Some considerations about the hierarchy of the technical solutions for the modernization of power plants

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Abstract — This paper aims at identifying and assessing the costs and revenues incurred by various solutions of development and modernization of a cogeneration power plant in order to optimize the way electric and thermal energy are produced and to conduct a sensitivity analysis of the main performance indicators in relation to the variations of the incoming economic data.

***Keywords* —** the energy market, modernization and development solutions, current operating revenue

I. INTRODUCTION

The Romanian energy system and the market thereof have gone a long way, from the vertically integrated model, to a decentralized system, characterized by decentralized production, transport and distribution. Romania chose the liberal market model, which can also be found in Europe, wherein both the producers and the suppliers are free to close sales and purchase transactions for electrical energy, [1].

Problems regarding the oil, becoming more and more intense, aspects regarding the growing up energy requirements together with the global warming had imposed on one hand scientific community mobilization in order to find the alternative solutions to produce energy and on de other hand implementation of the energy groups existing computerized management techniques. Increasing electricity needs with the development of human society, the economic progress, led on the one hand the superior technical solutions for production, distribution and supply of electricity and on the other hand to increase the efficiency of each link energy chain. All this has led to the development and use of computer and digital media communication in dynamic analysis of energy processes. The economic development implies the existence of some safe primary energy resources, all the efforts in this direction not being able to materialize without ensuring energy source, optimizing the flow of activities and environmental protection. To ensure the consumption of electricity and heat in our country, it is necessary to use an increasing amount of solid fuels inferior, lignite, and renewable energy. It is considered that the main risks which the developer of a cogeneration power plant may encounter are: the general risk of a non-regulated market – it occurs as a challenge to all energy producers, except for those of the "must run" type, the risk of non-dispatch – it can take the form of bilateral contracts, the general regulatory risk – it can occur to any producer, the risk of environmental legislation – it is the most difficult to estimate and manage, the non-credit risk – it is significantly reduced by an economical and financial analysis to persuade banks on the feasibility of the project, the fuel price risk – this is one of the most visible risks. The easiest, most secure way to manage this type of risk is by closing long-term contracts, if the conditions of the fuel market allow it, [1].

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II. THE COGENERATION POWER PLANT IN ENERGY MARKET

The production of electric and thermal energy of the cogeneration power plant in question is based upon the existence of several important industrial and urban consumers. The power plant features the following capacities: the 420 t/h steam generators, fueled by powdered burnt lignite and heavy fuel oil for the support flame, the 50 MW turbo generators and 25 MW turbo generators. The transfer of the produced power is done by means of a 110 kV switching substation to the National Energy System. The transfer of the thermal energy to the industrial and urban consumers within the municipality is done by means of technological and heating networks.

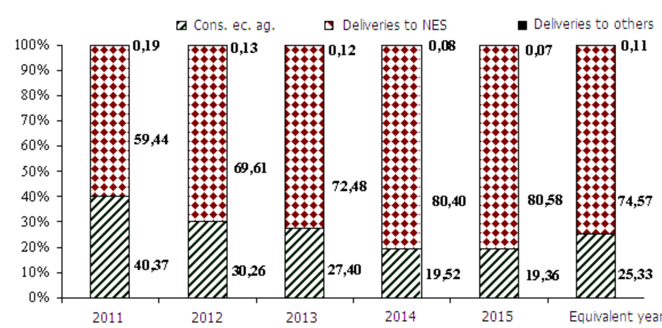

Fig. 1. Proportion of electricity consumers in an equivalent year

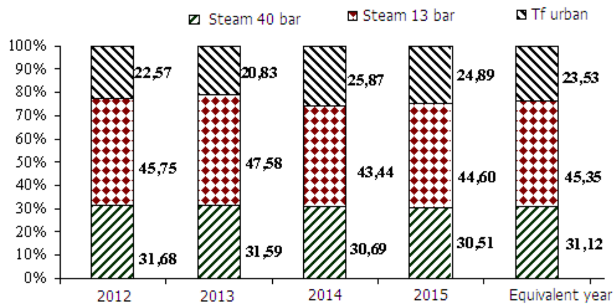

Fig. 2. The share of heat deliveries

It is worth noting that, unlike the other consumers, the average consumption of most important economical agent is close to the maximum and minimum average values, with a strong emphasis on supply continuity.

Nevertheless, questions arise referring to those potential consumers which are eligible to choose other suppliers. Therefore, although the current position on the Romanian energy market is relatively stable, things can change radically due to either one of the following reasons:

- the future of the economic agent – according to the current forecast, it is still the main consumer;
- the predictable development of the city – it is considered that the urban power, heat and water consumption is relatively constant;
- the development plans of the neighboring competitors – based upon their development plans resulting from various public documents: websites, government strategies, the general development policy of the system, or other studies.

The current analysis is mostly based upon the following working hypotheses: only the medium and long term programs were taken into consideration; the life cycle of a new group is 30 years; the life cycle of a deeply rehabilitated group is 15 years; the duration of the raw return is 10 years; a rehabilitated group is between 3 and 5% more efficient, which reduces its fuel consumption correspondingly; all expenses incurred by environmental protection (slag and ash heaps, desulphurization facilities) were taken into consideration according to the necessities resulting from the Treaty of Accession of Romania to the EU.

Also, the power plant produces thermal energy and supplies heat by means of the following thermal agents: 40 bar and 13 bar industrial steam and hot water for ”urban” consumers. The absence of the most important economic agent shall be decisive in the structure of the functioning scheme of the cogeneration power plant, figure 2.

III. POSSIBLE EVOLUTION SOLUTIONS FOR THE COGENERATION POWER PLANT

The current study suggests the following evolution solutions for the cogeneration power plant:

- Modernization alternative – keeping the current architecture and only adding a DKAR 22 turbine and the desulphurization facilities;
- Modernization and development alternative – keeping part of the current power plant scheme, namely the cogeneration stage which caters for the heating and domestic hot water needs;
- Development solution – closing the existing power plant and having new groups built/installed.

The “*development*” groups can keep the existing energy conversion technology – the Rankine-Hirn water-steam cycle – or they can use the mixed-cycle water-steam technology. The city's energy and heating needs are observed in both cases and the fossil fuel energy turns to electric and thermal energy more efficiently than in the current scheme. The possible solutions, depending on the type of fuel either lignite or coal, are:

- *Modernization of the existing facilities with existing fuel* - a “continuity” solution to be implemented after the start up of the new turbine, solution hereinafter referred to as S_a.
- *Modernization of the existing facilities and development by means of a new 100 MW facility, with no change of the conversion technology* - solution consists of connecting a steam generator inside the power plant to a simple cycle steam turbine, thus helping to increase the electricity production capacity of the plant, solution hereinafter referred to as S_b.
- *Modernization of the existing facilities and development by means of a new 220 MW facility, with no change of the conversion technology* - solution with an extended efficiency, consisting of turning 2-3 generators for intermediate superheating functioning, to a 2x50% scheme, with a new 220 MW turbine, solution hereinafter referred to as S_c.
- *Development by means of a new 225 MW unit, with no change of the conversion technology* - implies total replacement of the existing equipment and the installation of a new group, with intermediate superheating and urban connection, solution hereinafter referred to as S_d.

Primary fuel used is Oltenia lignite, support fuel – oil. Table 1 shows the energy characteristics of fuel use.

Table 1: Energy characteristics of fuels

Energy characteristic		Primary fuel	Support fuel
Chemical composition,%	C^i	23.10	87.15
	H^i	1.80	10.70
	O^i	9.60	0.70
	S_c^i	1.50	1.00
	N^i	0.63	0.15
	A^i	21.60	0.20
	W_t^i	41.77	0.10
Percentage participation at the combustion process, %		93-94	7-6
Low calorific power, H_i, kJ/kg		7753.60	40,595
Introduced energy, S_a, MWh/year		5,264,489	336,031
Introduced energy, S_b, ear		7,870,865	502,396
Introduced energy, S_c, ear		8,334,559	531,993
Introduced energy, S_d, ear		5,054,953	380,480

An environmental impact assessment was conducted for each energy solution, by taking into consideration the energy generators functioning on lignite and fuel oil as support fuel amounting to a 6% heating contribution, respectively the amount of solid particles issued, the amount – concentration of CO_2, SO_2, NO_x, [2].

The calculations impose, in a first stage, the determination to the equivalent fuel, the coal-HFO mixture, figure 3. The second stage aims at determining the combustion products, figure 4, [6]. Therefore, is determined:

- the theoretical amount of oxygen required for combustion, Nm^3/kg comb:

$$V_{O2}^0 = 1{,}867\frac{C^i}{100} + 5{,}6\frac{H^i}{100} + 0{,}7\frac{S_c^i}{100} - 0{,}7\frac{O^i}{100} \quad (1)$$

- the theoretical volume of dry air required for combustion, Nm^3/kg comb:

$$V_a^0 = \frac{1}{0{,}21}\left(1{,}867\frac{C^i}{100} + 5{,}6\frac{H^i}{100} + 0{,}7\frac{S_c^i}{100} - 0{,}7\frac{O^i}{100}\right) \quad (2)$$

- the theoretical volume of humid air needed for combustion, Nm^3/kg comb:

$$V_{aum}^0 = 1{,}0161 V_a^0 \quad (3)$$

- the theoretical volume of triatomic gases, Nm^3/kg comb:

$$V_{RO2}^0 = 1{,}867\frac{C^i + 0{,}375 S_c^i}{100} \quad (4)$$

- the theoretical volume of diatomic gases, Nm^3/kg comb:

$$V_{N2}^0 = 0{,}79 V_a^0 + 0{,}8\frac{N^i}{100} \quad (5)$$

- the theoretical volume of water vapor, Nm^3/kg comb:

$$V_{H2O}^0 = 0{,}112 H^i + 0{,}01244 W_t^i + 0{,}00161 \cdot x \cdot V_a^0 \quad (6)$$

- the theoretical volume of dry combustion gases:

$$V_{gu}^0 = V_{RO2}^0 + V_{N2}^0, \text{ Nm}^3\text{/kg comb} \quad (7)$$

- the theoretical volume of the combustion gases:

$$V_{ga}^0 = V_{gu}^0 + V_{H2O}^0, \text{ Nm}^3\text{/kg comb} \quad (8)$$

- the real volume of the combustion gases:

$$V_{ga} = V_{ga}^0 + (\lambda - 1)V_{aum}^0, \text{ Nm}^3\text{/kg comb} \quad (9)$$

- the actual flow of the combustion gases:

$$D_{gN} = B_{ech} \cdot V_g(\lambda) \quad (10)$$

Table 2: Enthalpy-temperature – coal -HFO mixture, q_p=6%

t [°C]	I_g^0	I_a	I^0_{aum}	$I_g = I_g^0 + I_a + (\lambda-1)I^0_{aum}$	
				λ_f=1.2	λ_f=1.4
100	434.90	15.24	318.1	514.2	576.9
200	883.04	31.97	638.9	1041.8	1171.3
400	1815.93	69.11	1299.7	2143.9	2402.1
800	3845.12	148.3	2710.2	4541.7	5080.04
1000	4930.64	193.1	3456.8	5811.6	6501.6
1400	7203.18	312.7	4994.8	8506.2	9507.9
1600	8392.3	382.	5772.	9912.7	11048.2

	3	4	5		

Using Matlab-Simulink software has been carried out the scheme for calculation of the combustion and the exit temperature of gases in the furnace. In figure 3 is given the scheme for determining the equivalent fuel chemical composition.

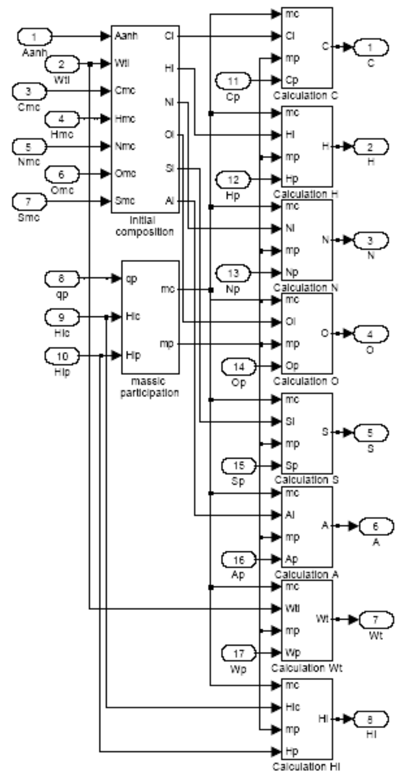

Fig. 3. Scheme for determining the equivalent fuel chemical composition

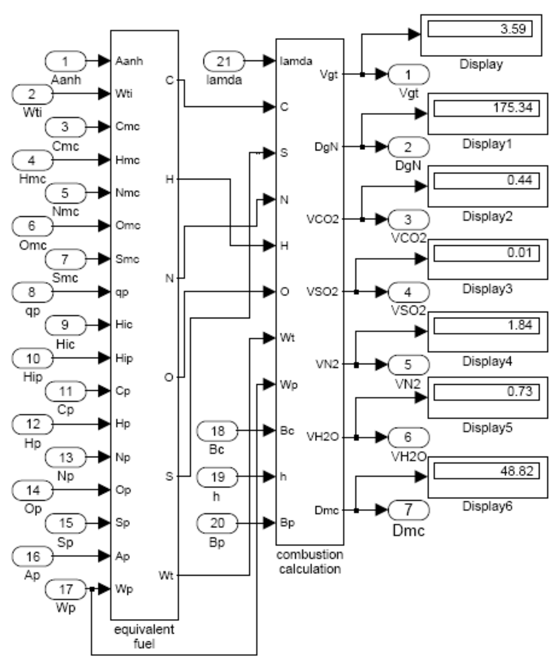

Fig. 4. Scheme for the calculation of the combustion products

The amount of particulate matter emitted is given by:

$$M_c = 10\left(A_{ech}^i + q_m \frac{H_{iech}}{32700}\right)\alpha_c B_{ech} \quad \text{[g/s]} \tag{11}$$

and the ash concentration before the electrostatic precipitator:

$$c_c = \frac{M_c}{D_{gN}} \tag{12}$$

The amount and concentration of CO_2 are:

$$M_{CO2} = 36.66 \cdot C_{ech}^i \cdot B_{ech} \quad [\text{g}_{CO2}/\text{s}] \tag{13}$$

$$c_{CO2} = \frac{M_{CO2}}{D_{gn}} \quad [\text{mg/Nm}^3] \tag{14}$$

The concentration of SO_2 before the desulphurization installation (with η=0.94 in order to respect the limit 400 mg/Nm^3) is:

$$c_{SO2} = \frac{M_{SO2}}{D_{gn}} \quad [\text{mg/Nm}^3] \tag{15}$$

The amount of NO_2 is given by

$$M_{NO2} = B_{ech} \cdot Q_{iech}^i \cdot k_{NO2} \tag{16}$$

and the concentration of NO_2

$$c_{NO2} = \frac{M_{NO2}}{D_{gn}} \quad [\text{mg/Nm}^3] \tag{17}$$

Therefore, for the technical options proposed be obtained: in case of the solution S_a the efficiency of the electrostatic precipitator is 99.9 %, efficiency of the wet scrubber: 94 %, primary method of NO_x reduction, carbon dioxide emissions: 2,114,832.2 tons/year, amount of ash in the funnel and in the electrostatic precipitators: 517,000 tons/year, necessary amount of limestone: 104,840 tons/year, production of dry cast: 148,020 tons/year; in case of the solution S_b the efficiency of the electrostatic precipitator is 99.9 %, efficiency of the wet scrubber: 94 %, primary method of NO_x reduction, carbon dioxide emissions: 3,098,030 tons/year, amount of ash in the funnel and in the electrostatic precipitators: 791,212 tons/year, necessary amount of limestone: 162,070 tons/year, production of dry cast: 212,008 tons/year; in case of the solution S_c the efficiency of the electrostatic precipitator is 99.9 %, efficiency of the wet scrubber: 94 %, primary method of NO_x reduction, carbon dioxide emissions: 3,298,105 tons/year, amount of ash in the funnel and in the electrostatic precipitators: 816,931 tons/year, necessary amount of limestone: 170,043 tons/year, production of dry cast: 228,100 tons/year; in case of the solution S_d: efficiency of the electrostatic precipitator: 99.9%; efficiency of the wet scrubber: 94 %; primary method of NO_x reduction; carbon dioxide emissions: 2,031,309 tons/year; amount of ash in the funnel and in the electrostatic precipitators: 502,089 tons/year; necessary amount of limestone: 102,476 tons/year; production of dry cast: 135,700 tone/an. Each solution shall require the following basic technical conditions in order to comply with the environmental regulations: efficiency of the electrostatic precipitator: 99.9 %; efficiency of the wet scrubber: 94 %; primary method of NO_x reduction; reduction of the rate of excess air upon exhaust (to approximately 1.4).

In terms of polluting emissions (calculated on a yearly basis, both in absolute terms and in relation to the power unit) the least polluting solution is the S_d - development by means of a new 225 MW unit, the second least polluting is S_c - modernization of the existing facilities and development by means of a new 220 MW facility and the last solution is S_b - modernization of the existing facilities and development by means of a new 100 MW facility.

The assessment of energy solutions is conducted according to the internationally recognized standards, as the indicators of the financial activity are estimated according to the *forecasted financial flow*. In the case of a new investment, the financial flows must refer to the implementation period thereof, as well as to a significant part of the life cycle of the respective facility. The forecast of the financial flows was based upon the direct costs, which can be associated to electrical and thermal energy production and related income.

The economic performance of the suggested solutions was analyzed under two possible circumstances: stability – the basic variant and uncertainty – the sensitivity analysis. For each solution it has been estimated that approximately 70% of the functioning costs are incurred by fuel expenses; this is a correct hypothesis, given the fact that a complete retechnologization/modernization of the power plant shall lead to a decrease of the proportion of the fixed costs within the total production cost.

The fuel prices taken into consideration in each case depend on the variation forecasting for the period of the economic analysis. Also, the generated income was determined based upon the price increase forecast for the electrical and thermal energy supplied by the power plant.

IV. THE SENSITIVITY ANALYSIS

An economic analysis implies a calculation of the financial indicators of the solutions. In order to do this it was used the discounted cash flow method, according to the internationally recognized standards. For the calculation of the performance indicators, the discounted financial flow also includes the financial flow and the investment value.

The solution performance evaluation is based upon the following criteria: the discounted financial flow, DFF; the internal rate of return, IRR; the amended return period, T_a.

The discounted financial flow, DFF, is calculated based on the annual financial flow, A_t, which analyzes the investment expenses, the functioning expenses and the achieved income. The future annual flows generated by the respective investment are updated upon the start-up of the new facilities. Project viability is determined if the annual net income, calculated over the entire period of time, t, is positive for the given actualization rate, a. The formula used for estimating the ANI is:

$$VNA = \sum_{t=1}^{n} \frac{A_t}{(1+a)^t} \tag{18}$$

The internal rate of return (IRR) is also based upon the actualized cash flow and it represents the “actualization” rate for which the ANI equals zero. It indicates the maximum interest rate which a loan can reach in order to finance the capital investment. The IRR is calculated based on the following formula:

$$\sum_{t=1}^{n} \frac{A_t}{(1+RIR)^t} = 0 \tag{19}$$

The amended return period (T_a) is superior to ANI. This method is used to actualize the annual net incomes to determine the return period. The acceptability criterion is a return period lower than the regulated duration of use. This period corresponds to the moment when the cumulative net income equals zero:

$$\sum_{t=1}^{T_a} \frac{A_t}{(1+a)^t} = 0 \tag{20}$$

The economic analysis, expressed by means of the calculated criteria of discounted financial flow, internal rate of return and return on values.

The results are presented in table 3. As shown in the table, the comparatively more efficient variants from an economic point of view are: the fourth solution that involves the development by means of a new 225 MW unit, with no change of the conversion technology, has the vest value of the economic efficiency indicators; the "continuity" solution and the solution with an extended efficiency are the second and third most efficient ones.

It is however noticed the fact that, in neither of the suggested solutions has ANI got a positive value, under the circumstances of reference prices.

Table 3. Values of the economic criteria

Nr	Solution	DFF, mil. euro	IRR, %	TRA, years
1	S_a	-1.008	0,64	-
2	S_b	-1.921	0,20	-
3	S_c	-1.836	2,66	-
4	S_d	-901	-	-

These results reveal a group of relatively more efficient solutions as compared to the rest of the technical options proposed.

The power plant will still be lignite-fueled, the use of coal cannot be an efficient option for the development of the power plant because of the significant amount of investment required for changing the boilers.

The installation of new groups, whether or not concomitant with the modernization of the existing ones, shall be decided depending on the valuation price for the resulting electric energy.

The purpose of the sensitivity analysis is to determine the variation of the value of the economic indicators when certain related parameters are modified. It also aims at verifying the ranking resulting from the economic analysis for various solutions envisaging the variation of the most relevant data.

The most important parameter checked for indicator sensitivity is the growth pace of energy prices. In the reference variant, this growth was estimated to an annual 10%.

The sensitivity of the economic efficiency of the project, expressed in the ANI variation, shall be studied when the growth pace goes from 5% to 15%. The resulting values, for the four suggested technical alternatives, are presented in table 4.

Table 4. ANI sensitivity at change the slope of increase of electricity price

Solution	Slope variation of increase of electricity price		
	5%	10% (ref)	15%
S_a	-1.979	-1.008	-33
S_b	-3.428	-1.921	-390
S_c	-3.588	-1.836	-68
S_d	-2.024	-901	231

The following conclusions can be drawn from this sensitivity analysis:

- the efficiency of a solution is highly sensitive to the variation of the valuation price for the resulting electric energy;
- unless a minimum 10% annual growth is recorded for the energy valuation price, the continuity solution, including the modernization of the existing equipment shall be the only eligible one;
- for an up to 15% of annual growth of the variation rate of the valuation price for the resulting electric energy, Sc becomes the most efficient solution, given the fact that it provides the highest annual amount of saleable electric energy.

V. CONCLUSIONS

The alternatives which involve lignite-fueled functioning are the only viable alternatives for the existence of the cogeneration power plant. The choice between one suggestion or another shall only be made based upon the analysis of the evolution of the energy valuation price. The solutions which include the use of coal cannot be an efficient option for the development of the power plant because of the significant amount of investment required for changing the boilers.

Thus, the following aspects shall be taken into consideration:

- closing long-term energy supply contracts at slightly higher prices than the market one;
- a more efficient activity of the branch by an increasing proportion of fuel in energy production;
- an increase of the cogenerated thermal energy by identifying low-need heat consumers (green houses); in this case, the power plant can only be profitable on a seasonal basis.

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