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Technical-economic evaluation of a cogeneration technology considering carbon emission savings

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ABSTRACT

The support of combined heat and power production systems has gained policy attention, because these are often considered to be less polluting and more efficient than conventional energy conversion systems. As a consequence, the potential market for these energy systems that contribute to reduce greenhouse gas emissions and to enhance energy security on a national level, is shifting from large-scale existing units to small and micro-size emerging technologies.

This paper presents a numerical model based on a cost-benefit analysis used to design an optimal cogeneration system for a small-scale building application, considering the Portuguese context and the comparison with the harmonized efficiency reference values for the separate production of electricity and useful heat. The model includes the identification of the objective function terms (i.e., the elements involved in the financial analysis across the system lifetime and the economic evaluation of costs) and benefits of the combined heat and power production system. The economic viability of cogeneration systems significantly depends on system technology, client energy requirements and support schemes implemented in the respective countries.

A strategic approach is necessary to adequately embed the new technology as a feasible solution in terms of investment and operational costs. Only by matching the energy supply to the needs and expectations of the energy users, it will be possible to improve the market competitiveness of these alternative power production plants. The optimal solution disclosed a positive annual worth, which is higher if the carbon emission savings are monetized. In addition, the optimal system represents a more efficient way to produce useful heat and electricity (i.e. a positive primary energy saving) and to reduce gas emissions. A cost-benefit analysis can be applied for the techno-economic evaluation of a *CHP* system by assessing the monetary socio-environmental costs and benefits of a capital investment over its useful lifetime.

Keywords:

Techno-economic Evaluation;
CHP Power Plants;
Carbon Emission Savings.

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1. Introduction

Combined Heat and Power (*CHP*) or cogeneration is well known as a thermodynamically efficient way of energy conversion. All thermal power stations produce heat during electricity generation, which is, in conventional separate systems, released and lost into the environment. This waste of energy in the separate production of electricity can be avoided by using cogeneration systems where most of this thermal energy is recovered as useful heat for a nearby client [1]. Thus, cogeneration brings several advantages, such as, high overall efficiency in the energy conversion process, reduction of fuel consumption by 20-30% and environmental benefits (Fig. 1).

Cogeneration was firstly implemented in large scale installations (>1 MW_e), nowadays in some countries it

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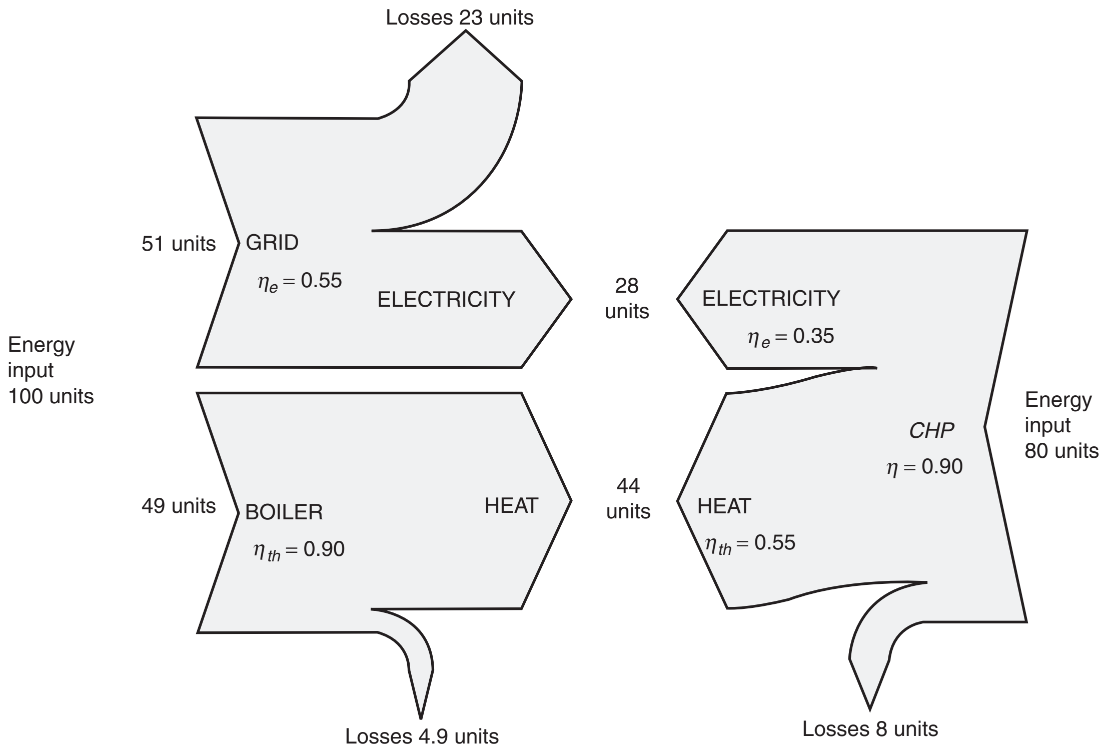


Figure 1: Schematic representation of conventional power production versus *CHP*.

already represents more than 40% of the total electricity produced. Nevertheless, a large potential still exists for small-scale applications in the medium-size building sector and for micro-scale applications in individual dwellings. Building applications include: hospitals, institutional and office buildings, hotels, and single or multi-family residential buildings. For these buildings, the cogeneration systems have to satisfy both electrical and thermal demands [2]. In the last years, distributed power systems have gained some relevance, mainly due to the liberalization of the electricity market and environmental benefits [3–5]. The competitiveness of these systems has gained a greater expression with the recent policies, which largely promote efficiency improvements, the sustainable development of the energy sector and the capacity of matching electrical and thermal load profiles. The European Directive 2004/8/EC [6] defines "small-scale cogeneration" as those units with an installed capacity bellow 1 MW_e and "micro-cogeneration" as those with a maximum capacity bellow 50 kW_e.

This directive aims at the promotion of high-efficiency systems led by useful heat demand and defines the Primary Energy Savings (PES). PES is the index through which the power plant is classified. For large- and small-scale systems, a PES of at least 10% is required, so that the system can be classified as high-efficiency and thus entitled for the legal support schemes. In the case of micro-scale systems, only a positive value of PES is required.

The European Energy Performance of Buildings Directive (EPBD) obliges all member states to ensure that (for new buildings with a floor area over 1 000 m^2) the economic feasibility of alternative systems, such as, decentralized energy supply systems based on *CHP* or renewable energy, is considered at the building design stage [7]. The Directive also outlines that the net grid energy requirements for all the new buildings should be near to zero by 2020.

Nowadays, the reduction of greenhouse gas (GHG) emissions is one of the highest concerns in Europe and cogeneration produce heat and power in such a way that, as less primary energy is required, therefore a reduction of GHGs emissions is also achieved. In 2010, the Portuguese Decree-Law 23/2010 [8] finally established the guidelines for high-efficiency cogeneration based on useful heat demand, which is considered a priority due to its potential primary energy savings and consequently reducing CO_2 emissions. This Decree-Law also established the remuneration scheme for the cogenerated electricity. Besides PES, another parameter commonly used to analyse the energy and environmental benefits from using cogeneration systems, is the equivalent CO_2 avoided emissions. However, for its calculation, the adopted mix of energy for that region/country must be considered [9, 10].

Most European member states created support schemes based on electricity Feed-In-Tariffs (FIT). These grid-selling tariffs are usually fixed throughout the day, and typically represent a premium comparatively to the buying-back prices. So, all the electricity produced can be sold to the national network, although the thermal energy produced should not exceed the required demand.

In the Portuguese scenario, the government has been promoting energy efficiency policies. The cogeneration has been benefiting from this political orientation, namely via feed-in-tariffs, and presently represents approximately 13% of the total National electricity production. According to the Portuguese Energy Services Regulatory Authority (ERSE) [11], between January 2008 and May 2011, the average FIT was 108 €/MWh$_e$ for large-scale *CHP* systems. Nevertheless, the FIT is monthly calculated via a rather complex formula that involves, among other factors, fluctuations of the oil market prices. The FIT for these large systems varies depending on the hour of the day, but is always higher than the buy-back electricity price. A recent law [12] guarantees a fixed FIT at any time of the day or night, for micro-cogeneration systems with a grid power connection not exceeding 3.7 kW$_e$ in the case of single dwellings, or 11 kW$_e$ in case of apartment blocks. For renewable micro- cogeneration systems (e.g. using biogas), the FIT is 280 €/MWh$_e$ during the first 8 years after commissioning, followed by 168 €/MWh$_e$ from years 9 to 15. In the specific case of non-renewable cogeneration, the corresponding FITs are 160 and 96 €/MWh$_e$ (or market value if above). Considering the Portuguese scenario, it is expected that this fixed hourly FITs will be soon extended to small-scale cogeneration systems up to 250 kW$_e$.

The current national energy scenario is characterized by a strong external dependency, with an energy sector heavily dependent on fossil fuels (e.g. fuel oil, natural gas and coal) as primary energy sources. In addition, a growth of the energy usage occurred until 2006, although Portugal has a lower level of electricity consumption per capita when compared with the EU's average [13]. However, the power consumer needs suffered an increase in recent years, mainly in the building sector. These two aspects lead to a growing dependence on foreign energy sources. In 2007, according to Eurostat, Portugal was one of the European Union (EU) countries with the highest energy dependence, importing in that year 82% of the total primary energy consumed, when compared to the EU-27 average (of about 53%) [14]. Energy demand has been increasing slightly faster than the rate of economic growth, and consequently the energy intensity is 4% higher than it was in 1991, being 10% above the EU 15-average. Thus, the Portuguese energy scenario is characterized by a huge import of primary fossil sources, which justifies the high energy dependence. In fact, the energy costs of imported fuel has been suffering a significant growth, and together with the external factors, notably those which cause variations of exchange rates in the international markets as well as the energy price variations, lead to the research and development of cleaner and more efficient alternatives of energy production.

Portugal has significantly shifted its electricity production system by introducing natural gas power plants, some new hydroelectric power plants and a huge investment in wind energy. Electricity production from natural gas has increased from zero to near 12.3 TWh between 1996 and 2006. The total installed capacity of production from all types of renewable energy sources has doubled from 1995 to 2009 and has reached 9.2 GW in March 2010. Plus, in 2020, it is expected that renewable electricity will represent almost 60% of the total electricity generation [15].

The use of renewable sources, as well as the rational use of energy has become an important objective of many countries. They represent a sustainable approach to energy production, by helping to ensure the security of energy supply and contribute to the accomplishment of the Kyoto Protocol objectives. The appropriate policies and regulations on the rational use of energy are, therefore, very important to achieve a sustainable development [16].

Considering the potential of cogeneration technology in producing energy through an efficient way and with environmental benefits, several studies and theoretical approaches for their techno-economic optimisation have been developed. Some of these approaches include a few key concepts of thermo-economics, such as, sizing constraints through component costing equations and the identification of thermodynamic variables (e.g. power, mass rate, heat rate, enthalpy, entropy, heat loss, efficiency, heat exchanger effectiveness) [5].

Some authors established that the introduction of *CHP* systems in the building sector requires the development of compact, cost efficient and systems of easy installation. In fact, it is believed that only with the development of more energy-efficient systems, which are able to reduce life-cycle costs, primary energy savings and CO_2 emissions, it will be possible to increase their market competitiveness [17]. Lazzareto and Toffolo [18] developed a study with the objective of identifying the best option to optimize thermal systems, where single- or multi-objective optimization approaches were discussed. The study was performed using evolutionary algorithms to optimize the design parameters of a *CHP* plant, and by defining an assessment model based on energy, economic and environmental issues. De Paepe et al. [19] compared different commercially available cogeneration systems and concluded that the system cost is the main obstacle against the introduction of these plants in the residential sector. Pilavachi et al. [20] defend that the development, construction and operation of small and micro-*CHP* systems must be evaluated according to economic, social and environmental aspects in an integrated way and that evaluation results should be compared by means of the sustainability scores. Alanne et al. [17] presented a techno-economic strategy to evaluate the performance of different configurations for a Stirling engine residential micro-cogeneration system in order to minimize the annual thermal losses of the system. In the evaluation procedure, the variables considered were the annual costs, primary energy use and CO_2 emissions. In their study, the economic viability of the system is based on the capacity to recover the capital investment cost by the annual savings during a certain period of time (i.e. payback period). Pehnt [21, 22] studied the environmental impacts of distributed energy systems for micro scale applications. In his research, the potential of different cogeneration systems was investigated by evaluating their impacts throughout a life-cycle assessment. The author concluded that the performance of micro cogeneration with respect to environmental concerns depends mainly on the overall conversion efficiency and the type of energy sources that the *CHP* plants work with.

The main objective of this paper is the development of a numerical optimization model for a cogeneration system based on a micro-gas turbine. This technology was chosen because it is one of the most mature and has a high potential for cogeneration applications [23, 24]. The thermodynamic cycle of Micro-gas is more complex than with conventional large-scale simple-cycle gas turbines. The low pressure-ratio compressor (typical of these machines due to cost reasons), implicates the inclusion of an internal regenerator to reduce fuel consumption (thereby substantially increasing efficiency), although it introduces internal pressure losses that moderately lower efficiency and specific power. The thermal energy contained in the exhaust gas improves system economics heat can be recovered and used to, for instance, water or space heating, which represents an economic gain. These power plants with internal regeneration can achieve 30% of electrical efficiency and the overall efficiency is in the range of 75–85% (based on Low Heating Value – *LHV*).

The numerical model should be able to get the optimal values for different physical variables (e.g., compressor pressure ratio, turbine inlet temperature, pre-heater effectiveness) providing the best economic output. A set of cost equations were defined for each system component, in order to compose the economic model. The thermo-economic model was based on a cost-benefit analysis, which is established on the economic balance between the incomes and the costs from the system operation. In the paper, two case studies are presented in order to understand the weight of the carbon emission savings and if its monetization is a relevant income in the thermal-economic model.

The next section of this paper presents the description of the cogeneration system that was optimized. Then, the third section describes the formulation of the mathematical model, including the definition of the objective function, decision variables, constraints and the optimization method. The two last sections correspond to the results and discussion and the main conclusions of the paper, respectively.

2. CHP plant descritption

The problem presented in this study aims to optimize and size a small-scale cogeneration system by producing electrical power, and simultaneously be able to fulfil both the heating and the domestic hot water needs, for a building of residential apartments. For this scale of application, the system must operate, approximately, 4000 h which corresponds to a heat output of 125 kW. The building consists of a 52 individual dwellings with an individual floor area of 150 m^2 (or 7800 m^2 in total). The annual thermal power duration curve of the building was calculated according to the Portuguese regulation for the thermal behaviour of buildings (RCCTE, Decree Law 78/2006) [25], by summing the hourly heating load and the hourly hot water needs. The domestic hot water needs calculations were performed considering an occupation of 4 people per dwelling with a daily domestic hot water consumption of 40 L per person, at a temperature of 60 °C. The building hourly heating loads were calculated considering a class B minus building and local climate (i.e. north of Portugal).

This study is based on a small-scale cogeneration system designed under the *Joule-Brayton* cycle. Fig. 2 illustrates the layout of a micro turbine based *CHP* system. The turbo machinery and the electric generator are connected to a common shaft rotating at high speed. An inverter decouples the high frequency of the produced current from that of the grid, thus enabling variable speed operation. For so small applications with a low-pressure compressor, gas turbines require an Internal air Pre-Heater (IPH) or regenerator, to provide a satisfactory electrical efficiency. The thermal energy of the Exhaust Gases (EG) is recovered as useful heat for heating water.

Atmospheric air is compressed (C) and fed to the IPH before entering the Combustion Chamber (CC) where it is mixed with Natural Gas (NG).

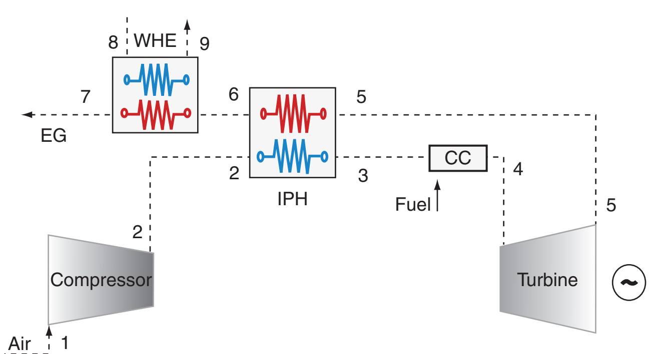


Figure 2: Schematic representation of the micro gas turbine *CHP* system.

The high temperature combustion gases expand in the Turbine (T). The EG, leaving the turbine, are firstly used in the IPH to pre-heat the incoming compressed air and subsequently for the production of hot water in the external heat recovery system, before exiting to the atmosphere. The latter is a Water Heat Exchanger (WHE), where a fixed flow rate of water is heated from 313 K to 353 K.

3. Development of techno-economic optimization model

A fundamental basis for an economic assessment of a *CHP* system is a complete methodology that takes into account all relevant decision variables. When assessing the potential of a *CHP* system, it should be noted that both economic-environmental costs and benefits affect the decision-making process. Therefore, the implementation of *CHP* systems requires a cost-benefit analysis, which includes: investment, operation, maintenance and environment costs. The evaluation of the economic feasibility of a *CHP* system can be processed in three main steps: (1) assessment of the technical data, (2) costing methodology, and (3) evaluating the economic viability of the *CHP* residential system. The information on the economic costs and the environmental benefits shall lead to a decision concerning the economic viability. Cost estimation has to be made considering the investment associated with the installation of the *CHP* system. The cost methodology allows the user to define the costs in a transparent manner, so that options can be validated and compared in an equitable manner. Firstly, there is the need to gather and validate the cost data. For this, one can collect cost data from literature, technology suppliers and consultants. Secondly, the cost components have to be defined and allocated into: investment cost, operation and maintenance costs, revenues and avoided costs. Finally, it is necessary to use some parameters (e.g. exchange rates, inflation, and discount and interest rates) in order to enable a fair comparison of different *CHP* residential systems. These data are used to estimate whether the annual worth (*AW*) of the investment is positive or negative. A positive *AW* indicates that investment in the *CHP* system is, actually, cost effective.

Thus, the maximization of the *AW* was defined as a nonlinear objective function with nonlinear constrains.

Most of those constraints account for the physical and thermodynamic limitations of system operation. Six decision variables were selected for the optimization algorithm, which was solved in MatLab® environment.

In this section, the mathematical formulation of the optimization model is presented, as well as, the numerical solution adopted. The model is further described in [26].

3.1. Mathematical model formulation

The optimization model comprises the definition of the objective function, the constraints and the decision variables. In this study, the objective function was defined as the maximization of the *AW* of the system operation, as expressed by Eq. (1):

$$Max \quad AW_{CHP} \Leftrightarrow$$

$$Max \quad (R_{sell} + C_{avoided} + R_{CO_2} + R_{res} - C_{inv} - C_{fuel} - C_{maintenance}) \tag{1}$$

The *AW* value results from the balance between the revenues and the costs from the *CHP* system operation. In terms of revenues, one of the main advantages of *CHP* systems is the possibility of selling the energy to the power distribution network, which is appropriate to the "producer-consumer" profile. In this study, it is considered that the client sells all the produced electricity (E_{prod}) to the grid, being the income (R_{sell}) from selling power to the net grid by the *CHP* system, expressed in Eq. (2):

$$R_{sell} = E_{prod} \cdot p_e \tag{2}$$

where p_e represents the electricity price. Accordingly to the current legal framework in Portugal, the selling price of electricity to the grid (i.e. FIT) of the micro-cogeneration energy systems (with the exception of biomass cogeneration systems) is equal to the purchase prices of the tariff applicable to the consumer.

When the combined production, by the *CHP* system, is compared with the conventional power generation, it is clear that a full separate system (typically a boiler) to produce heat is not required. In fact, one of the most important economic benefits of micro-*CHP* systems, over conventional ones, is related to their capacity to use the waste heat from electrical power generation. Therefore, the avoided cost ($C_{avoided}$) to produce the same useful thermal energy by the *CHP* system (Q_{CHP}), to fulfil thermal needs of the building (space heating or hot water), can be considered as an economic advantage in the model, as expressed by Eq. (3):

$$C_{avoided} = p_{fuel} \cdot \left(\frac{Q_{CHP}}{\eta_b} \right) \tag{3}$$

where p_{fuel} represents the fuel price for the boiler operation and η_b is the efficiency of reference for conventional boilers.

The residual value of the equipment at the end of its useful lifetime (R_{res}) should be considered as revenue. From the economic point of view, the residual value of equipment is usually estimated as a percentage (ψ) of the initial system investment cost, as in Eq. (4).

$$R_{res} = \psi \cdot C_{inv} \tag{4}$$

As an environmental benefit, the monetization of the carbon emission savings from the *CHP* unit was considered. The quantification of avoided carbon emissions was calculated by Eq. (5), assuming a constant price (p_{CO_2}) per ton of CO_2 that is saved [27]:

$$R_{CO_2} = p_{CO_2} \cdot FE_{CO_2} \cdot t \cdot E_{prod} \tag{5}$$

The reference values and CO_2 emission factors depend on the technology used to produce electricity and heat. So, considering that the NG is the fuel used to run the *CHP* system, and according to data from DGEG, the NG emission factor (FE_{CO_2}) was assumed as 64.1 gCO_2/GJ, during the micro-*CHP* system working period (t).

In terms of costs, the following elements may be considered: the purchase cost of each component of micro-*CHP* system, which corresponds to the annualized investment costs (C_{inv}) that should include the acquisition and installation of the cogeneration system; and the total operational costs (C_{op}) resulting from the sum of the maintenance costs ($C_{maintenance}$) and the fuel costs for the micro-*CHP* unit operation (C_{fuel}).

The annual system investment cost is calculated according to the annualized capital cost. Annualizing the initial investment cost corresponds to the spreading of the initial cost across the lifetime of a system, while accounting for the time value of the money. The initial capital cost is annualized as if it was being paid off a loan at a particular interest of discount rate over the lifetime of the option. The Capital Recovery Factor (*CRF*) is used to determine the equal amounts of *n* cash transactions for an investment and can be expressed as in Eq. (6):

$$CRF = (P \rightarrow A, i_e, n) = \frac{i_e(1+i_e)^n}{(1+i_e)^n - 1} \tag{6}$$

where *A* is the annuity (a series of equal amount cash transactions); *P* is the present value of the initial cost; i_e is the effective rate of return, and *n* is the number of years of the lifetime operation. For thermal-economic optimization, the effective rate of return can be approximated as: nominal rate of return (i.e. interest rate), minus inflation rate, plus owners' risk factor and a correction for the method of compounding. Thus, the C_{inv} can be calculated according to Eq. (7):

$$C_{inv} = \sum_i C_i \cdot CRF \tag{7}$$

where C_i is the purchase cost of each component of the *CHP* system. The mathematical expression that defines the cost of each *CHP* component $C_i \rightarrow (C_c;\ C_{cc};\ C_T;\ C_{IPH};\ C_{WH})$ accounts for the physical parameters, which are based on works from literature [28, 29], adjusted for small-scale units and real data from micro-turbines available in the market (Capstone® 65). The physical model that calculates the thermodynamic relationships is fully described in [26]. This model allows the calculation of the temperatures evolution, the mass flow rates, the heat transfer areas and all parameters needed to build the numerical model that describes the power plant operation. C_{fuel} is calculated through the cumulative fuel consumption during the micro-*CHP* system working period, considering the fuel price per energy unit and the fuel mass flow rate ($\dot{m}_{fuel}$), usually *LHV* basis. The C_{fuel} can be expressed by the Eq. (8):

$$C_{fuel} = p_{fuel}\ \dot{m}_{fuel}\ LHV\ t \tag{8}$$

The maintenance costs are usually defined as a percentage (φ) of the initial investment as in Eq. (9):

$$C_{maintenance} = \varphi \cdot C_{inv} \tag{9}$$

The appropriated optimization models, in this type of application, are very complex and therefore, some assumptions have to be made for the success of the computational modelling:

I. The heat provided by the cogeneration plant should never exceed the user demand;
II. The thermal efficiency of the boiler should be considered equal to the reference value of the conventional boilers ($\eta_B = 90\%$) [7];
III. The plant should operate in steady state, according to the thermal load profile of the user;
IV. A period of 15 years is reasonable for the plant lifetime;
V. The maintenance costs are assumed as a fraction of the annualized investment cost ($\varphi = 0.15$), roughly equivalent to 6 €/MWh_e [26];
VI. The residual value of the power plant, at the end of its useful lifetime, was assumed as ($\psi = 0.10$) of the annualized investment cost of the cogeneration plant [29];

3.2. Decision variables

Six physical parameters were selected as decision variables of the optimization model: the compressor pressure ratio (r_C); the isentropic efficiency of the air compressor (η_C); the isentropic efficiency of the gas turbine (η_T); the air temperature at the internal pre-heater (T_3); the temperature of the combustion gases at the turbine inlet (T_4) and the electrical production ($\dot{W}$). The simulation was performed considering upper and lower bounds for the decision variables as Eq. (10) to (15):

$$3.0 \le r_C \le 6.0 \tag{10}$$

$$0.70 \le \eta_C \le 0.90 \tag{11}$$

$$0.70 \le \eta_T \le 0.90 \tag{12}$$

$$500 \le T_3 \le 1000 \tag{13}$$

$$1000 \le T_4 \le 1400 \tag{14}$$

$$90 \le \dot{W} \le 120 \tag{15}$$

The limits for the electrical production variable were based on the actual heat-to-power ratio (λ) that defines the relationship between the amount of useful heat (considered to be a fixed value in this study) and the electricity produced by the *CHP* system. Typically, the heat-to-power ratio of micro-gas turbines is approximately 1.25.

3.3. Constraints

Seventeen inequality constraints were formulated in order to give physical significance to the mathematical model. These constraints bound the variables within feasible limits of the system operation. For instance: the inlet temperature of the air (T_1) is lower than the air temperature at IHP inlet (T_2); the turbine inlet temperature (T_4) is the highest temperature reached in the system; the high-pressure air is pre-heated upstream the CC, and hence, it is required that the temperatures (T_2) and (T_3) are lower than that of the exhaust gases (T_5).

The difference between the inlet and outlet temperatures in each heat exchanger flow should be limited to ensure the effectiveness heat transfer process between the fluids. In order to allow an effective heat transfer in the IPH and in the WHE, lower and upper limits were defined to guarantee a temperature differential between the two streams. Moreover, it is also important to make sure that the exit gas temperature (T_7) is above 363 K, in order to prevent condensation in the heat recuperating system.

Besides the constraints related to the evolution of the temperature in the system, PES was also included in the model as the eighteenth inequality constraint in order to guarantee that the system may be classified as high-efficient *CHP* power plant. Thus, PES allows to estimate the total primary energy savings that are possible to achieve by a cogeneration unit (considering the combined electric and thermal efficiencies) when compared with the conventional power production process [3]. The amount of primary energy provided by cogeneration production (in percentage) is calculated according to the Eq. (16):

$$PES = \left(1 - \frac{1}{\dfrac{\eta_{th_{CHP}}}{\eta_{th_{ref}}} + \dfrac{\eta_{e_{CHP}}}{\eta_{e_{ref}}}} \right) \cdot 100 \qquad (16)$$

where $\eta_{th_{CHP}}$ is the cogeneration heat efficiency, defined as the annual useful heat output divided by the fuel energy input. The terms $\eta_{th_{ref}}$ and $\eta_{e_{ref}}$ are the efficiency reference values for the separate production of heat and electricity, respectively. Finally, $\eta_{e_{CHP}}$ is the electrical efficiency of the cogeneration production defined as annual electricity from cogeneration divided by the fuel input used to produce the sum of useful heat output and electricity from cogeneration power plant.

3.4. Numerical solution

The problem is solved with resource to the Pattern Search (PS) algorithm, a search method without the need of analytic derivatives. Generalized Pattern Search (GPS) algorithms are derivative free methods for the minimization of smooth functions [31]. At each step the algorithm generates a set of points, called mesh. The mesh is generated by creating a set of vectors based on the pattern (P_k), multiplying each i^{th} direction vector (P_k^i) by a scalar that corresponds to the mesh size, Δ_k. The pattern vector that defines a *mesh* point is considered its direction. The algorithm polls the points in the current mesh by computing their objective function. If the algorithm fails to find a point that improves the objective function, the poll is called unsuccessful, remaining the current point as the best for the next iteration. After polling, the algorithm changes the value of the mesh size, expanding or contracting its size. The mesh expansion depends on the polling step. Chosen the initial point (x_k), a trial step is defined considering at iteration k the convergence tolerance (ξ), the length of search step and the initial direction.

Considering that the poll option controls how the algorithm "vote" the mesh points at each iteration, the simulation was carried out considering the complete poll "on" in order to choose the point with the best objective function value by checking all the points in the mesh at each iteration. The poll method chosen was the GPS Positive Basis 2N algorithm and the search method was defined as the Nelder-Mead. The maximum number of function evaluations was defined as 20 000.

A feasible initial point is required to start the iteration process, in this study the initial approximations for the six decision variables were: $r_C = 4.0$, $\eta_T = \eta_C = 0.85$, $T_3 = 850$ K, $\dot{W} = 100$ kW$_e$ and $T_4 = 1\,200$ K.

4. Results and discussion

The results of the optimal solution are presented in this section. A base case scenario was simulated considering the natural gas with a *LHV* of 47 100 kJ/kg and a price of 10 €/GJ, an electricity FIT of 0.12 €/kWh, and a price of 24 €/ton for the CO_2.

In order to evaluate the economic benefit from including the carbon emissions in the optimization model, two case scenarios were studied with the corresponding results presented in Table 1. Case 1 corresponds to the optimal annual costs and benefits considering the carbon emission savings, while Case 2 corresponds to the optimal solution when the bonus from carbons emissions is not considered in the calculations.

Table 1: Optimal annual costs and incomes of the *CHP* system for the two tested cases.

Annual costs and revenues (€/year)	Case 1	Case 2
Capital Investment Cost, C_{inv}	(14 770)	(12 187)
Total operational costs C_{op}	(47 998)	(39 488)
Revenue from equipment residual value, R_{res}	1 477	1 219
Revenue from selling Electricity to Grid, R_{sell}	53 568	42 902
Income from Carbon Emission Savings, R_{CO_2}	7 043	–
Avoided cost of separate heat generation, $C_{avoided}$	20 000	20 000
Annual Worth of *CHP* System	19 321	12 445

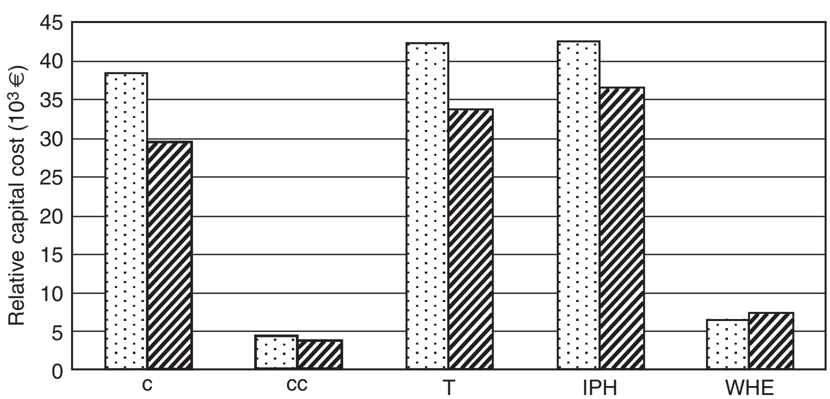
According to Table 1, it is possible to obtain a positive profit for both tested cases. It is observed that the maximum annual worth is relatively higher if the income from carbon emission is considered (a significant increase of 55.2%). For both cases, the predominant costs are operational, where the main contribution comes from the fuel costs.

In terms of income, the revenue from selling electricity to the grid largely depends on the amount of electricity (sixth decision variable) that the system will produce. The more expensive system of Case 1 is able to produce more electricity due to a better electrical efficiency. This result is also influenced by the relatively high FIT. The avoided cost to produce heat (20 000 €) is constant and equal for both cases, once it is assumed that the system is able to deliver a fixed amount of heat flux, 125 kW_{th} and that it operates 4 000 hours per year.

The estimated cost of each plant component for both tested cases is presented in Fig. 3.

For obvious reasons, manufacturers do not reveal detailed cost information for separate components of their currently available micro-turbines. However, it is predictable that the IPH, the compressor and the turbine will be the most expensive components of the power unit. Results show that IPH and turbine are the costlier components, representing 31.7% and 31.5%, of the total *CHP* unit cost. Comparatively, the Case 2 scenario represents a lower-priced solution in terms of equipment purchase costs.

The competitiveness of this technology is mainly due to their investment cost, which for micro turbine-based



	c	cc	T	IPH	WHE
Case 1	38.328	4.4718	42.367	42.665	6.691
Case 2	29.605	3.7716	33.698	36.652	7.274

Figure 3: Optimal Capital cost for each *CHP* system component.

CHP applications is estimated to vary within the range of 1 000 to 1 700 €/kW$_e$ [24]. The optimization model disclosed, for each case scenario, an investment cost of 1 205 €/kW$_e$ (Case 1) and 1 242 €/kW$_e$ (Case 2).

Table 2 shows the optimal values for the six decision variables. The results for the decision variables corresponded to similar power plants, meaning that there is no significant difference for the optimal values of the decision variables. The main difference lies on the size of the micro gas turbine, larger in Case 1, in order to deliver a higher electrical power (higher mass-flow of air - affecting the size of all components - and comparatively larger regenerator with higher T_3 and lower T_6). For instance, in Case 1, the results show a compressor pressure ratio of r_C = 5.74 and a Turbine Inlet Temperature of T_4 = 1 385 K. These two decision variables, together with the regenerator effectiveness, are the most important parameters in micro gas turbines cycles. Both results are higher than the values for the models currently available in the market (an r_C of 4 and a T_4 of approximately 1 200 K). A possible explanation for this difference is the use of low cost materials in the equipment manufacturing, which imposes some boundaries to these operational variables.

The compressor and turbine isentropric efficiencies (~84.0% and 86.9%, respectively) seem to be within the expected values for this kind of systems. According to the results for the optimal solution, the resulting *CHP* system is able to produce about 111.6 kW of electrical power. Considering the electricity production output, the optimal system has a heat-to-power ratio of λ = 1.12.

In Table 3, the results of efficiencies and the performance criteria for the optimized solution are revealed. Considering the results for the various operational variables, an electrical efficiency of 35.1% was obtained that is slightly higher than the current values observed with the real micro-gas turbines (25–31%). The total efficiency of 74.4% is a reasonable value for the use of micro turbines on cogeneration applications. The performance of a cogeneration system can be evaluated by comparison with the separate production of heat and electricity. In this study, PES and CES were calculated considering the guidelines that established harmonized efficiency reference values for separate production in application of Directive 2004/8/EC.

Table 2: Results for the decision variables of the small *CHP* system.

Decision Variables	Case 1	Case 2
r_c	5.743	5.630
η_c (%)	83.99	83.44
η_T (%)	86.92	86.67
T_3 (K)	982.2	976.6
T_4 (K)	1385.0	1381.8
$\dot{W}$(kWe)	111.6	89.4

Table 3: Efficiencies and performance results.

Efficiencies & Performance Criteria for Case 1 (%)	
Electrical efficiency, η_{el}	35.1
Total efficiency, η_{total}	74.4
Primary Energy Savings, *PES*	13.7
Carbon Emission Savings, *CES*	28.7

The calculations included the correction factors regarding the average local climate and the avoided grid losses. The optimal configuration allows a PES of 13.7%.

Considering that the cogeneration reduces the amount of primary energy used to produce the same energy output (when compared with the conventional production), carbon emissions are saved and its quantification represents an environmental and economic benefit. Also, it is possible to avoid ~29% of carbon emissions. Thus, this result confirms that the cogeneration plants are systems that improve the efficiency in the energy production and that bring noteworthy environmental benefits.

Figure 4 presents the trends of carbon emission savings as a function of heat-to-power ratio and electrical efficiency.

The carbon emission savings were calculated for different values of electric efficiency for the typical range of micro-gas turbines: 26%, 28%, 30% and 32%.

Results show that carbon emission savings are higher for turbines with higher heat-to-power ratios. Also, the carbon emission savings increase for systems with higher electrical efficiencies. Trends in CO_2 emissions from fuel combustion illustrate the need for a more sustainable energy paradigm. It seems that the use of more efficient energy conversion systems, such as cogeneration power plants, contributes for a more sustainable energy production scenario.

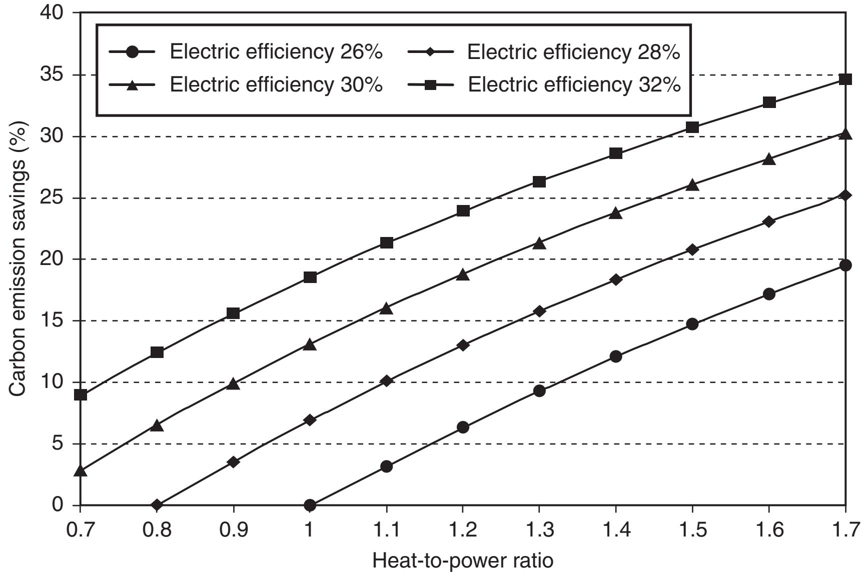


Figure 4: Carbon emission savings versus heat-to-power ratio.

5. Conclusions

A nonlinear constrained optimisation model was applied to simulate a small-scale cogeneration system based on micro-gas turbine technology, for a building application. It was numerically solved using a derivative free optimisation method. The results exposed the technical configuration that leads to the best economic output in terms of the maximized annual profit, including or excluding carbon emission savings. For both cases, the optimal solution disclosed a positive annual worth, being higher if the carbon emission savings are monetized. The case study proves that the cogeneration system represents a more efficient way to produce heat and power (positive PES) and allows a way to recover the investment costs by selling electricity to the grid. The results also prove that if the environmental benefits from using *CHP* technologies are accounted economically, this type of technologies will become more attractive as an effective alternative for energy supply. Obviously, the results of the optimal solution are deeply related to the constants assumed in the model, namely, the fuel price and the electricity FIT. Also, the optimal solution is strongly correlated with the components performance/cost equations included in the model.

From a techno-operational perspective, the optimisation criteria include fuel savings, CO_2 emissions, and monetization of the energy surplus. All of these criteria can be applied to assess how well the system promotes the rational use of energy. In conclusion, this study showed that the use of optimisation models is an effective tool to perform a technical-economic evaluation of the cogeneration plant.

The economic viability of *CHP* mainly depends on the monetary operational savings to recover the investment costs, but it is evident that a more comprehensive assessment is required. Therefore, a cost-benefit analysis can be used for the economic evaluation of *CHP* systems by also including the assessment of the monetary socio-environmental costs and benefits of a capital investment over its useful lifetime. The principles of a cost-benefit analysis have to incorporate externalities into the mathematical model, i.e., the social and environmental impacts, as well as economic costs and benefits. In this way, cost-benefit analysis can be used to estimate the social welfare effects of an investment. Considering the climate characteristics in Portugal, the viability of this energy power plants in small-scale applications is justified by the specificity of the Portuguese energy policy in this issue, especially the figure of producer–consumer created by the Decree-Law 68/2002, the relative huge Portuguese market potential for cogeneration of <150 kW_e in size; and the cogeneration European Directive 2004/8/EC that promotes the high efficiency cogeneration development. Plus, *CHP* market competitiveness depends on interest taxes in the economical evaluation and sensibility analysis of the payback period, fuel price and FIT.

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