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Energetic, Economical Analysis and Avoided CO_2 Emissions in a Cogeneration System Regarding the Legislation

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Abstract: The access to energy is essential to our quotidian. The energy markets are currently under tremendous pressure caused by instability in fuel prices and environmental issues. Thus, the European citizens are affected by the constant increase in fuel prices, by the threat to the security of energy supply and by climate change resulting from an environmental policy neglected. A sustainable energy, competitive and secure is one of the main foundations upon which the western civilization, as we know it today, is supported.

So, cogeneration systems arise as a way of producing high efficiency energy, lower environmental impacts, and a decrease in the consumption of primary energy. However cogeneration, to date recognized as one of the most efficient ways of producing electricity and thermal energy, has seen its future in jeopardy because of the recent austerity policies which have decreased the remuneration regarding the electricity produced.

The objective of this work is the approach to the new legal framework applicable to the cogeneration activity in Portugal and the execution of feasibility studies according to the new legislative rules that resulted from the publication of the new applicable remuneration regime. In that way an energy audit based on the survey to consumption to the company (annual historic) and based on measurements was performed on an existing cogeneration plant, comparing the results obtained by applying the new legal framework with the results obtained by previous legislation. The avoided CO2 emissions per MWh of electricity produced in the cogeneration process when compared with separate heat and electricity production were calculated. Finally a sensitive economic analysis was carried where PES, NPV and IRR were analyzed in function of fluctuations of the prices of electricity, fuel and cost investment.

Key words: Cogeneration, NPV, IRR, PES, Energy Audit.

1. Introduction

Energy is an indispensable factor for any human activity. Transport, industrial production, trade, communications, etc. depends on the energy availabity. The generation and the rational and efficient use of energy in a way influence the actual society, whether for economic reasons (competitiveness), either for environmental impact reasons.

However, the satisfaction of our energy needs has been made mostly at the expense of conventional energy such as oil, coal and natural gas. Although, present in large-scale in the planet, they are not renewable on a human scale, bringing negative consequences to the environment. This leads to a new concept, called sustainable development (rational use of energy and energy needs) coming to try to reduce this issue.

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Traditionally, consumers satisfy their energy demand by purchasing separately electricity and fuel from distribution companies. Regarding the electricity acquired by consumers, much of it is generated in thermal power plants. In most modern plants, operating in combined cycle the efficiency is about 52.5 %. If it is taken into account the losses inherent in the transportation of electricity, the figure becomes 48.5 %. Therefore, it can be seen that over 50 % of the energy used to generate electricity in large power plants power is inevitably lost to the environment, without the possibility of practical use.

The power generation of thermal energy produced from fuels purchased by consumers is obtained in burning systems whose average efficiency are, at best, about 90 % (referred to the lower calorific value of the fuel). From the foregoing, it can be seen once again that at least about 10% of the fuel energy used to generate heat is also lost to the environment without the possibility of practical use.

Given these issues, arises the need to increase the efficiency of production processes for electricity and heat generation in order to reduce the financial and environmental costs.

Thus, as an alternative to large power plants and distribution networks of high voltage emerges the decentralized production of electricity, and in particular the Combined Heat and Power (CHP) or Cogeneration, in order to take advantage of the inherent limitations on the conversion of heat into work [1-3]. Through a succinct definition, CHP is a process of exploration and production of combined heat and power, in an integrated system, from the same primary source, Fig. 1. The use of the same primary energy source to generate electricity and heat simultaneously results in high levels of savings and hence a very significant reduction of the energy bill without changing the production process of the consumer.

In this work a case study of a CHP facility in Portugal was carried out with a detailed analysis of NVP, IRR and PES and how the fluctuations of the prices of electricity, fuel and cost investment influences these factors. In addition, a study was done regarding the avoided CO_2 emissions of the CHP.

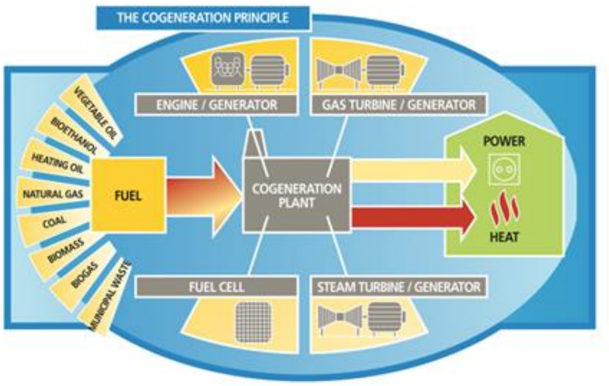

Fig. 1 – The cogeneration principle [4].

2. Results of an Energy Audit to a Cogeneration Facility

It was performed an energy audit into a Portuguese company that owns a cogeneration facility. This cogeneration plant consists of an alternative engine working on Otto cycle running with natural gas (ROLLS-ROYCE KVGS16G4) with an electrical output of 3220 kWe. It is connected to a recovery boiler for the production of saturated steam at 11 bar. The engine is coupled to an alternator for the production of electricity at 4025 kVA. The exhaust gases of the engine, after undergoing the recovery boiler are sent to the atmosphere through a chimney. Part of the thermal energy contained in the cooling water circuit of the engine is also recovered in the form of hot water for supplying the productive process of the factory.

The facility was monitored with measuring devises located in several points, namely:

• Fuel: gas meter outside the facility, mounted on the regulating and metering station;

• Steam produced: flowmeter installed in the feed pipe of the manifold;

• Hot water (cooling water circuit of the engine): flowmeter mounted in the heat pipe connection (forward and return) to the heat exchanger;

• Electricity sold: energy meter mounted after the transformer, in the interconnection with the national grid;
• Temperature and pressure: sensors located in the most important points of the facility.

2.1 Results of an Energy Audit to a Cogeneration Facility

In a cogeneration facility, several parameters must be evaluated, namely:

• Electrical efficiency, $\eta_{electrical}$:

$\eta_{electrical} = E_{gross\ elctricity}$ /Total fuel consumed

• Thermal efficiency, $\eta_{thermal}$:

$\eta_{thermal} = E_{gross\ thermal}$ /Total fuel consumed

• Global efficiency of the system, η_{global}:

$$\eta_{global} = \frac{E_u + Q_v + Q_{AQ} - Q_a}{Q_{GN}} \times 100 \quad (1)$$

• Primary Energy Savings, PES:

In the context of Decree-Law No. 23/2010, of 25 March, [5], the promotion of high-efficiency cogeneration based on a useful heat demand is a priority. This is due to its potential for saving primary energy and, consequently, reduction of CO_2 emissions. It is also related to the significant decrease in network losses associated with decentralization of electricity production as well as to the potential contribution to security of supply. For the purposes, the same decree law, the PES of the cogeneration activity when compared with separate production of heat and electricity is calculated according to the following formula:

$$PES\,(\%) = \left[1 - \frac{1}{\frac{\eta_{thermal}}{Ref\eta_{thermal}} + \frac{\eta_{electrical}}{Ref\eta_{electrical}}}\right] * 100\% = \left[1 - \frac{1}{\frac{H\eta}{RefH\eta} + \frac{E\eta}{RefE\eta}}\right] \times 100 \quad (2)$$

The absolute value of PES of cogeneration activity is determined by the following equation:

$$PES = \frac{H_{CHP}}{RefH_\eta} + \frac{E_{total}}{RefE_\eta} - F_{total} \quad (3)$$

where $Ref\eta_{thermal}$ and $Ref\eta_{electrical}$ are respectively the reference values for harmonized efficiency for separate heat production and for separate electricity production. They are influenced by a correction on the average climatic conditions (Annex III) and a factor concerning network losses (Annex IV) of Directive 2004/8/EC, [6]; H_{CHP} is the useful thermal energy produced, E_{total} is the total electrical energy produced and F_{total} is the consumed fuel.

• Equivalent electrical efficiency of the facility, EEE, is can be expressed through the following relation:

$$EEE = \frac{Useful\ electricity}{Thermal\ energy\ of\ natural\ gas - \frac{Useful\ thermal\ energy}{0{,}9}} \quad (4)$$

For the evaluation of these mandatory parameters, it is previously necessary to calculate the following ones:

• Useful electricity, E_u;
• Thermal energy of the steam to the process, Q_V:

$$Q_V = M_v \times \frac{H_v}{3600} \quad (5)$$

where M_v and H_v are respectively the vapour consumption and enthalpy

• Thermal energy in hot water of the engine cooling system, Q_{AQ};
• Thermal energy of the feed water to the boiler, Q_A:

$$Q_A = M_a \times \frac{H_a}{3600} \quad (6)$$

where M_a and H_a are respectively the water consumption and enthalpy.

• Thermal energy of natural gas, Q_{GN}:

$$Q_{GN} = \frac{V_{GN}}{1000} \times \frac{PCI_{GN}}{3600} \quad (7)$$

where V_{GN} and PCI_{GN} are respectively the natural gas consumption and lower heating value.

2.2 Results of the Survey and New Measurements

In the year 2012 an audit was done to the cogeneration facility (annual historic – January to December), based on the measured values obtained with the instrumentation already installed in the system (as stated earlier). In the year 2013 (March) a new visit was done, where more sensors were installed. All the parameters described in section 2.1 were evaluated. Table 1 summarizes the main ones.

Table 1 - Comparison of the main results obtained based on the survey consumption of the company and the measured ones.

Parameters	Audit	Measurements
Electrical efficiency, net %	35.7	40.0
Thermal efficiency %	36.4	31.5
Global efficiency, %	72.1	71.5
PES, %	11.9	14.7
EEE	0.60	0.62

As can be seen, the EEE during the annual audit was 0.6. The licenced value was equal to 0.63 in the frame of the Decree-Law No. 538/99. However, the real value now obtained, although lower, is within the minimum limits imposed by this law and still within the tolerance of 0.05 relative to EEE licensed in accordance with the same decree. Therefore, the facility is running on the lower limits.

During the measurements performed in 2013, it was obtained an EEE = 0.62. This, although higher than the annual history, in some way confirm the order of magnitude of the predicted value at the time of licensing.

According to calculations made during the audit, it was found that the average annual PES throughout the audit period was 11.9% which is equivalent to an absolute value of 5662 MWh / year. As indicated in the Decree-Law No. 23/2010, this facility is classified as high-efficiency cogeneration, since the value of PES is higher than 10%.

2.3 Ratio electricity / heat and overall efficiency of the installation.

The same Decree-Law, Annex II, states that electricity from cogeneration shall be considered equal to the total annual production of the unit measured at the output of the generators, if the overall efficiency is ≥ 75% (for combustion engines internal).

However, the same directive must be adjusted the obtained values of the audit adjusted due to several benchmarks, namely:

• benchmark in efficiency for separate production of electricity (ISO conditions) is 52.4%, as defined in Annex I of the same Directive.

• benchmark in efficiency for separate production of electricity, adjusted by the correction factor for avoided grid losses is 49.5%.

• benchmark in efficiency for the production of heat (using natural gas) is 90%, as indicated in Annex II of the same Directive.

• correction factor for grid losses avoided by the power delivered to the Public Service Electric Grid (PSEG) is 0.945 and the voltage supply of electricity in connection PSEG is 15 kV.

• Ref H_η = 90%

• Ref E_η = 49.5%

Applying these values to all parameters, it was obtained the following ones for the audit, shown in Table 2.

Table 2 – Adjusted values of the audit (2012).

E_{total}	15 188.67 MWh
H_{CHP}	15 272.30 MWh
F_{total}	41 919.71 MWh
E_η	36.2%
H_η	36.4%
η_{global}	72.6%

In this case, the cogeneration plant has an overall efficiency 72.6% calculated on the survey of 2012. Thus, it is necessary to determine the ratio of C (electricity / heat) of the installation, in order to evaluate the amount of electricity from cogeneration.

Thus, to obtain an overall efficiency of at least 75%, maintaining the fixed electrical efficiency of 36.2%, the thermal efficiency must be 38.8%. Based on this thermal efficiency and for the same fuel consumption, the useful heat will be equal to 16 279.26 MWh. It follows that:

$$C = 0.93$$

and the electricity from cogeneration is:

$$E_{CHP} = (\frac{36.4}{38.8}) \times 15\ 188.67 = 14\ 249.16\ MWh$$

2.4 CO_2 Emissions

To make the calculation of CO_2 emissions associated with the production of electricity in the installation, as well as the avoided emissions of CO_2, emission factors defined by the IPCC, (Intergovernmental Panel on Climate Change) were used [7]:

CO_2 emissions for natural gas - 202 kg CO_2/MWh being necessary first to calculate the fuel consumption of the cogeneration process, not associated with the production of electricity:

$$F_{CHP} = F_{total} - F_{nCHP}$$

where:

$$F_{nCHP} = \frac{E_{total} - E_{CHP}}{\frac{E_{total} + \beta \times H_{CHP}}{F_{total}}} = \quad (8)$$

$$= \frac{15\ 188.67 - 14\ 249.16}{15\ 188.67/41\ 9197171} = 2\ 593\ MWh$$

For the installation under analysis it was calculated a value of F_{CHP} 39 326.7 MWh / year.

The CO_2 emissions associated with the production of electricity in the process (fuel: natural gas) is obtained using the following the formula of the EIGO (Entity Issuer Guarantees of Origin) manual:

$$(E.CO2)_{CHPi} = \frac{(F_{CHP} - \frac{H_{CHP}}{RefH_{\eta}}) \times (E.CO2)_i}{E_{CHP}} \quad (9)$$

$$(E.CO2)_{CHPi} = \frac{\left(39326.7 - \frac{15272.30}{0.9}\right) \times 202}{14249.16} = 316.95\ kg/MWh$$

The avoided CO_2 emissions per MWh of electricity produced in a cogeneration process when compared with separate heat and electricity production is obtained using the formula of the EIGO manual:

$$(E.E.CO2)_i = \frac{PEP}{E_{CHP}} \times (E.CO2)_i = \quad (10)$$

$$(E.E.CO2)_i = \frac{PEP}{E_{CHP}} \times (E.CO2)_i = \frac{5662}{14249.16} \times 202 = 80.27\ kg/MWh$$

3. Economic Analysis of Replacement of an old CHP by a New One

In the previous case, a real situation was analysed in order to verify if it satisfies the new legal regulation versus the older one. The facility was running at full power and therefore there was no need to do any kind investment.

However, when it is necessary to invest in new systems a detailed economic analysis must be carried out.

The economic risk associated with the investment project in a cogeneration plant lies in the possibility to check if the operating results are consistent with the originally planned study of economic and technical feasibility. For that, it was analysed the technical and economic potential of a real situation concerning the installation of a new cogeneration plant operating with natural gas, replacing the current existing one that runs with fuel oil (18 years old, at the end of its useful life). The selling price of electrical energy to the grid, the cost of fuel and the actual investment made are relevant factors to the financial sustainability of the project.

The selling price of electrical energy, ruled by the reference tariff published periodically by the government, ends up by being indexed to the value of light arabian breakeven, while the cost of natural gas is also indexed to the value of arabian light breakeven or value of Brent (as supplier).

Given the importance of the three factors mentioned above (selling price of electricity, fuel cost and investment), it was elaborated a sensitivity analysis aiming to determine the influence of the variation of these three factors may have on the major indicators that measure the profitability of project IRR (Internal Rate of Return), NPV (Net Present Value) and Payback, [10]. The actual facility went through all the steps of mandatory maintenance either preventive or curative, [11]. In spite of that, several equipment stops to run.

As already mentioned, the current cogeneration existing fuel oil will suspend its operation for lack of profitability. In terms of fuel consumption (fuel oil) in annual terms, considering the thermal energy annually required, based on surveys conducted is 4079 MWh / year, which is about 419 ton of fuel oil with an approximate cost price 600 € / Ton.

For the new CHP to be installed it was considered the same needs of thermal energy as the old one.

Based on that, the following parameters were evaluated:

Electrical efficiency: 40.1%

Thermal efficiency: 39.3%

Global efficiency: 79.4%

PES: 21.2 % (high efficiency CHP)

Regarding the economic analysis, the obtained results are:

Investment: 870000€

Payback period: 6.8 years

NPV: 85241€ (loan of 7%)

IRR: 8.9%

In spite of the point economic parameters calculated, it is important to analyse how they are influenced by variations of electricity price, fuel cost and investment costs. Tables 3 to 5 presents the changes made to the actual feasibility study, originated by a fluctuation of 10 percentage points relative to the baseline scenario presented (no variations, 0%).

Table 3 - Variation of indicators due to the selling price of electric energy.

Price variation of kWhe	IRR (%)	NPV (€)	Payback (years)
+ 10%	14.97	374943	5.2
+ 5%	12.03	230 092	5.9
0 %	8.90	85 241	6.8
- 5 %	5.60	-59 610	8.1
-10 %	1.97	-204461	9.8

Table 4 - Variation of indicators due to the cost of fuel.

Price variation of gas	IRR (%)	NPV (€)	Payback (years)
+ 10%	2.38	-188 826	9.6
+ 5%	5.79	-51 792	8.0
0 %	8.90	85 241	6.8
- 5 %	11.87	222 275	6.0
-10 %	14.66	359 309	5.3

Table 5 - Variation of indicators due the investment.

Investment variation	IRR (%)	NPV (€)	Payback (years)
+ 10%	6.96	-1 759	7.5
+ 5%	7.91	41 741	7.2
0 %	8.90	85 241	6.8
- 5 %	10.00	128 741	6.5
-10 %	11.20	172 241	6.1

Following the above tables, Table 6 summarizes the variations of the economic indicators point values on the basis of factors of production, compared with their initial values (case 0%).

Table 6 - Summary of variation (%) of the indicators.

	Variation of Production factors	Variation of IIR	Variation of NPV	Variation of Payback
Cost of Whe	+10 %	+ 68%	+ 336%	- 24%
	+ 5 %	+ 35%	+ 170%	- 13%
	0 %	-	-	-
	- 5 %	- 37%	- 170%	+ 19%
	-10 %	-77%	- 336%	+ 44%
Cost of fuel	+10 %	- 73%	- 322%	+ 41%
	+ 5 %	- 35%	- 161%	+ 18%
	0 %	-	-	-
	- 5 %	+ 33%	+ 161%	- 12%
	-10 %	+ 65%	+ 322%	- 22%
Investment	+10 %	- 22%	- 102%	+ 10%
	+ 5 %	- 11%	- 51%	+ 6%
	0 %	-	-	-
	- 5 %	+ 12%	+ 51%	- 4%
	-10 %	+ 26%	+ 102%	- 10%

Fig. 2 reflects the variation in the tariff for electricity sale to the public network induced by varying the PES of the cogeneration plant.

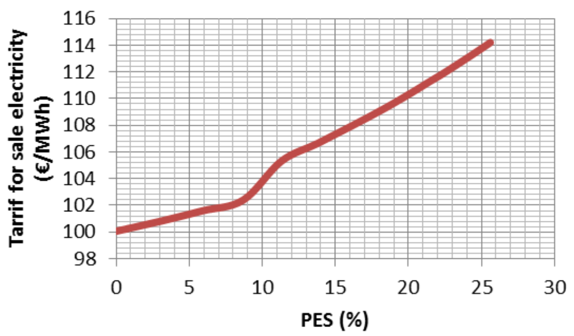

Fig. 2 -Variation of the electric tariff due to PES of the installation.

From this sensitivity analysis performed it can be concluded the following findings:

• The variation in the tariff for sale of electrical energy to the grid varies in a substantially linear manner to PES values compatible with the notion of "high efficiency cogeneration" and assumes a very sharp fall when the values of PES approach 10% or are lower (see figure 2);

• The variation of indicators (IRR, NPV and payback) of a cogeneration project is mainly influenced by the selling price of electricity. Indeed it is verified that variations of about 10% on the selling price of electricity induce variations in the value of IRR ranging from (-) 77% and (+) 68% from baseline (see table 5);

• The variation of indicators (IRR, NPV and payback) of a cogeneration project is secondly influenced by the cost of fuel. Indeed it is verified that variations of plus or minus 10% of the cost price of fuel induce variations in IRR value ranging between (-) and 73% (+) 65% from baseline (see Table 5);

• The variation of indicators (IRR, NPV and payback) of a cogeneration project is, within certain limits, much less influenced by the change in the value of the investment. Indeed it is verified that variations of plus or minus 10% of the value of the investment induce variations in IRR value ranging between (-) and 10% (+) 10% of the initial value (see table 6).

Thus, it can be concluded that, as a minimum, to enable a profitable operation of a cogeneration facility, the following basic precautions should be taken:

1. Sizing the cogeneration plant always maximizing thermal usages in such a way that the obtained values for PES exceed 10%;
2. Adjusting the operating system of the cogeneration facility to the operating profile of the consumer installation to ensure that in any situation, in monthly actual operation, values of PES less than 10% are never obtained. In this way it promotes the value of the tariff for sale of electricity to the grid;
3. Choose, in the design phase, a generator whose electrical efficiency is as high as possible in order to reduce fuel consumption and thus favour the second largest factor of production (cost of fuel);

4. Ensure a minimum number of annual operating hours to allow the amortization of the investment in a reasonable period of years.

As already mentioned, the latest legislative changes defined by the Portuguese Government makes the profitability of cogeneration highly dependent on the price of electricity and fuel costs systems. The tariff resulting from the application of Ordinance No. 140/2012 of 14 May, [9] is about 70% of the tariff in the previous legal framework.

Thus, the "business" of cogeneration should be managed by experts and should be viewed in terms of investment as more equipment associated with the production unit whose goal will be to increase the global competitiveness of the productive unit.

The figures for the profitability of the past should be reassessed and assumed values more compatible with current reality.

However, in some European countries, the trend is exactly the opposite, which recently led to an increase of electricity tariffs associated with cogeneration facilities. Therefore, Portugal is going in the reverse direction of several countries of the European Union (EU) regarding cogeneration.

5. Conclusions

The cogeneration technology, to date recognized as one of the most efficient ways of producing electricity and thermal energy, has seen its future in jeopardy because of the recent austerity policies, which have decreased the remuneration regarding the electricity produced.

The objective of this work was the approach to the new legal framework applicable to the cogeneration activity in Portugal and the execution of feasibility studies according to the new legislative rules that resulted from the publication of the new applicable remuneration regime. In that way, an energy audit based on the survey to one company (annual historic) and based on measurements was performed on an existing cogeneration plant, comparing the results obtained by applying the new legal framework with the ones obtained by previous legislation. The main conclusions are: the cogeneration plant should designed in order to obtain PES values that exceed 10%; the operating system of the cogeneration facility must be adjusted to ensure that in any situation, in monthly actual operation, values of PES less than 10% are never obtained. In this way it promotes the value of the tariff for sale of electricity to the grid. A generator must be chosen with an electrical efficiency as high as possible to reduce fuel consumption and thus favouring the second largest factor of production (cost of fuel); ensure a minimum number of annual operating hours to allow the amortization of the investment in a reasonable period of years.

The avoided CO_2 emissions per MWh of electricity produced in the cogeneration process when compared with separate heat and electricity production was calculated.

A sensitive economic analysis was carried where PES, NPV and IRR were analysed, originated by a variation of 10 percentage points of production factors (electricity price, fuel cost) and investment relative to the baseline scenario. The main conclusions are: the variation of indicators IRR, NPV and payback of a cogeneration project is mainly influenced by the selling price of electricity and by the cost of fuel. However, they are much less influenced by the change in the value of the investment.

Therefore, cogeneration plants in different countries with different regulations must take into account an economical sensibility study.

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