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CASE STUDY

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Evaluation of the economic viability of the application of a trigeneration system in a small hotel

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Abstract

Energy is an indispensable factor for any human activity. Transport, industrial production, trade, communications, etc. depend on the energy availability. Traditionally, consumers meet their energy demand by buying separately electricity and fuel to the distribution companies. With regard to electric energy generation acquired by consumers, a good portion is produced in conventional thermoelectric power plants. In modern power plants, the total losses in energy can go up to 52.5 % without any kind of recovery. Thermal energy is obtained from the fuel purchased by consumers in burning systems with a maximum average efficiency, at best, about 90 % (10 % lost). Faced with this problem arises the need to increase the efficiency of electricity production processes and heat generation in order to reduce the financial and environmental costs. Thus, as an alternative to large conventional power plants, decentralized production of electricity arises, and, in particular cogeneration, in order to take advantage of the inherent limitations of the conversion of heat into work. CHP (Combined Heat and Power) is a combined process of production and exploitation of thermal energy and electricity, in an integrated system, from the same primary source. In spite of not being a new technology its applications are mainly used in the industry. These kind of systems contributes also for a decrease of CO_2 emissions to the environment. The aim of this study is to analyse the technical and economic potential of a real situation in a small hotel located in a city of Portugal. Instead of using only a CHP, the generated heat was also used for cooling - CHCP (Combined Heat, Cooling and Power). For that, besides the energetic analysis carried out, a detailed economic analysis was done in order to evaluate its feasibility and risk regarding the main parameters to be taken in account, namely the NPV (Net Present Value), IRR (Internal Rate of Return), Payback Period and PES (Primary Energy Savings) and Avoided Emissions (AE) of CO_2. The main conclusions obtained are that the CHCP contributes to a PES of 57 tep/year, the AE being 68 teq CO_2/year. The payback period is 3.6 years.

Keywords: CHCP, CO_2 emissions, NPV, IRR, AE, PES, Energetic analysis

Background

Satisfaction of our energy needs in cities 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) that emerges to try to reduce this issue.

Traditionally, consumers satisfy their electrical energy demand by purchasing separately electricity and fuel from distribution companies. Regarding the electricity acquired by consumers, much is produced in thermal power plants. The older ones, running in single cycle, typically convert only about 37 % of the chemical energy contained in the fuel into electrical energy. Taking into account energy losses inherent in the transport, low overall efficiencies of around 33 % are obtained, meaning that about 67 % of the energy is lost as waste heat. In most modern power plants operating in combined cycles, efficiency values are about 52.5 % at the central outlet and approximately 48.5 % if it is taking into

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account the losses inherent in the transport of electricity, which means that about 51.5 % of the primary energy continues to be lost to the environment as waste heat.

The power generation of thermal energy produced from fuels purchased by consumers is obtained in burning systems. The average efficiency is, 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.

Among the primary sources used in cogeneration systems are: oil products (fuel oil), natural gas, propane gas, coal, biomass, industrial waste, etc. 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 [4, 5].

This technology can also be applied in almost cities or buildings on a large or small scale (not only in the industry). If part of the heat obtained from the system is used to run an absorption chiller, it is possible to obtain chilled water for cooling. The sketch of principle of trigeneration (CHCP) principle is shown in Fig. 2.

Benefits and drawbacks of CHCP

The CHCP when compared with conventional systems for the same purpose have benefits to the countries, for the consumers and for electric energy companies.

For the country:

Economics of primary energy: The successful implementation of cogeneration and trigeneration leads to a reduction of fuel consumption by approximately 25 % compared to conventional power generation. At the national level encourages decentralized generation, reducing the need for installation of large thermal power plants, and increases the stability of the electrical network in the country. It also contributes to increasing local employment.

Greater energy diversity: due to taking profit of waste heat from the energy production process. Likewise, endogenous resources could be utilized for energy production in cogeneration.

Reduced environmental impact: the reduction of atmospheric pollution follows the same proportion. With the utilization of natural gas instead of oil or coal fuels, SO_2 emissions and particles are reduced to zero.

Improvement of the national energy efficiency: due to the use of conversion systems with much higher efficiencies.

Security of supply: some applications require uninterrupted availability of energy, such as hospitals and industrial establishments, where the process interruption can cause major disruption. As such, cogeneration can function as uninterruptedness guarantee,

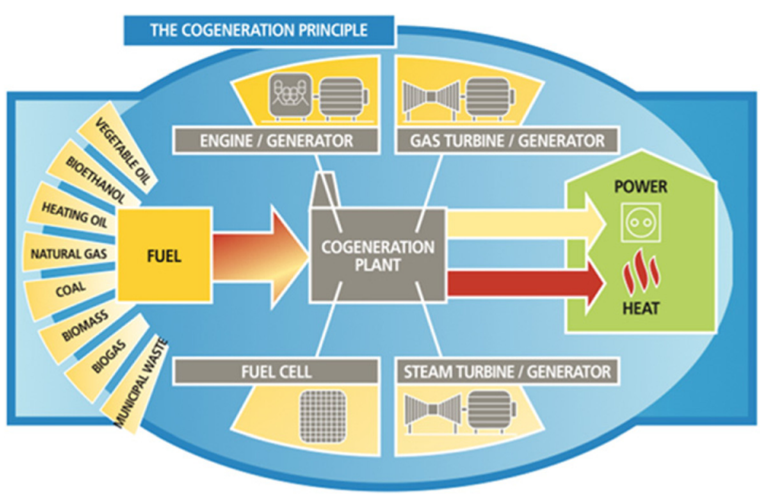

Fig. 1 The cogeneration principle, [15]

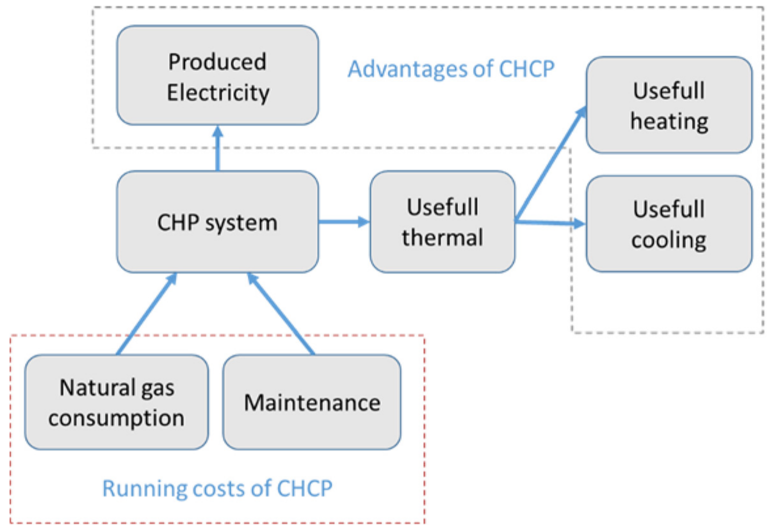

Fig. 2 Sketch of principle of trigeneration (CHCP)

always operating, even when electrical power is unavailable.

For the consumers:

Lower losses: with decentralized energy production - the transmission and distribution energy have lower losses.

Reduction in energy bills: lower cost of electricity consumed allows economic cost savings, reducing the production costs of industrial units and promoting increased competitiveness.

Continuous power supply: through a cogeneration plant operated in parallel with the external network, one can have an uninterrupted power supply with a security guarantee that in case of failure of the external network the own energy produced can meet the needs of the user.

For producers of electric energy companies:

Increased available electricity – there is greater guarantee of supply of electricity to consumers by the distributor of electricity.

Reduction of reserve power: it is not necessary to have high reserve powers as at any time as mall CHP facility can sell this, releasing any surplus resulting from the production of electricity and thermal energy.

Drawbacks:

Need for appropriate legislation:

Appropriate legislation is mandatory and will need to arbitrate conflicts and disputes that necessarily occur between independent producers and the electricity generating companies.

Infrastructures:

It is necessary to create appropriate infrastructures to monitoring compliance with legislation and technical regulations and for the implementation of appropriate maintenance and repair operations, so there are no serious failures in the supply of electricity to the grid from small producers.

Network control problems:

The parallel connection of the cogeneration plant with the power supply network creates regulatory problems. Leave that on the dependence of power failures provided by independent producers.

Market Reduction: If independent producers (cogeneration) which logically produce most of the energy they consume there will be smaller market for producers and electricity distributors.

Investments:

Companies are required to more investment and on top of that in a branch where they have their greatest skills, and facing unknown risks.

Environmental:

Increased pollution in the vicinity of manufacturing process due to emission of products of combustion cogeneration, although at national level there is a decentralization, and reduced pollution.

Methodology

In this study, a CHCP system was designed for a hotel located in a city of Portugal. The transient energy needs for heating and cooling were simulated hour per hour all the year around. It was used the software HAP (Hourly Analysis Program) from Carrier. The energy needs for sanitary hot water (SHW) was evaluated through the Solterm code, [6]. In this case it was considered that all days of one month would have the same hourly consumption according to the established utilization profile. The next step was to choose the most adequate CHCP system for the hotel in accordance with national laws

[5–9]. Once chosen the system, several parameters of viability were carried out, namely an energy analysis, an environment impact assessment and a study of the economic viability.

Heating and cooling loads

The hotel with eight floors has all the facilities that can be found in a 5* hotel. After the characterization of the envelope, the heating and cooling loads and energy spent for the sanitary hot water were evaluated as shown in Fig. 3.

The results are displayed

The design values used for the heating and cooling calculations are as follows. Summer: external temperature = 30 °C, outside relative humidity = 37,3 %, Internal temperature = 25 °C, and inside relative humidity = 40 %. Winter: external temperature = 1,7°C, outsider relative humidity = 49,5 %, Internal temperature = 20 °C and inside relative humidity = 50 %. This values are the ones obtained by RCCTE, [7].

The total area of the hotel to be heated and cooled is 5942,4m^2. From the second floor until the eight floor, there are eight identical rooms per floor. In the ground floor there is the lobby, reception, bar, offices, laundry, kitchen. In the first floor there meeting rooms, hall, restaurant and gym.

The total heat energy needed to run all the three subsystems is the sum up of each one. While the heat harnessed by CHCP drives directly the environment heating loads and sanitary hot water, for the cooling system is needed an absorption chiller. It was chosen one with a COP value of 0.72. So, in order to get all the heat energy needed by the whole system, the cooling load must divided by mentioned value of the COP, which results in a total thermal load of 742 MWH for all the year.

Due to the fact that the selling price of electricity to the public network is substantially lower in off-peak hours and super empty, turning off the CHCP overnight (from 00:00h till 07:00 h am.) as also the advantage of reducing the annual hours of operation and thereby increase the time between repairs. Figure 4 summarizes the results for one year in both situations.

Legal framework for cogeneration in Portugal

Once know the energy needs of the hotel, several parameters of viability were evaluated [8], namely an energy analysis, an environment impact assessment and a study of the economic viability.

National legislation for cogeneration application has over the years suffered a lot of changes. At the time of the opening of the hotel, several Decree-laws, Ordinances and Dispatch were in force and were used for the legal framework for cogeneration in Portugal, [9–13].

- EEE (Equivalent Electrical Efficiency)
  By the Decree Laws in force, this parameter is given by equation 1:

$$EEE = \frac{E}{C - \frac{T}{0.9\ -\ 0.2\frac{CR}{C}}} \tag{1}$$

Where:

E [kWh]: electricity generated annually by the cogeneration system, excluding the consumption in internal auxiliary power generation systems;

T [kWh]: useful thermal energy consumed annually from the thermal energy produced by cogeneration, excluding the consumption in the internal auxiliary power generation systems;

C [kWh]: the primary energy consumed annually in the cogeneration system, evaluated from the lower heating value of fuel and other resources used;

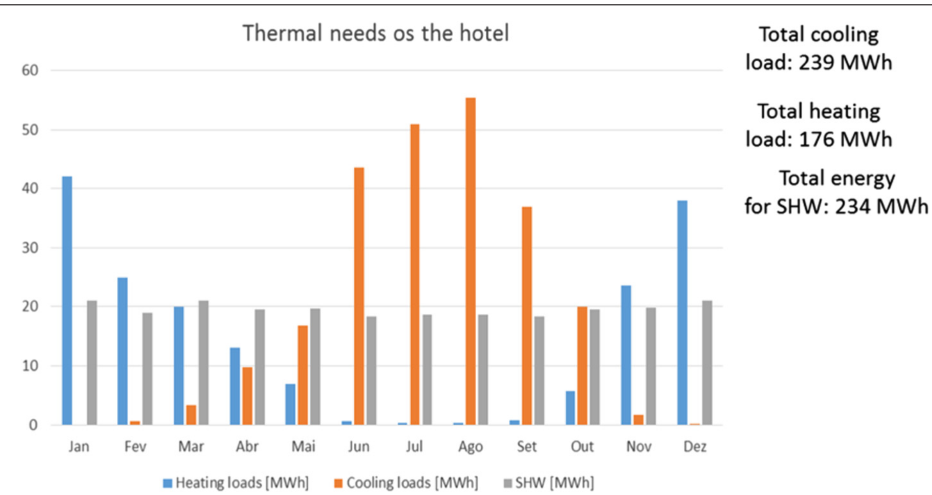

Fig. 3 Thermal loads of the hotel

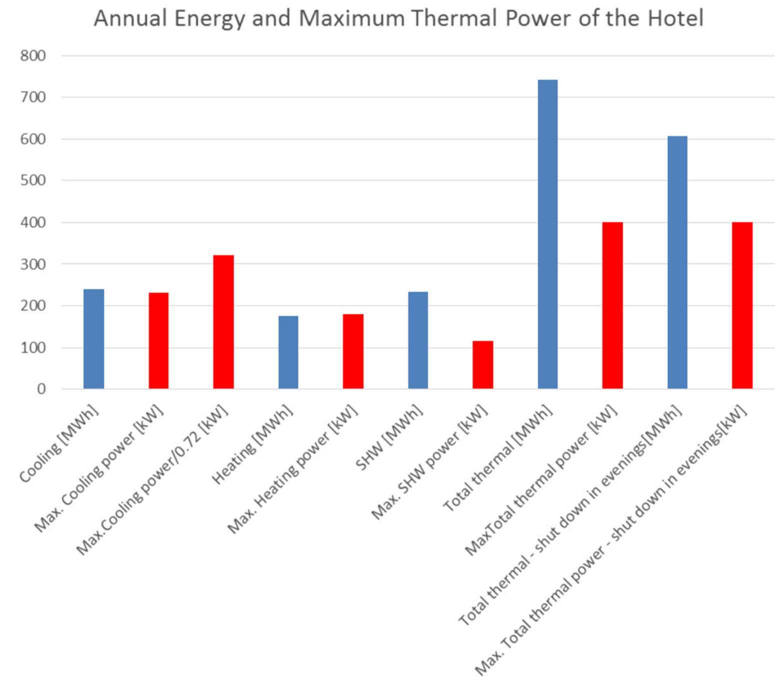

Fig. 4 Annual energy and maximum thermal power needs

CR [kWh]: equivalent energy of renewable resources or industrial waste, agricultural or urban consumed annually in cogeneration facility.

EEE must assume the following values, according to the same Decrees-Laws:

- EEE ≥ 0.55 for installations using natural gas as fuel, gas petroleum or liquid fuels with the exception of fuel;
- EEE ≥ 0.50 for installations using fuel oil as fuel, alone or together with waste fuels;
- EEE ≥ 0.45 for installations using biomass as fuel or residual fuels, alone or in conjunction with a fuel support, a percentage not exceeding 20 % annual average.

- Before proceeding with the analysis of the remaining parameters, it is necessary to choose the appropriate CHP engine for the hotel. The choice was between internal combustion engines and micro turbines running with natural gas (comparing with fuels obtained from petroleum or coal, there are no emissions of SO_2 and particles to the environment). Regarding to the selling market, it was found only one that has an EEE ≥ 0.55 running with natural gas.

The main characteristics of the four stroke spark engine (6 cylinders in line) are, [14]:

$$\text{Electric output} = 70\ \text{kW};\ \text{Heat output} = 104\ \text{kW at } 81^\circ\text{C};\ \text{Fuel input (LHV)} = 204\ \text{kW};\ \text{Fuel input (gross)} = 226\ \text{kW}$$

- E_{er}: maximum quantity of electricity to provide annually to the Electric System of Public Service not higher than the value given by equation 2:

$$E_{er} = \left(4.5\frac{E+T}{E+0.5T} - 4.5\right)E \tag{2}$$

- As the power to be installed is lower than 10MW (actually it is 0.7 MW), the same Decree-Laws are also applicable. So, the selling price of the electricity to the national grid from the cogeneration system is given by equation: 3

$$SP_m = \left[PF(VRD)_m + PV(VRD)_m + PA(VRD)_m\right]/(1 - LEV) \tag{3}$$

Where:

SP_m is the remuneration applicable to cogeneration installations, in month m;

$PF(SP)_m$ is the fixed portion of compensation applicable to cogeneration installations,

in month m;

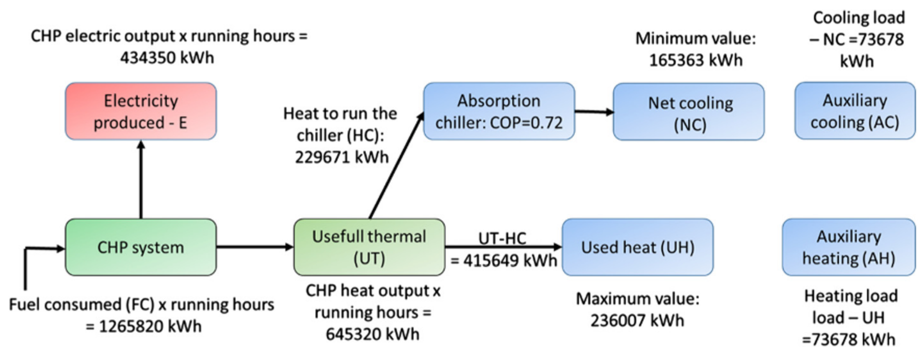

Fig. 5 Global energy fluxes

$PA(SP)_m$ is the environmental portion of the compensation applicable to cogeneration facilities in the month m;

LEV are the losses in transmission and distribution networks, avoided by the cogeneration plant.

- Saving Energy Index (SEI): ratio of the fuel economy obtained in the cogeneration engine when compared to the amount of fuel consumed in a conventional installation, i.e. an electrical plant with an efficiency η_c, a boiler with an efficiency η_b and an electric chiller with a COP_{comp}. It is given by equation 4:

$$SEI = 1 - \frac{1}{\frac{\eta_{e,C}}{\eta_c} + \frac{\eta_{e,C} xRCE}{\eta_b} + \frac{\eta_{e,C} xRFE}{COP_{comp}}} \quad (4)$$

Where:

RCE and RFE are respectively the ratios between heat and electricity and the ratio between cooling and electricity in the CHCP;

- Demand rate of primary energy (DRPE): ratio between the amounts of fuel consumed in cogeneration/ trigeneration by the corresponding amount of a conventional system. Compared to the SEI, is:

$$DRPE = 1 - SEI \quad (5)$$

When DRPE is less than one, the implementation of cogeneration allows a fuel economy (primary energy), whereas if its value is greater than one means that are no energy advantages.

- Payback time: is the project's operating time necessary to obtain the sum of revenue and expenditure flows that equalize the value of the investment, equation 6:

$$Payback = \frac{Initial\ Investment}{Annual\ Revenues} \quad (6)$$

- Net Present Value (NPV): is the calculation of the sum of annual revenues obtained updated in the chosen rate and deducting the amount of investment, upgraded at same rate, equation (7):

$$NPV = -Inv0 + \sum_{k=1}^{n} \frac{R_k - D_k}{(1 + TA)^n} \quad (7)$$

Where:
Inv0 is the initial investment in year 0;
R_k are the annual revenues
D_k are the annual expenses
TA is the discount interest rate
N is the number of years of the project life

For a project to be viable, the NPV must be positive, only because in this case the project will generate benefits, which will recover the investment made and provide a more cost effective alternative reference. This criterion is strictly dependent on the discount rate. It is related to three parameters:

Table 1 TOE of a conventional system

		η	COP	Necessary thermal energy [kWh]	Conversion [TOE/kWh]	TOE
Conventional system	UH	0.9		262230	$0.086/10^3$	23
	NC		2.8	59058	$0.29/10^3$	17

Table 2 TOE of the CHP system

		Energy [kWh]	Conversion [TOE/ kWh]	TOE
CHP	Fuel consumed (FC)	1265820	$0.086/10^3$	109
	Electricity produced (E)	434350	$0.29/10^3$	126

Table 3 Economic analysis of the CHP system

E [MWh]	T [MWh]	C [MWh]	CR [MWh]	T/E	EEE	Eer [MWh]
434	465	1266	0	1	0.58	26367
As E< Eer, all the electrical energy produced can be sold to grid						
SEI =0.15			DRPE = 0.85 <1			
			The cogeneration allows a fuel economy (primary energy)			

1. Real compensation desired for own funds, based on the real interest rate of a risk-free investment;
2. Economic and financial risks associated with the project;
3. Annual rate of expected inflation. This rate will only influence the calculations were all forecasts of revenue and expenses are made at current prices because the constant price method considers the future absence of inflation and devaluation mount.

Discussion and evaluation

Once known the thermal loads of the hotel and already chosen the CHP engine, it is possible to carry out a global analysis of the system for all the year, the results being shown in Fig. 5. It must be noticed that the cooling power is the product of the heat output of the CHP (104 kW) by the COP of the absorption chiller installed (0.72), which is equal to 75 kW. It can also be seen that the CHP that doesn't satisfy all the thermal energy needed, reason why there is a need for an additional chiller and boiler. The chiller can be based on a vapour compression cycle with a power between 180 and 190 kW and the boiler with a power of 190 kW.

It is necessary to compare the benefits of the CHP to be installed with conventional systems for the same purpose, heating and cooling. So, for a conventional system, the choice for the cooling demand was on a chiller based on a vapour compression system with a power in the range of 230-240 kW and a COP =2.8; for the total heating demands it was chosen a boiler running with natural gas with a power of 300 kW and an efficiency of 0.9. In order to make a correct comparison between the two situations the energy, MWh, was converted in TOEs as shown in Tables 1 and 2.

Taking into account Tables 1 and 2, the primary energy savings (PES) is obtained by the following equation:

Table 4 Annual revenues of produced heat

UH (kWh)	236007
η_b	90 %
LHV_{NG} [kWh/m^3]	10,54
Boiler consumption [m^3]	24879
Selling price of natural gas [€/m^3]	0.5
Annual revenue	12440 €

Table 5 Annual revenues of produced cooling

	Annual energy consumed and associated costs		
	Peak hours	Off peak hours	Empty
Total [kWh]	9928	37328	11803
Price [€(kWh)$^{-1}$]	0.114	0.0765	0.05
Partial [€]	1132	2856	590
Annual revenue = 4577 €			

$$\text{PES [TOE]} = (W_e + UH + NC) - F_{CG} = 57 \text{ TOE/year} \quad (8)$$

Once calculated the PES value it is possible to evaluate the avoided CO_2 emissions to the environment. By the same Decree Laws, the CO_2 emissions per kgOE are equal to 0.0012 tonnes of CO_2 equivalent (TOE)/kgOE. So the avoided emissions (AE) are:

$$AE = 68 \text{ TOE } CO_2/\text{year}$$

It is noticeable that this facility is friendly to the environment because that are saved emissions into the environment in the order of 68 tons of CO_2 compared to conventional systems.

To evaluate the economic analysis according to the equations shown in section 3, it was taken in account all the necessary parameters involved. Table 3 displays the results obtained.

To carry out the final economic analysis, it is necessary to know the annual revenues and expenses of the CHCP.

Annual revenues

The annual revenues are due to the electricity produced and sold to the public network. The useful heat and cooling are achieved savings, considered in the study as equivalent revenues. As said, the selling price of electricity to the public network is substantially lower in off-peak hours and super empty hours, and are a function of several parameters as already shown. Besides, from Monday to Friday the electric tariff is the same, being different on Saturdays and Sundays. Also they differ from summer and winter time. So, taking in account all the electric tariffs the SP_m per year is:

$$SP_m = 65120 \text{ €/year}$$

Table 6 Costs of natural gas

Energy consumed (FC) [kWh]	1265820
LHV_{NG} [kWh/m^3]	10,54
Natural gas consumed [m^3]	120097
Selling price of natural gas [€m^{-3}]	0.289
Annual expenses [€]	34708 €

To assess the annual price of useful heat in cogeneration system, it will be compared with the same energy produced in a conventional boiler with an efficiency of η_b = 90 %. The annual consumption of natural gas of the boiler is:

$$Consumption\ of\ natural\ gas\ \left(m^3\right) = \frac{\frac{UH[kWh]}{\eta_b}}{LHV_{NG}\left[\frac{kWh}{m^3}\right]} \tag{9}$$

Where LHV_{NG} is the Lower heating value of the natural gas.

The annual revenue is displayed in Table 4.

To evaluate the annual price of useful cooling of the CHCP, the cooling needs were compared to the ones obtained with an electric chiller with a COP of 2.8. The results are shown in Table 5.

Total expenses

The total expenses are due the cost of natural gas consumption for the CHP system and the costs of installation maintenance.

Regarding the cost of natural gas for the CHP, the tariff was published by the Regulatory Authority for Energy Services by Dispatch no. 4/2008, [7], which use different formulas before obtaining the final value. However traders apply the rate 0.289 €/m^3, which will be applied in this study. Table 6 shows the estimated annual expenditures associated to cost of natural gas in the studied installation.

The costs associated to the CHP maintenance is the product of the maintenance factor (0.013 € (kWh^{-1}) of electricity produced), times the electricity produced, E, which results in an annual cost of 5647 €.

So, the annual balance is the difference between the total revenues and total expenses:

Annual balance = 41782 €

The total initial investment of the CHP is 150000 € and the payback period is:

$$Payback = \frac{Initial\ Investment}{Annual\ Revenues} = \frac{150000}{41782} = 3.6\ years$$

For the evaluation of the NPV it was considered a discount rate of 8 % and the NPV was calculated over a period of 10 years.

Over ten years, the NPV is 236870 €. It must be noticed that the lifetime of the engine is higher.

Conclusions

The aim of this study is to analyse the technical and economic potential of a real situation in a small hotel located in a city of Portugal. Instead of using only a CHP, the generated heat was also used for cooling – CHCP.

The study is very attractive to the tertiary sector, housing and services, with the implementation of cogeneration/trigeneration having as primary fuel natural gas.

The equivalent electrical efficiency, make it immediately delete cogeneration systems that might not be the most advised individually.

Cogeneration is mandatory for large buildings (floor area greater than 10000m^2), however, as shown by this study, the implementation of these systems can be very useful in smaller sized buildings using also trigeneration (5942m^2, in this case).

It was achieved a primary energy savings in the order of 57 TOE per year, and the associated reduction of emissions of greenhouse gas effect in the order of 68 tonnes of CO_2 equivalent, compared with conventional power generation systems.

The result of the economic balance is also very attractive because beyond having a short payback time, around 3.6 years, brings significant savings (net present value), in the first 10 years of operation in relation to the conventional system.

It was shown that when a cogeneration system is well designed, is advisable to be implemented it in small towns, neighborhoods in cities and factories. The technology is the same.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

The contributions of the authors were mainly to prove in a real situation, that the trigeneration technology is critical for the rational use of energy and to reduce the CO_2 emissions to the environment. It has also proven that this technology is economically advantageous for companies that use it, and can be implemented in city neighborhoods. Both authors read and approved the final manuscript.

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