cogeneration plant is taken into account by using an utilisation factor of 0.8.

For a unit cost of electricity ($c_{en.el}$) of 0.292 RON / kWh, the annual revenue from the sale of electricity would be ($C_{en.el}$):

$$C_{en.el} = E_{el} \cdot c_{en.el} = \\ 2{,}408{,}537.47 \text{ RON / y} = 561{,}430 \text{ € / y} \qquad (15)$$

Annual costs related to fuel

To achieve maximum power, the boiler thermal load is 4033 kW. Unit cost of fuel (c_{cb}) is 0.09142 RON/kWh (according to EON Gaz consumer category B5).

Annual costs related to fuel consumption; (C_{cb}) depends on the thermal load of the boiler, the annual number of hours and the load factor (c_{cb}).

$$C_{cb} = \tau \cdot n_h \cdot \dot{Q}_a \cdot c_{cb} = 2{,}870{,}848 \text{ RON / y} \\ = 669{,}195 \text{ € / y} \qquad (16)$$

Annual operating and maintenance costs

The unit costs of operation and maintenance as mentioned in the references are:

0.002 \$/kWh = 0.00157 €/kWh.

Annual operating and maintenance costs depend on the unit cost, power developed in the turbine and the annual number of operation hours, as follows:

$$C_{O\&M} = c_{O\&M} \cdot P_T \cdot \tau \cdot n_h = 12950 \text{ €/y} \quad (17)$$

For operating conditions without extraction, which corresponds to a maximum electrical power, it came out that accounting for fuel cost and annual operation and maintenance costs exceed income from the sale of electricity.

Table 5

Annual revenue	
Revenues from sold electricity	561,430 Eur
Total revenue	**561,430 Eur**
Annual expenditure	
Fuel cost	669,195 Eur
Operating and maintenace cost	12,950
Total expances	**682,145 Eur**

Regime II

The maximum thermal load of the steam turbine (931.4 kW) corresponds to a power of 1007 kW.

It is assessed the electricity that could be annual produced by the steam turbine cogeneration plant:

$$E_{el} = P_T \cdot \tau \cdot n_h = 7{,}057{,}056 \text{ kWh / y} \qquad (18)$$

For a unit cost of electricity of 0.292 RON/kWh, the annual revenue from the sale of electricity would be:

$$C_{en.el} = E_{el} \cdot c_{en.el} = 480{,}340 \text{ € / y} \qquad (19)$$

Fuel savings obtained by heat produced in cogeneration

Maximum thermal load available at the steam turbine extraction is 931.4 kW.

The annual amount of heat that can be produced in the steam turbine cogeneration plant is:

$$E_t = \dot{Q}_p \cdot \tau \cdot n_h = 6{,}527{,}251 \text{ kWh / y} \qquad (20)$$

If this heat is separately produced in a boiler, with an efficiency of 0.9, the related annual costs would be:

$$C_{en.t} = \frac{E_t \cdot c_{cb}}{\eta_{caz}} = 596721{,}2 \; RON / y = 139{,}095 \text{ €} / y \qquad (21)$$

Annual cost related to fuel

To achieve maximum power, the boiler thermal load is 3935 kW.

The unit costs associated with fuel consumption depends on the boiler thermal load, the annual number of hours and the load factor:

$$C_{cb} = \tau \cdot n_h \cdot \dot{Q}_{cazan} \cdot c_{cb} = 2{,}521{,}041\ \mathrm{RON/y} = 587{,}655\ €/\mathrm{y} \tag{22}$$

Annual operating and maintenance costs

Annual operating and maintenance costs are:

$$C_{O\&M} = c_{O\&M} \cdot P_T \cdot \tau \cdot n_h = 11{,}079\ €/\mathrm{an} \tag{23}$$

For this exploitation conditions, with extractions, it results that annual income from the sale of electricity and annually fuel economy is higher than the annual cost for fuel plus operation and maintenance costs.

Table 6.

Annual revenue	
Revenues from sold electricity	480,340 Eur
Revenues from sold thermal energy	139,095 Eur
Total revenue	**619,435 Eur**
Annual expenditure	
Fuel cost	587,665 Eur
Operating and maintenace cost	11,079 Eur
Total expances	**598,744 Eur**
The difference between revenues and expenses	**20,691Eur**

5. CONCLUSIONS

Thermodynamic and economic analysis of cogeneration potential use in the studied plant reveals the following:

- While operating the plant without extraction, waste heat in the condenser is not usable; revenues from electricity fuel costs do not cover annual operating and maintenance costs; this is mainly due to the fact that the steam pressure is small. Therefore the investment in equipments mentioned above is not justified.
- For an extraction operation regime, an annual rate of return of 20,000 € can be obtained. The annual income return on investment does not provide a reasonable pay back period.

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