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# Techno-Economic Assessment of Micro-CHP Systems

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**Abstract**

Developing efficient energy generation technologies has become essential due to scarcity and high prices of fossil fuels and environmental concerns. The purpose of the present study is to develop a conceptual model based on a cost-benefit analysis applied to a cogeneration system for a micro-scale application, considering the Portuguese framework. The economic viability assessment of a micro-CHP system is of utmost importance in the decision making process when considering a new investment. The micro-CHP systems offers some benefits that underlie their economic viability: the capacity of producing heat and power at consumption place; allows the reduction of transmission and distribution losses; maximizes the utilization of primary energy by reducing waste heat; and finally offers significant contribution to pollutant emissions reduction. The development of optimization models has proven to be a valuable tool for the design and techno-economic assessment of micro-CHP systems.

**Keywords**: Micro-CHP system; Optimization; Economic viability.

## 1 Introduction

Combined Heat and Power (CHP) is a well-known technique for producing heat and power simultaneously onsite from a single primary energy source. The changes occurred in the energy sector during the last decade, particularly concerning to the increase of electricity consumption in the building sector, have led to several innovations and the research focused on high efficiency technologies. These high efficiency decentralized plants have been applied to small and micro-scale level applications (residential and commercial services) where the cogeneration systems can supply both power and thermal needs of the buildings (Jackson, 2007; Cardona et al., 2006; Alanne et al., 2010). Additionally, its potential is well recognized in terms of energy saving when comparing them with the separate production.

This process triggered new challenges for the development of new strategies towards the diffusion of new energy systems, regulatory measures, incentives related with the power production from renewable sources and the promotion of more sustainable environmental-friendly energy generation solutions.

Performance assessment is an approach to the evaluation of the viability of micro-cogeneration systems in comparison with alternative options for residential energy supply. Several approaches have been conducted in order to study the thermo-economic performance of a number of technologies in this field. Some authors established that the introduction of CHP system in the residential sector requires the development of compact, cost efficient and easily installed systems. 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 is possible to increase its market competitiveness (Alanne et al. 2010).

Lazzareto & Toffolo (2004) developed a study with the objective to identify the best option to optimize thermal systems where single- or multi-objective optimization approaches are discussed. The study was performed using evolutionary algorithms to optimize the design parameters of a CHP plant defining an assessment model based on energy, economic and environment issues. De Paepe et al. (2006) compared different commercial available residential CHP systems and concluded that the system cost is the main obstacle against the introduction of cogeneration systems in the residential sector.

Pilavachi et al. (2006) 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 the results of the evaluation should be compared by means of the sustainability scores. Huangfu et al. (2007) present a study in which an evaluation and analysis of a micro-scale combined cooling, heating and power system were performed. The economic efficiency of the system is discussed in terms of different criteria: payback period, initial costs, annual savings, annual profits, operating cost, interest rate calculation, time of payment and net present value. Alanne et al. (2010) presents a techno-economic strategy to evaluate the performance of different configurations of a Stirling engine-based residential micro-cogeneration system. The study was performed modelling and simulating the micro-cogeneration system in the IDA-ICE (Indoor Climate and Energy) building simulation program to identify the system configuration, in order to minimize the annual thermal losses. In the evaluation procedure, the variables considered were the annual costs, primary energy use and $CO_2$ emissions. In this study, the economic viability of the system is based on the capacity to recover the capital investment costs by the annual savings during a certain period of time. Shaneb, Coates & Taylor (2011) developed a deterministic linear programming model to minimize the annual costs of the system considering the systems sizing. The investigation was conducted considering the most used technologies for this kind of application: the internal combustion engine, the Stirling engine and the fuel cells. The authors concluded that the electricity and heat demands are essential inputs for any sizing model and that different technologies lead to different sizes. The consideration of environmental costs/concerns in the design of energy conversion plants aims to achieve the maximum efficiency at minimum cost and with the minimum environmental impact. The process of quantifying the impacts (direct and indirect) on the environment is extremely complex and not always easy to accomplish.

Gullí (2006) presented a social cost-benefit analysis of small CHP distributed generation system. The analysis is based on the determination of internal (calculation of optimal electricity and fuel prices) and the external costs by applying the *ExternE* methodology. The *ExternE* methodology includes the weighting of the external impacts using quantitative procedures in order to transform these impacts into monetary units. The author developed a comparison between the centralized and the decentralized energy supply concluding that the implementation of these decentralized power production systems in residential sector still does not represent a competitive solution. Pehnt (2008) studied the environmental impacts of distributed energy systems for micro scale applications. On his research, the potential of different cogeneration systems was investigated by evaluating their impacts through a Life Cycle Assessment (LCA). 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 purpose of the present study is to develop a conceptual model based on a cost-benefit analysis applied to a cogeneration system for a micro-scale application, considering the Portuguese framework. The model should include the identification of the objective function and the terms involved in the financial analysis across the lifetime of the system as well as the economic evaluation of costs and benefits from this combined heat and power production. The motivation for this research was the necessity to develop a tool able to determine the economic viability of a micro-CHP system. This tool presents a decision making process based on accurate data to assess the real economic costs of a particular cogeneration system. In this paper, a methodology is presented to evaluate the economic sustainability of a CHP system.

# 2 Background for Micro-CHP Portuguese Scenario

The current national energy scenario is characterized by a strong external dependency, with an energy sector heavily dependent on fossil fuels (fuel oil, natural gas and coal) as primary energy sources. In addition, a growth of the energy demand is verified although Portugal has one of the EU's lowest electricity consumption levels per capita (DGEG, 2012). However, the electricity consumption greatly increased in recent years, mainly in the building sector. In fact, the Portuguese economy is dominated by the services sector (63%). Therefore, the Portuguese government has been implementing and promoting energy efficiency policies, most of them based on subsidized schemes for renewable energies. Cogeneration has benefited from this political push and it contributes with more than 12% of total national electricity production. In 2002, the Decree-Law 68/2002 allowing the power production in low tension: at least 50% of the produced electric energy must be self-consumed and the maximum power that can be delivered to the power utility is 150 $kW_e$. So, the fact that consumers can reach incomes from selling electricity to the national grid opened a good opportunity for the application of cogeneration to micro-scale.

The European Directive 2004/8/EC states the energy efficiency and improves security of supply by creating a framework for promotion and development of high-efficiency cogeneration of heat and power, based on useful heat demand and PES. The Directive distinguishes "small-scale cogeneration" as the units with an installed capacity bellow 1 $MW_e$ and the "micro-cogeneration unit" as the systems with a maximum capacity bellow 50 $kW_e$, and indicates that member states may particularly facilitate these two classes of smaller size systems. This directive, which came into force in 2006, identified the technologies covered by the methodology for calculating the electricity from cogeneration and a methodology for determining the efficiency of cogeneration process. According to the Directive 2004/8/EC, cogeneration systems for micro-scale applications can be classified as high-efficiency cogeneration systems if it provides Primary Energy Savings (PES).

In 2010, the Decree-Law 23/2010 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 thus reducing $CO_2$ emissions. This Decree-Law also established the remuneration scheme for the cogeneration production. Moreover, the Directive 2010/31/EU introduced the philosophy that buildings should become energy producers and outlined a goal for 2020 in which the new building energy requirements should be near to zero. It is expected that the rising costs of fossil resources and the future economic incentives associated with this legislation, will lead to a strong growth of CHP systems in the building sector.

# 3 Micro-CHP Model Development

A number of different conversion technologies have been developed for the application in the residential scale. Some of these technologies are still in the development phase and so the economic viability analysis at mini-and micro-scale level is incipient. In this section, the most common micro-CHP technologies and their performance characteristics (electrical efficiency, heat recovery capacity, gas emissions) will be summarized. Then, the conceptual cost-benefit model applied to a cogeneration system for a micro-scale application will be presented.

## 3.1 Overview on Current Technology

The actual technologies include Internal Combustion (IC) engines, micro-turbines, Fuel Cells, Organic Rankine Cycle (ORC) systems and Stirling engines. IC engines have been successfully commercialized for all sizes including the CHP systems, ranging in size from a few hundred kW to several MW of electrical output. In CHP systems, the engine drives an electric generator and the exhaust heat, as well as the heat from the oil and engine cooling, is recovered using heat exchangers. Micro-turbine systems provide reasonable electrical efficiency of about 30%, have the capacity to work with several fuels and have a great potential for heat recovery. Micro-turbines for cogeneration applications can achieve an overall efficiency above 80%. There are micro-turbine systems in the size range from 25 to 80 kW, a range suitable to meet the thermal and electrical requirements of multi-family residential, commercial or institutional buildings. Fuel Cells technology is an under development technology with a great potential for both electricity and cogeneration applications through the conversion of chemical into electrical energy. The advantages of this technology are related to their low emissions and noise levels, which are particularly suitable for residential and commercial buildings. According to some researchers (Onovwiona & Ugursal, 2006; Alanne et al., 2010) Fuel Cells for cogeneration applications in the range of 1-50 kW present an overall efficiency of about 80% and a reduced environmental impact. A recent technological development is the Organic Rankine units. The most familiar Rankine engine is the steam engine, in which water is boiled by an external heat source, expands and exerts pressure on a piston or turbine rotor, producing useful work. Some of these systems use an organic fluid and operate at temperatures and pressures much closer to conventional heating and refrigeration purposes. The electrical efficiency of the units is around 12-15%, with overall efficiencies up to 80%. The Stirling engines have been developed in recent years as external combustion engines with regeneration suitable for cogeneration applications. They can be operated from a variety of sources: natural gas, biomass, solar energy, geothermal, or waste heat, which represents a great advantage of this technology. Stirling technologies have two principles of operation, the kinematic driven and free-piston that immediately produce electricity. The Stirling engines have an electric efficiency that varies between 10% and 35% and a total efficiency in the range 70–90% (Monteiro el at., 2009). Comparing the technologies, it seems that Stirling engines have a great potential to achieve high overall efficiencies despite the moderate electrical efficiency. The reciprocating engines are the technology with higher maturity, which represents a great advantage with respect to their diffusion in the market. Reciprocating engines theoretically requires more periodic maintenance representing a cost increase when compared with other technologies. Fuel Cells and Rankine engines are still under development with some pilot plants being currently tested. The major potential of these two technologies lies in the highest electrical efficiency and the almost zero pollutant emissions (Pehnt et al., 2006). The comparison of the electrical efficiency (electrical output (kW)/fuel input (kW)), the total efficiency (useful heat (kW) + electrical output (kW) /fuel input (kW)) and the energy sources used for each technology is shown in Table 1.

Table 1: Comparison of different micro cogeneration technologies

| Technology | Electrical Efficiency (%) | Total Efficiency (%) | Energy Source |
|---|---|---|---|
| IC Engine | 20 – 30 | 75 - 85 | Natural Gas, Diesel |
| Micro-Turbines | 26 – 30 | 75 - 80 | Natural Gas, Diesel |
| Fuel Cells | 28 – 30 | 80 - 85 | Hydrogen, hydrocarbon |
| Organic Rankine Engine | 12 - 15 | 70 - 85 | Any type of Fuel |
| Stirling Engine | 10 - 35 | 70 - 90 | Any type of fuel, solar radiation |

Sources: Onovwiona & Ugursal, 2006; Pehnt, 2008; Thomas, 2008

## 3.2 Conceptual and Mathematical Model Formulation

The development of a micro-CHP model aims the construction of an effective way to globally analyse a thermal system from the techno-economical point of view. The micro-CHP system sizing depends on the requirements for the application. This means that the system components have to be sized according to the thermal and power demands of the consumer (Shaneb, Coates & Taylor, 2011). The identification of energy demands has a great importance in the definition of technical characteristics of the CHP unit. The definition of energy consumption profiles is determinant in finding out the appropriate relationship between the power production and its consumption. So, for residential scale applications, it is important to define if the system can satisfy the energy needs of a single and/or multi-family dwelling.

The optimization involves the definition of the objective function, the decision variables and the constraints. The complexity of the thermal systems design results in the definition of non-linear numerical models whose objective function is usually associated with two main purposes:

- Maximization of micro-CHP efficiency by meeting the energy demands;
- Maximization the annual worth of micro-CHP system operation.

Considering these two purposes (the best output in terms of efficiency and the maximization of the annual worth of the system operation), a possible approach is to define an objective function that encompasses both aims, assigning them a weighting parameter, $k_1$ to the efficiency ($\varepsilon_{\mu-CHP}$) and $k_2$ to the Annual Worth ($AW_{\mu-CHP}$). The objective function can be expressed by Equation (1),

$$Max \quad k_1 \cdot \varepsilon_{\mu-CHP} + k_2 \cdot AW_{\mu-CHP} \tag{1}$$

where $k_1$ and $k_2$ varies between 0 and 1, according to the value assigned to each objective function terms.

The thermal power ($Q_{\mu-CHP}$) and the electrical power ($W_{\mu-CHP}$) are usually defined as decision variables of the optimization model as well as other thermodynamic variables, which are specific to each type of technology. The optimization mathematical model should include physical and economic constraints: the decision variables should be bounded and the thermodynamic relationships can be translated as equality and/or inequality constraints. As the objective is to optimize a high-efficiency micro-cogeneration system, the primary energy saving should be a problem constrain.

The $AW_{\mu-CHP}$ results from the balance between the Revenues (*R*) and the Costs (*C*) from the micro-CHP system operation accordingly to Equation (2),

$$AW_{\mu-CHP} = \sum \mathrm{Re}venues - \sum Costs \tag{2}$$

In terms of revenues, one of the most advantages of micro-CHP systems is the possibility of selling the surplus energy to the power distribution network due to the "producer-consumer" profile contemplated by the legal framework. The income ($R_{sell}$) from selling power to the net grid represents the power produced by the CHP system ($E_{prod}$) multiplied by the selling price ($p_{sell}$). This relation is expressed by the Equation (3).

$$R_{sell} = E_{prod}\, p_{sell} \tag{3}$$

Under the current legal framework in Portugal, the selling price of electricity to the grid 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. This means that the owner of the CHP system can choose whether to sell all the power produced to the network.

When the combined production by the micro-CHP systems is compared with the conventional power generation, it is clear that a full separate system (typically a boiler) to produce heat it 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 (Lazzaretto & Toffolo, 2004). Thus, as an economic advantage, it can be considered in the model the avoided cost ($C_{avoided}$) to produce the same useful thermal energy by the CHP system (HCHP) to fulfil thermal needs of the building (space heating or hot water) as expressed by Equation (4),

$$C_{avoided} = \left( p_{fuel} \left( H_{CHP} / \eta_{boiler} \right) \right) \tag{4}$$

where $p_{fuel}$ represents the fuel price for the boiler operation and $\eta_{boiler}$ is the efficiency of reference for conventional boilers, usually considered equal to 90%.

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 of the initial investment cost in the system. Therefore, the revenues in the financial analysis can be expressed as Equation (5):

$$\sum \text{Re}\,venues = R_{sell} + C_{avoided} + R_{res} \tag{5}$$

In terms of costs, the following parcels may be considered: the purchase cost of each component of micro-CHP system, which corresponds to the investment costs ($C_{inv}$) which should include the acquisition and installation of the equipment; the fuel costs for the micro-CHP unit operation ($C_{fuel}$); the costs with power imported from the grid for the CHP system starting ($C_{egrid}$); the costs for the acquisition of a backup boiler ($C_{bb}$) when the system is not able to fulfil the thermal needs. The maintenance costs ($C_{op}$) should also be included in the cost accounting. The value of maintenance costs, usually a cost per unit of power produced depends on the type of technology. Thus, the cogeneration costs may be defined as Equation (6):

$$\sum Costs = C_{inv} + C_{fuel} + C_{egrid} + C_{bb} + C_{op} \tag{6}$$

The critical step in the financial cost analysis is the simulation of optimal prices of electricity and fuel taking into account that the energy demands varies significantly over the time, and so, it is important to perform a sensitivity analysis of the feed-in-tariffs, gas and electricity prices. The micro-CHP economic lifetime for this application field should be assessed carefully. According to Pehnt (2008), the economic evaluation of micro-CHP systems should be performed for a period between 15 and 20 years.

In addition to this operational analysis, it is important to consider some aspects that differentiate the cogeneration systems from the centralized energy production and which can be relevant in cost-benefit analysis. Cogeneration systems reduce the imports of the fossil resources due to more efficient fuel conversion, which represents a gain not only for the CHP system owner but also for the economic balance of a given country. Another benefit from using cogeneration plants is the reduction of transmission and distribution losses, which should also be considered in the economic balance.

However, monetized these parameters is a complex but important task. Combining internal and external costs in the development of an economic model provides a total cost evaluation of this decentralized energy systems. Then, the results of this evaluation may be compared with the total costs involved in the centralized energy supply in order to achieve the benefits of decentralised technologies.

# 4 Methodologies for Economic Costs and Benefits Evaluation

The most explicit way to compare costs and benefits in an economic evaluation is monetized both. A fundamental basis for an economic assessment of a CHP system is a complete methodology that takes into account all decision relevant facts (Solino et al., 2009). According to Solino et al. (2009), when examining a CHP system for potential application, it should be noted that both economic and environmental costs and benefits affect the decision-making process. Therefore, the implementation of CHP systems requires cost-benefit analysis including investment, operation, maintenance and environment costs that have intrinsic relation to the Environmental Performance Evaluation (EPE). In this section, the methodology proposed for the economic assessment of a CHP residential system is presented.

## 4.1 Cost-Benefit Analysis

The CHP system variables monitoring are the basis for the environmental and economic assessment, mainly for the cost-benefit studies developed. The external costs are based on the quantification of the resources consumption and pollution emission, particularly $CO_2$, before and after CHP system implementation. Environmental benefit calculus considers the avoided emissions or reduction of resource consumption. Especially for energy intense consumption (decrease), the cost of the energy avoided (conversion technologies) is firstly quantified. Secondly, the emission factor is used to evaluate the benefit according to the type of energy employed.

The evaluation of the economic feasibility of a CHP residential system could include three main steps: (1) assessment of environmental effects, (2) costing methodology, (3) evaluating the economic viability of the CHP residential system. The information on the economic costs involved and environmental benefit should lead to a decision concerning the economic viability (EUROPEAN COMMISSION, 2006).

*1) Assessment of Environmental Effects*

The impact assessment determines which alternative offers the greatest level of protection of the environment as a whole. The initial step of the process is to identify the scope and the alternatives that are available and could be implemented, followed by the formulation of the inventory of emissions (releases of pollutants, consumption of raw materials, energy consumption and waste) for each CHP system in consideration.

The emission inventory enables the calculation of environmental effects. This step allows the user to express the potential environmental effects (grouped into 7 topics: human toxicity ($NO_x$, $SO_x$ emissions), global warming ($CO_2$, $CH_4$ emissions), aquatic toxicity, acidification (presence of $NO_x$, $NH_3$, and $SO_x$), eutrophication, ozone depletion, potential for photochemical ozone creation) provided for each of the pollutants, so that a wide range of pollutants can be directly compared or aggregated and expressed as an overall effect. The most common environment effects identified for the CHP residential system and analysed in this project are: reduction in consumption and emission of pollutant gas emissions, the reduction in energy and water consumption. In the specific case of this study, as it is intended to optimize a micro-CHP system based on Stirling engine with a renewable energy source, a solar collector, the challenge is apportioning costs (money) to the avoided emissions when compare to centralized energy production. Emissions from current Stirling engine burners can be ten times lower than those of internal combustion (IC) engines based on Otto or Diesel cycles without catalytic converters (Aliabadi, 2009). So, a possible approach is to determine the Cost Effectiveness (CE) of the annual reduction of emissions by the micro-CHP system by attributing a monetary value on this reduction. This could be a path to monetize an environmental benefit from the use of micro-CHP systems.

*2) Costing Methodology*

Estimation has to be made of the cost drives of the investment associated with the implementation of a particular 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 such as 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 candidate CHP residential system is cost effective (EUROPEAN COMMISSION, 2006).

*3) Evaluating the economic viability of the CHP residential system*

This step addresses ways to express the cost-effectiveness and how the environmental benefits can be valued. This is useful because it allows the economic cost to be balanced against the benefit that a CHP residential system offers to the environment, and it can also help to clarify whether or not the execution of a technique is cost-effective in terms of environmental benefits.

The external impacts can be divided into costs (negative externalities) and benefits (positive externalities) depending on the impacts being negative and positive, respectively (Solino, 2004). The incorporation of environmental externalities into the assessment of CHP residential systems offers the advantage of expressing all costs and benefits (whether private or external) into a common measuring unit (i.e. monetary value), and thus provides a single measure of the attractiveness of an alternative option.

For a better understanding of the external costs related to the CHP residential system analysed, a division into five main groups was carried out, through research and collection in the literature of the main environmental and social impacts of the CHP systems. The (number) groups of externalities are classified as follows: air, water, soil, natural resources and social impacts.

## 4.2 Sustainability of Micro-CHP Systems

The performance of micro CHP technologies with respect to environmental aspects depends mainly on the total conversion efficiency that can be accomplished. The introduction of these systems in the residential sector intended the replacement of gas-condensing boilers as their competing heat-supply technology. The actual challenge is to make those technologies more competitive. The emission-reduction and potential of micro-CHP could partially be offset by a "rebound effect", implying that energy savings achieved by a more efficient technology are compensated, by an increase in energy demand. This depends, among other aspects, on the degree to which micro-CHP possession is perceived as ecologically relevant, and on an understanding of its effects. Micro-CHP systems have mainly relied on natural gas, although other fossil fuels, and in a limited extent, renewable energy carriers, can be used in most technologies. One of the most important questions that arise nowadays is if most micro-CHP systems, which operate on fossil sources, may compete with renewable energy supply systems, for example, solar collectors or biomass boilers. Although micro-CHP and solar collectors require different integration in the respective building, for a new building that can be equipped with a micro CHP plant, this could improve the competitiveness for developing renewable-fuel-based technologies for operating micro CHP systems, particularly Stirling engines (Chicco & Mancarella, 2009).

Therefore several important advantages with regard to key sustainability criteria can be summarized: micro CHP reduces greenhouse gas emissions and resource consumption compared to average energy supply and even compared to efficient and state-of-the art separate production of electricity in power plants and heat in condensing boilers; micro-CHP systems are part of the transformation process for power generation, since the use of micro CHP allows more flexibility solutions when compared to centralized power production; micro CHP plants can have positive effects on the supply security of electricity grids, particularly where heat storage facilities exists and an integration with smart grids is possible; and finally, micro-CHP reduces the external energy dependency through cuts in fossil fuel imports (Pehnt, 2008).

# 5 Discussion

The implementation of a CHP residential system can contribute significantly to the reduction of environmental problems. Yet, it requires additional expenses (namely, in terms of investment costs and operation and maintenance costs), while providing environmental and, in many cases, also economic benefits.

The technical and economic challenges in the development of thermal plants are significantly higher for micro-CHP than for larger scale systems, because the costs per unit of power tend to rise exponentially as size reduces. On the one hand, the economic viability of the micro-CHP systems is associated with the capacity of design systems at a cost that can be recovered from the savings and incomes during its useful lifetime. The financial analysis depends on both the capital investment and the value of electricity produced by the unit, which represents the most valuable income from the systems operation. For any given system, the payback relies on the unit's operating hours and consequently the total electricity produced annually. Clearly, it is not only the system purchase costs that are important to calculate. The installation and the frequency of the maintenance service over the system-working lifetime have to be quantified. In fact, the capital cost of micro-CHP units is an essential parameter and fluctuates according to the system sizing.

The economic viability of micro CHP mainly depends on achieving savings to recover the investment costs, but it is evident that a more comprehensive assessment is required. Therefore, a cost-benefit analysis can be applied for the economic evaluation of micro-CHP systems by assessing 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.

Some costs are easy to value such as the capital, operating and fuel costs of the CHP unit; however, other costs are more difficult to achieve. The value attached to the visual impacts or the noise levels can be considered "priceless". Costs are also subject to change over time – imposition of different interest rates, political changes, fluctuations of fuel and electricity tariffs – requiring a sensibility analysis of the payback period to the fuel price and feed-in-tariffs.

The so-called high-efficient power plants, such as the cogeneration systems, generate a positive environmental externality given the decrease of air pollutants emissions. Pollutant emissions are difficult to account for the evaluation of the environmental externalities. Usually, the evaluation of this environmental benefit is made by two factors: the reduction of total consumption of primary energy and the reduction in $CO_2$ emissions.

# 6 Concluding Remarks

Summarizing, and besides the cash flow analysis, it is important to note that the micro-CHP systems offers some benefits that underlie their economic viability: the capacity of producing heat and power at consumption place; the reduction of transmission and distribution losses; maximizes the utilization of primary energy by reducing waste heat; and finally offers significant contribution to pollutant emissions reduction. Concerning to the Portuguese scenario, the development and optimization models for micro-CHP systems may be justified by a few reasons: (1) the specificity of Portuguese policies for the energy field thought the definition of producer-consumer profile allowing each consumer to sell electricity to the grid; (2) the potential of the building sector for cogeneration systems due to the increase of energy needs; (3) the increase of the search for high-efficient energy solutions.

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