STUDY OF COGENERATION SYSTEMS IN A CHEMICAL INDUSTRY

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Abstract – **The analysis of the energy demands of a chemical factory revealed the possibility of using combined cycles or diesel engine cogeneration systems, keeping the existent compression refrigeration units, or gas turbines cogeneration systems with absorption refrigeration units. In terms os economic attractiveness, the analysis was based on the internal method of heat recovery. The results have shown that the schemes composed of reciprocating engines and combined cycles with compression chillers, as well as the gas cycle scheme with absorption chiller, present a return period of up to 3 years, showing that the investment in cogeneration could be of great interest for this factory..**

Keywords: *cogeneration, chemical factory, compression chiller, absorption chiller, feasibility.*

1. INTRODUCTION

Before implementing a cogeneration system, its technical and economic viability must be attested, especially for continuous process in which the possible energy peaks or idles may cause huge financial losses, not only of raw materials (fuels) but also because of the required time to re-start the production.

The aim of this paper is to compare different configurations for the cogeneration systems, that may be proposed to the factories of the chemical industry, and to study the feasibility of incorporating ammonia-water absorption chillers in comparison with the compression systems used currently.

2. CONCEPTS OF COGENERATION

The cogeneration is the energy generation process in which two or more forms of energy, such as thermal and electric energies, are produced simultaneously by using the same energy installations and the same fuel sources (organic fuel, nuclear fuel, waste, regenerable energy).

It is usually the cogeneration description as an energy conservation process because of the energy efficiency improvement obtained by the thermal recovery, in opposition to the conventional generation in which more than one primary energy is consumed to satisfy the energy needs of a procces plant. The common way of providing the necessary energy to the process plant is to purchase the electric energy from the National Energy System (SEN) and to produce the necessary thermal energy [1]. In this way, the cogeneration can be considered as a new modality of energy production (figure 1).

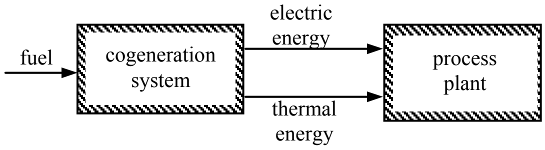


Figure 1: Cogeneration system.

Some thermal cycles are commonly proposed to compose the cogeneration schemes: steam cycle (figure 2) with heat recovery steam generators and steam turbines; gas cycle with gas turbines (figure 3) without or with heat recovery; combined cycle (figure 4) as a composition of the preceding ones; internal combustion engines cycles, especially the those composed by diesel engines.

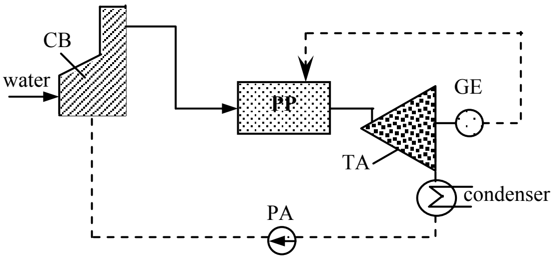


Figure 2: Cogeneration system – steam cycle:
CB – conventional steam generator; PP – process plant; TA – steam turbine; GE – electrical generator; PA – condensat pump.

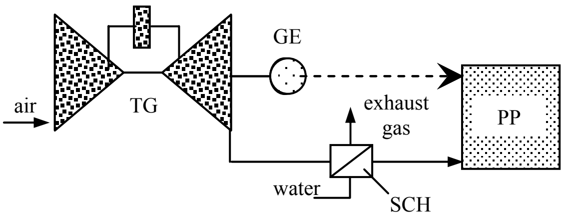


Figure 3: Cogeneration system – gas turbines:
PP – process plant; TG – gas turbine; GE – electrical generator; SCH – gas - water heat exhange.

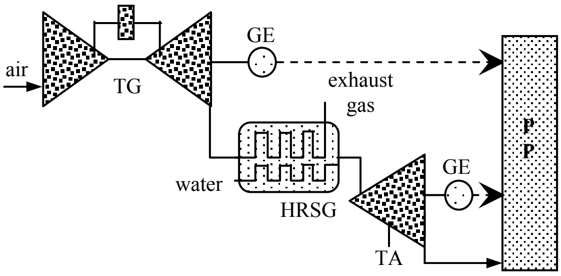


Figure 4: Cogeneration system with gas turbines: PP – process plant; TG – gas turbine; TA – steam turbine; GE – electrical generator; HRSG – heat recovery steam generators.

These cycles present different characteristics related to the capacity of thermal and electric generation, fuel consumption, load operation etc. The thermal power is the parameter used to establish the relative capacity of producing both forms of energy at the same time. The efficiency of a cogeneration cycle is determined as the inverse of the heat consumption in this cycle [expressed in kJ/kW·h or kW_{el}/kW_{th}].

The thermal power value should be compared to an equivalent value evaluated from the taking over of data from the process plant, taking into account the electric and thermal energy consumption patterns. Although it is not mandatory, the thermal power value can be of interest to the designer in deciding the cogeneration schemes to be investigated, considering first those values that are close to the process plant value. Table 1 illustrates a thermal power values range for the above-mentioned thermal cycles.

No.	Thermal cycle		Value
1	with steam turbines	with back pressure	0.10 …0.30
		with pure condensation	0.40 …1.50
2	with gas turbines		0.30 …0.80
3	with combined cycles		0.60 ...1.50
4	with reciprocating engines		0.80 …2.40

Table 1: Thermal power for thermal cycles

3. PROCESS PLANT CHARACTERISTICS

In this paper it is presented an energy analysis of a chemical company with specific consumptions of electric and thermal energy for one year, which are shown in figure 5. The utilities are delivered according to the scheme of figure 6 in this way: *steam* – two dry steam generators operating with fuel oil and producing a flow of 10 ton/h at pressure of 550 kPa. The average dry steam flow necessay for the operation of process plant at nominal parameters is 7.5 ton/h, that is finally condensed and returned to boilers; *cold water* – four compression chillers, each with capacity of 160 m^3/h, produce a mixture of water and monoethylen-glicol with 20% concentration at –0.5°C. Along one year, three such chillers are operating continuously and are sufficiently for operation the process plant, the fourth compression chiller operating only in summer for increasing the system energy efficiency; *electric energy* – is purchased at 69 kV and transformed to different voltage levels, depending on consumer units demands.*water* – four compression chillers, each with capacity of 160 m^3/h, produce a mixture of water and mono-ethylen-glycol at 20% at –0.5ºC. Troughout the year, three are sufficient to operate the process plant, fourth compression chiller is powerd only in summers for energetical efficiency increase of system; *electricity* – is purchased at 69 kV and transformed to different voltage levels, depending on consumer units demands.

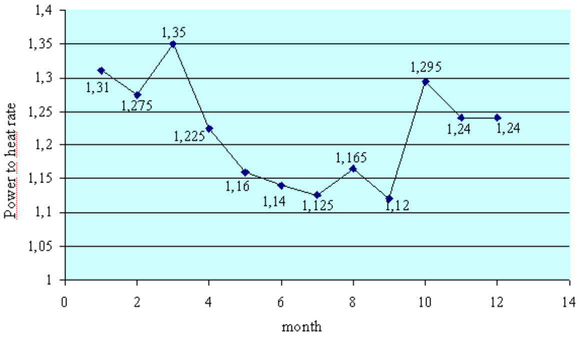


Figure 5: Electrical and thermal energy demand for the chemical factory by year 2003.

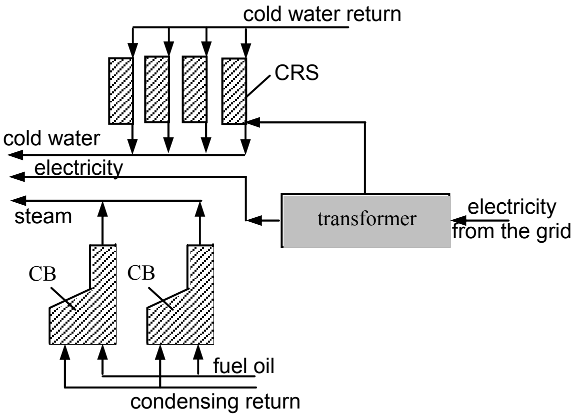


Figure 6: Simplified facility scheme: CB – conventional steam generator; CRS – compression refrigeration system.

Also, in Figure 7 is presented power to heat rate, along 2003 year.

The following consumptions are relevant data to the analysis: annual electric consumption (41,506 MW·h), average electric consumption (3,458.83 + 227.29 MW·h/month), maximum electric consumption – in March (3,926 MW·h), minimum electric consumption – in June (3,168 MW·h), maximum thermal power consumption – in March (1.36), average thermal consumption (1.22), annual fuel oil consumption (42,070 kJ/kg, respectively 42,517 MW·h), annual steam consumption (34,014 MW·h) and average steam consumption (2,834 MW·h/month).

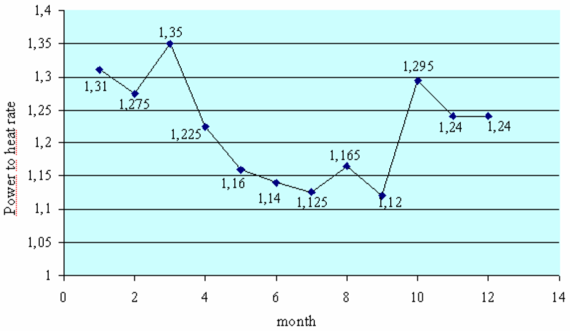


Figure 7. Thermal power value on a monthly basis.

As this was not performed here and to avoid the lack of energy production for the proposed cogeneration systems, it was adopted as a surplus of 10% over the maximum values listed before and so the design data are the following: process plant (total) electric energy demand (E_t=5,998 kW), compression chillers electric energy demand (E_{ch}=3,710 kW) and process plant thermal (steam) demand (S_p=6,148 kW).

4. PROPOSITION OF SCHEMES

As thermal power of a process plant has an important role in choosing one or another from the versions of achieving the cogeneration cycles, it is very important to perform an as exact as possible analysis regarding the energy and economic performances of these cycles.

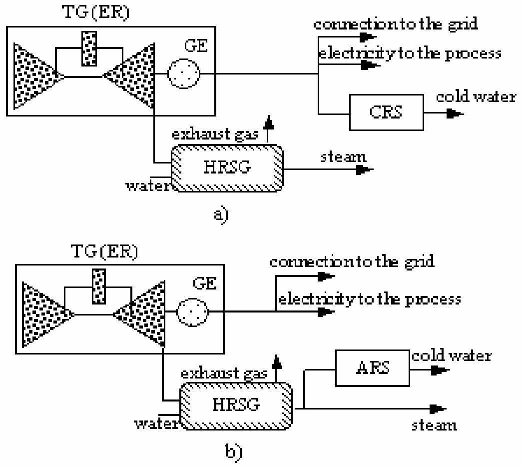


Figure 8. Refrigeration installation gas turbine cycle – with compression (a) and with absorption (b): TG – gas turbine; ER – reciprocating engine; GE – electrical generator; HRSG – heat recovery steam generator; CRS – compression refrigeration system; ARS – absorption refrigeration system.

This paper performs such an technical analysis for absorption or compression refrigeration systems (CRS, ARS) with following thermal cycles: *gas cycle* – composed of a gas turbine or reciprocating engine and a heat recovery system for producing steam necessary of the process plant (figure 8); *steam cycle* – composed of a conventional steam generator and a back pressure steam turbine directly connected to the process plant (figure 9); *combined cycle* - composed of a gas turbine, a heat recovery system and a back pressure steam turbine (figure 10).

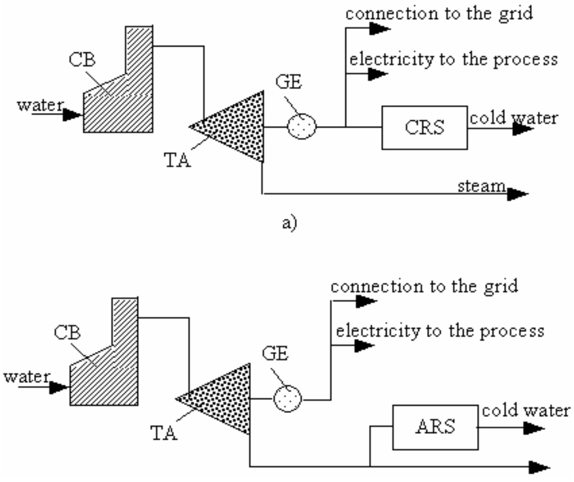


Figure 9. Refrigeration installation steam turbine cycle with compression (a) and with absorption (b): CB – conventional boiler; TA – steam turbine; GE – electrical generator; CRS – compression refrigeration system; ARS – absorption refrigeration system.

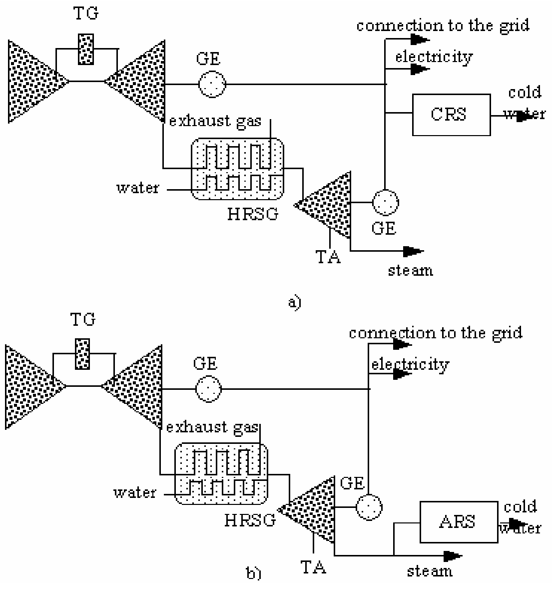


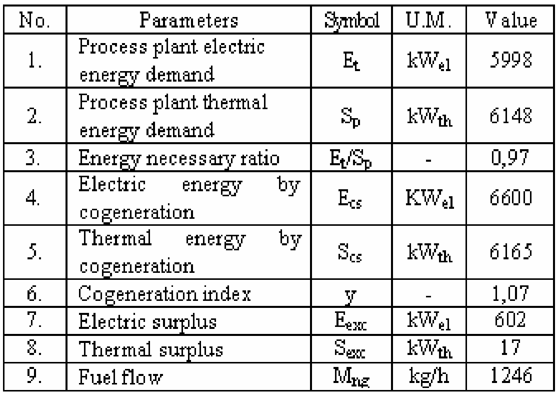
Figure 10. Refrigeration installation combined cycle – with compression (a) and with absorption (b): TG – gas turbine; TA – steam turbine; CRS – compression refrigeration system; GE – electrical generator; HRSG – heat recovery steam generator; ARS – absorption refrigeration system.

For all the proposed schemes, we consider: the used fuel shall be the natural gas with heating power of 40,487 kJ/m^3 and density of 0.65 g/m^3, according to the local utilization; it is not necessary a supplementary thermal agent for heat recovery; the compression chillers will consume the electric energy produced by the cogeneration system; the steam supplied to the absorption chillers has the same parameters as the technological steam, delivered to the technological installation, compatible with the thermal level of ammonia-water system.

The most suitable schemes shall be analysed from the economic attractivity point of view, the adopted criteria for choosing them being: acceptable cogeneration index; the cogeneration system chosen must produce under normal operating conditions both the required electric energy, and the thermal one, and even a surplus; the electric surplus is acceptable only of it does not exceed 50% of the process plant necessary; the thermal surplus is not timely because it cannot be commercialized and to it would be recorded with losses.

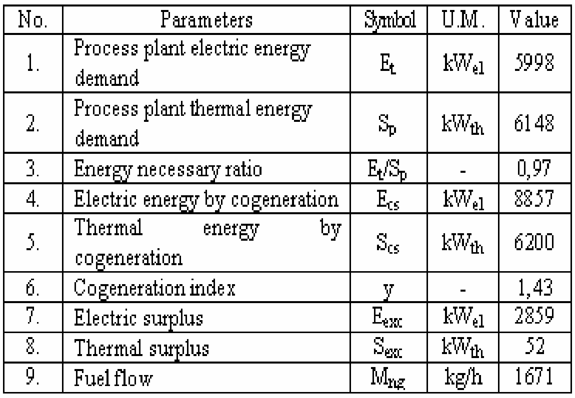
5. TECHNICAL AND ECONOMIC ANALYSIS

Having in view these conditions, the three schemes considered adequate for a detailed analysis are:



No.	Parameters	Symbol	U.M.	Value
1.	Process plant electric energy demand	E_t	kW_{el}	5998
2.	Process plant thermal energy demand	S_p	kW_{th}	6148
3.	Energy necessary ratio	E_t/S_p	-	0,97
4.	Electric energy by cogeneration	E_{cs}	KW_{el}	6600
5.	Thermal energy by cogeneration	S_{cs}	kW_{th}	6165
6.	Cogeneration index	y	-	1,07
7.	Electric surplus	E_{exc}	kW_{el}	602
8.	Thermal surplus	S_{exc}	kW_{th}	17
9.	Fuel flow	M_{ng}	kg/h	1246

Table 2: Technical results for Case 1



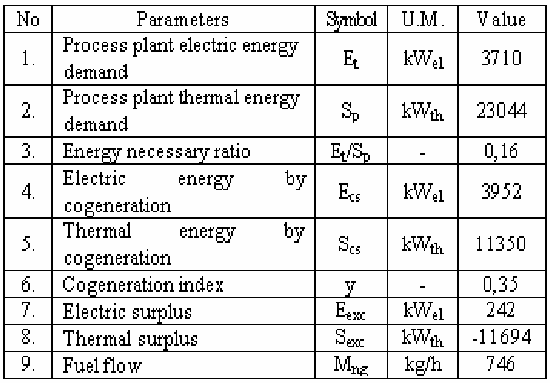
No.	Parameters	Symbol	U.M.	Value
1.	Process plant electric energy demand	E_t	kW_{el}	5998
2.	Process plant thermal energy demand	S_p	kW_{th}	6148
3.	Energy necessary ratio	E_t/S_p	-	0,97
4.	Electric energy by cogeneration	E_{cs}	kW_{el}	8857
5.	Thermal energy by cogeneration	S_{cs}	kW_{th}	6200
6.	Cogeneration index	y	-	1,43
7.	Electric surplus	E_{exc}	kW_{el}	2859
8.	Thermal surplus	S_{exc}	kW_{th}	52
9.	Fuel flow	M_{ng}	kg/h	1671

Table 3: Technical results for Case 2

Case 1 – reciprocating engine associated with a heat recovery steam generator (HRSG) and a compression refrigeration system (CRS) (table 2);

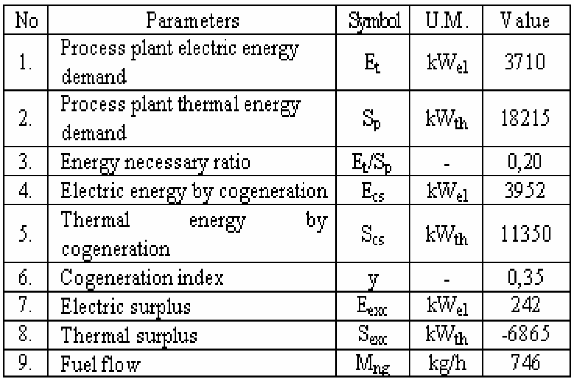
Case 2 – combined cycle associated with a heat recovery steam generator (HRSG) and a compression refrigeration system (CRS) (table 3);

Case 3 – gas turbine associated with a heat recovery steam generator (HRSG) and an absorption refrigeration system (ARS) (table 4, 5 and 6).



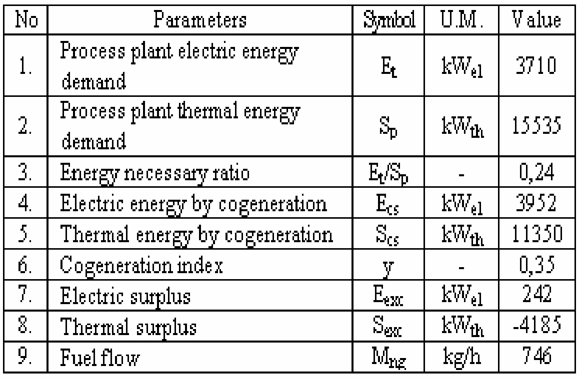
No	Parameters	Symbol	U.M.	Value
1.	Process plant electric energy demand	E_t	kW_{el}	3710
2.	Process plant thermal energy demand	S_p	kW_{th}	23044
3.	Energy necessary ratio	E_t/S_p	-	0,16
4.	Electric energy by cogeneration	E_{cs}	kW_{el}	3952
5.	Thermal energy by cogeneration	S_{cs}	kW_{th}	11350
6.	Cogeneration index	y	-	0,35
7.	Electric surplus	E_{exc}	kW_{el}	242
8.	Thermal surplus	S_{exc}	kW_{th}	-11694
9.	Fuel flow	M_{ng}	kg/h	746

Table 4: Technical results for Case 3 from coefficient of performance COP=0,5



No	Parameters	Symbol	U.M.	Value
1.	Process plant electric energy demand	E_t	kW_{el}	3710
2.	Process plant thermal energy demand	S_p	kW_{th}	18215
3.	Energy necessary ratio	E_t/S_p	-	0,20
4.	Electric energy by cogeneration	E_{cs}	kW_{el}	3952
5.	Thermal energy by cogeneration	S_{cs}	kW_{th}	11350
6.	Cogeneration index	y	-	0,35
7.	Electric surplus	E_{exc}	kW_{el}	242
8.	Thermal surplus	S_{exc}	kW_{th}	-6865
9.	Fuel flow	M_{ng}	kg/h	746

Table 5: Technical results for Case 3 from coefficient of performance COP=0,7



No	Parameters	Symbol	U.M.	Value
1.	Process plant electric energy demand	E_t	kW_{el}	3710
2.	Process plant thermal energy demand	S_p	kW_{th}	15535
3.	Energy necessary ratio	E_t/S_p	-	0,24
4.	Electric energy by cogeneration	E_{cs}	kW_{el}	3952
5.	Thermal energy by cogeneration	S_{cs}	kW_{th}	11350
6.	Cogeneration index	y	-	0,35
7.	Electric surplus	E_{exc}	kW_{el}	242
8.	Thermal surplus	S_{exc}	kW_{th}	-4185
9.	Fuel flow	M_{ng}	kg/h	746

Table 6: Technical results for Case 3 from coefficient of performance COP=0,9

In case 3, the electric energy consumption relative to the four compression chillers used currently was deducted from the process plant electric energy total demand. Case 3 differs slightly from case 2 because the absorption system is evaluated for different coefficients of performance, corresponding to single and double stages. The decrease of the electric energy demand is compensated by the increase of the thermal energy demand that incorporates the demanded process plant refrigeration capacity.

The cogeneration index is determinated with relation:

$$y = \frac{E_{cs}}{Q_{cs}} \tag{1}$$

The electric and thermal surpluses determinate with relations:

$$E_{exc} = E_t - E_{cs}\ [\mathrm{kW_{el}}] \tag{2}$$

$$S_{exc} = S_p - S_{cs}\ [\mathrm{kW_{th}}] \tag{3}$$

A general observation about these results must be done: *Case 1* – is the one from the best and it fits the energy needs of the process plant; *Case 2* – presents the highest capacity of producing electric surplus; *Case 3* – presents the lowest electric energy demand because it is associated with an absorption system, but with a thermal deficit that may be eliminated by using of supplementary firing.

For the economic analysis of the systems, their investment costs are stated as follows, considering the components of importation and taxes for Romanian conditions: *reciprocating engine* – USD 3,990,000.00; *combined cycle* – USD 26,041,000.00; *gas turbine* – USD 7,340,544.00. The investment costs for the compression refrigeration system and the absorption refrigeration system were approximated by 100 and respectively 300 [USD/kW], according to the informations obtained from the some factories. The attractiveness for each case was obtained by the calculation of the pay off period and the internal rate return [2, 3]. The following data were considered in this analysis: t=8,640 [h/year] – operation time; P_e= 0.070 [USD/kW·h] – electric utility purchase rate; P_f – fuel costs (0.014 USD/kW·h for fuel oil and 0.010 USD/kW·h for natural gas); η_{boiler}=0.8–steam generator efficiency; η_{el} – electric efficiency (32% for case 1 and case 3, 50% for case 2); E'/S' – power to heat rate for the steam generator.

Disposing of the investment costs, according to the expression of Uniform Present Worth (UPW):

$$UPW = \frac{(1+i)^n - 1}{(1+i)^n \cdot 1} \tag{4}$$

in which „i" is the annual interest rate (assumed as 12% per year); „n" is the expected life of the systems (assumed to be 20 years), economic results are presented in Table 7.

No.	Case	Payback [years]	IRR_1 [%]	IRR_2 [%]
1.	1	0,83	30,00	40,00
2.	2	2,29	-	5,00
3.	3	2,13	6,00	25,00

Table 7: Results of economic analysis

6. CONCLUSIONS

The economic results show that the reciprocating engine associated with compression refrigeration systems of Case 1 is more attractively when this case compares to the others. The possibility of the electric surplus selling of Case 2 (combined cycle) was initially considered. However, this scheme was discarded after a detailed economic analysis. Since the energy industry (in reference) decided that the electric surpluses cannot be commercialized, the first alternative being once again recommended.

It is important to note that in comparison with the FOB costs, the investment costs are increased substantially when the transportation and other taxes were considered. Although the internal return rate in both formulae indicated corresponding positions of the same order, it must be noted that the variation may be significant at the deciding for an investment in the energy generation capacity, in comparison with the other opportunities existing on the market.

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