PEM fuel cell for cooperating households: a convenient combined heat and power solution for residential applications

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Abstract

In this paper we compare the technical and economical performances of a high temperature proton exchange membrane fuel cell with those of an internal combustion engine, for a 10 kW combined heat and power residential application. In a view of social innovation, this solution will create new partnerships of co-operating families aiming to reduce the energy consumption and costs.

The energy system is simulated through a lumped model. We compare, in the Italian context, the total daily operating cost and energy savings of each system with respect to the separate purchase of electricity from the grid and production of the thermal energy through a standard boiler. The analysis is carried out with the energy systems operating with both the standard thermal tracking and an optimized management. The latter is retrieved through an optimization methodology based on the graph theory. We show that the internal combustion engine is much more affected by the choice of the operating strategy with respect to the fuel cell, in terms long term profitability. Then we conduct a net present value analysis with the aim of evidencing the convenience of using a high temperature proton exchange membrane fuel cell for cogeneration in residential applications.

Keywords: Combined Heat and Power, Cogeneration, Control strategy optimization, Investment analysis, Fuel Cell, Energy efficiency, Social innovation

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1. Introduction

Cogeneration, referred also as Combined Heat and Power (CHP), is the simultaneous production of electricity and thermal energy from a single energy input such as oil, coal, natural or liquefied gas, biomass or solar energy [36]. The concept of cogeneration, that dates back in the 1880s for steam engine applications [52], has recently attracted an increasing attention due to oil shortage, environmental concerns, and geopolitical issues [10]. In addition, CHP plants are usually placed close to the final energy user thus minimizing electricity transmission and distribution losses [46]. On the other hand, the large initial investment required for CHP plants may hinder a large scale diffusion of cogeneration [16]. Thus a thorough economical evaluation of CHP solutions is needed to identify new feasible applications of CHP.

Buildings share slightly about 40% of the final energy consumption in Europe [55]. In the USA the situation is similar and buildings energy consumption in 2010 accounted for 41% of primary energy consumption [2]. Moreover, this consumption is expected to grow in the next years all over the world [38]. Therefore, boosting the energy efficiency in the residential sector, is crucial to diminish the final energy consumption and consequently the environmental pollutants. In fact, the European Union (EU) stimulates its members to promote the development of CHP systems, that are characterized by high efficiency and low environmental impact [19].

Fuel Cells (FC) are addressed as one of the most promising technologies for power and thermal generation in residential buildings [8], due to their high efficiency [50], excellent partial load operation [9], limited pollutant emissions, low levels of noise [27], and reduced maintenance costs [34]. In the last two decades, different fuel cell technologies have been developed and some have entered the market of distributed CHP systems. Most of the installations worldwide are micro-CHP systems with a nominal power lower than 10 kW. Asia dominates this fuel cell market with about 60% of the installations, thanks to the financial support of the public institutions. In fact, more than 90,000 installations have been made in Japan up to 2013 (about 50000 in the only 2012). North America, with a market share of 37%, represents the second market for micro-CHP based on FC. Also South Korea is supporting a large demonstration program and represents one of the most promising fuel cell markets, with a significant expertise in manufacturing different kind of fuel cells. In Europe the installations are slightly less than 1000, mainly under the Callux residential field trials in Germany, the FC-District Project operating in Spain, Greece and Poland, and other small-scale trials around Europe. However, the International Energy Agency (IEA) foresees a production volume above 70000 units per year in 2020 [28, 30, 32, 37]. Also in the US, the stationary fuel cells market is growing very rapidly, with more than 300 installations in the sole California, where the Self-Generation Incentive Program (SGIP) has generated 317 fuel cell projects at various stages of development, for a total installed capacity of 131 MW [59]. Almost one third of these installations are CHP systems. 74% of these projects use natural gas, accounting for 66% of the total capacity, and 25% use biogas, including digester and landfill gas. Considering all the energy systems installed in California, fuel cells mainly compete with internal combustion engines and microturbines in terms of capacity ranges, and represent today almost the 20% of all the installations since 2001 [59].

The attributes such as low weight, quick response in power output and low design challenges and the results achieved, in terms of efficiency, reliability and durability, across a wide range of applications, including automotive, CHP systems, distributed back-up power and micro-applications in portable devices, have made PEM the only mature technology for commercialization below 100 kW of nominal power. As a matter of fact, at the end of 2012, PEM-FC represented almost the 88% of the total fuel cell market. SOFCs are still in a pre-commercial stage, with only few demonstration units available [29]. High Temperature PEM fuel cells (HT PEM-FC) are a new emerging technology for polymeric cells, that are characterized by an operating temperature up to 200°C, and can tolerate a CO concentration of 4% in the fuel, thus reducing the complexity of the fuel processing units [67].

Three types of micro-CHP systems for residential use are compared in [16], concluding that fuel cell does not represent a good solution by an economic perspective, because of the high initial investments and low returns. However, this analysis that dates back ten years ago is based on the hypothesis that most of the generated electrical power is sold to the national grid. On the other hand, recent studies (see for example [58]) evidenced that, despite the high initial cost, fuel cell systems can be recognized as a good option for residential micro-CHP.

In this paper, we evaluate and compare the technical and economical performances of an ICE and an HT PEM-FC for a residential CHP application with different operating strategies. We select an energy demand representative of a group of three families and we evaluate the Net Present Value (NPV) of both cogenerative plants to identify the most appropriate technology [57]. The NPV analysis is performed by comparing the costs for the energy supply of these two plants with respect to the separate production of electricity and heat, under the current Italian energy market conditions. In the separate production, that is the reference scenario in this case study, electricity is acquired from the national grid, and thermal energy is produced using a state of the art natural gas fuel boiler.

An effective control strategy is fundamental to exploit all the advantages expected from CHP plants [22, 23, 49], in particular when innovative technologies, such as FC, are involved [9, 21]. Thus, we utilize an optimization algorithm to determine the operating strategy that minimize costs for each plant configuration. This allow us to describe how such fuel cell systems behave in their whole operating range under variable load requests, also in comparison with ICEs. Moreover, the optimized control strategy determines the energy supply costs and energy sales revenues used as the input for the NPV analysis, instead of the usual approach that considers only a single, fixed working condition. Moreover, the effects of the control strategy in terms of energy consumption and costs are dissected comparing the economically optimal set-point management to a standard thermal tracking management.

The paper is organized as follows: in Section 2 we describe the methodology utilized for the economic analysis. In particular, the methodology for the determination of the daily cost is introduced in Section 2.1, and the investment analysis is described in Section 2.2. In Section 3 we present the case study in terms of energy demand (Section 3.1) and plant configurations (Section 3.2). Results are discussed in Section 4. Finally, conclusions are drawn in Section 5.

2. Methodology

The choice of the proper operating condition of the power plant is fundamental to exploit all the advantages related to cogeneration, as the plant performances are strongly influenced by the effective working conditions of its subsystems [3, 9, 23, 33, 49]. As a consequence, the NPV analysis should rely on a proper forecast of the CHP control strategy that, in turn, determines the cash flow of the system.

2.1. Optimal plant control strategy

The optimal management strategy for CHP applications is influenced by several parameters, such as, energy costs and demand profiles, environmental conditions, and part load efficiency of the energy converters within the plant [3, 9, 23, 24]. Here, we use the methodology described in [3] and further developed in [24] to obtain the optimal set points for the power plant, that is the control strategy that minimizes the total daily cost. Thus, the objective function to be minimized (G) includes all the costs related to fuel (C_F), maintenance (C_M), and cold start (C_S), as well as the revenues coming from the exchange of electricity with the national grid (R_G) as follows

$$G = \sum_{h=1}^{24} \left[C_M(h) + C_F(h) + C_S(h) - R_G(h) \right] \tag{1}$$

We note that G is evaluated on a daily basis as the sum of hourly costs and revenues. Thereafter, the utilized procedure can account for deferred energy usage through any kind of energy storage system that decouples the production and the demand of energy.

To determine the costs in Eq. (1), it is necessary to model the single components of the plant and their interactions through energy and mass flows. All the devices are treated as black-boxes, i.e. modeled through a transfer function that converts a single energy input in one or more energy carriers [3, 24]. Such transfer functions are the efficiencies of the energy converters as functions of their set-point. The energy flows internal to the plant and from the plant to the energy user represent the constraints that the system must fulfill. A certain state of the system is considered acceptable only if satisfies the energy demand. The major technical limitations to the control strategy, such as the maximum number of cold starts, are considered as further constraints.

It is worth to note that the determination of the optimal control strategy requires the minimization of a non-linear objective function (see. Eq. (1)), since the efficiencies, and, in turn, the fuel costs, are functions of the set-point. The problem is discretized with respect to the plant set-point and to the time, and represented as a weighted and oriented graph. Then, we seek the optimal control strategy as the shortest path across the graph utilizing dynamic programming [15, 24, 65].

The optimization model requires the following inputs: (i) the electric, thermal, and cooling power demand in an hourly basis; (ii) the selling and purchase prices of electricity; (iii) the rated performances and the efficiency curves for all the energy converters; (iv) the unit cost of the energy input of each device; (v) the maintenance and cold start costs, for each component; (vi) the capacity and the efficiency of the heat storage; (vii) the minimum duration of working intervals and the efficiency penalty related to cold start; (viii) the effects of the environmental conditions on the energy converters performance. For more details on the optimization algorithm the reader can refer to [24].

The main outputs of the optimization methodology are the costs ($\bar{C}_j$) and revenues ($\bar{R}_j$) obtained operating the plant according to the optimal control strategy for the generic day j of the year.

2.2. Net Present Value analysis

In this section we describe the NPV methodology used to compare the different plant configurations [64], i.e. the HT PEM-FC, the ICE and the separate energy production. First, we determine the annual costs $\mathcal{C} = \sum_{j=1}^{365} \bar{C}_j$ and revenues $\mathcal{R} = \sum_{j=1}^{365} \bar{R}_j$. Then, the avoided costs ($\Delta\mathcal{C}$) and the additional revenues ($\Delta\mathcal{R}$), with respect to the reference scenario are estimated as:

$$\Delta\mathcal{C} = \mathcal{C} - \mathcal{C}_{\text{ref}} \,, \tag{2a}$$

$$\Delta\mathcal{R} = \mathcal{R} - \mathcal{R}_{\text{ref}} \,, \tag{2b}$$

where $\mathcal{C}_{\text{ref}}$ and $\mathcal{R}_{\text{ref}}$, are the costs and revenues obtained purchasing the electric power from the grid and producing the thermal energy through a standard boiler (i.e. the reference scenario). Finally, the NPV at year y is defined as

$$\text{NPV}(y) = \sum_{t=1}^{y} \left(\frac{\Delta\mathcal{R}_t}{(1+r)^t} - \frac{\Delta\mathcal{C}_t}{(1+r^*)^t} \right) - I_0 \,, \tag{3}$$

where I_0 is the initial investment, r and r^* are the discount rates for the additional revenues and avoided costs respectively, and the summation on the years t is extended over the expected life of the plants. A reasonable lifetime for a small sized commercial ICE is 10 years, and we consider this value as the length of our project and our analyses. Thus $y = [1, 2, ..., 10]$ for this analysis. Additional revenues and avoided costs are discounted at different rates, because they imply different risks. In particular, r represents the cost of capital, while r^* could be either the risk free rate, if I_0 is available, or the cost of debt, if I_0 is borrowed through a loan.

The risk free rate is assumed to be $r^* = 1.26\%$ according to the yield of a 10 years Germany Bund [6, 13]. On the other hand, we assume $r^* = 6.70\%$ as that for those families that borrow the money for I_0, according to the "energy loan" of an Italian bank [4]. The discount rate r for $\Delta\mathcal{R}$, must be calculated as the expected return of an investment of a company of the same sector with the same risk. Thus, we consider the Enel S.p.A, listed in the Italian stock market, as the representative company of the same business in the same country.

According to the capital asset pricing model [43] the cost of capital r is calculated as:

$$r = r_f + \beta_{\text{unl}}\text{ERP} = 5.38\% \,, \tag{4}$$

where $r_f = 1.26\%$ is the risk free rate [6, 13], ERP $= 7.68\%$ is the Equity Risk Premium for the Italian market [13], and β_{unl} represents the corrected unlevered value of the sensitivity of the stock to the market portfolio, defined in Eq. (5).

$$\beta_{\text{unl}} = \frac{\beta}{[1 + (1-\tau)D/E]} = 0.54\% \,. \tag{5}$$

In Eq. (5), $\beta = 1.04$ [63] is the the sensitivity of ENEL S.p.A. to the market portfolio and $\tau = 31\%$ is the Italian tax rate [13]. Equation (5) shows how the financial structure of Enel S.p.A., which is characterized by a net debt of 43.72 billions € and an equity capitalization of 31.96 billions €, affects the risks and the expected return to the investors.

3. Case study

3.1. Energy demand

The summer and winter profiles of electrical, thermal, and chilling energy demand, reported in Fig. 1 and Fig. 2, are representative of a residential energy demand for a developed country [58]. Thermal demand includes domestic hot water and space heating. Thus, the thermal and electrical demands are comparable during summer, while in the winter the thermal demand doubles the electrical one, facilitating the utilization of cogenerated heat. Chilling energy demand is present only in the hot season being required only for air conditioning.

The starting assumptions of this analysis is the collaboration among families to share costs and risks in order to reduce energy consumption and costs, in a view of social innovation. Social innovations are defined as “new ideas, products, processes or services that simultaneously respond to collective needs and at the same time create new social partnerships” [51]. Thus, citizenship involvement is needed to achieve sustainability [40]. In fact, this case study is based on a group of households, i.e. an aggregate of customers also referred as microgrid

[60], that cooperate to deal with the following collective needs: i) reduce energy consumption and environmental pollution; ii) reduce energy costs, and, consequently, guarantee electricity access also to lower income families, that is crucial to bring positive outcomes in terms of health, income and education [44]. The social partnership hypothesized in this paper could represents also a way to enhance the attention towards citizens environmental behavior [5] for a sustainable lifestyle, thanks to the immediate benefits related to costs reduction.

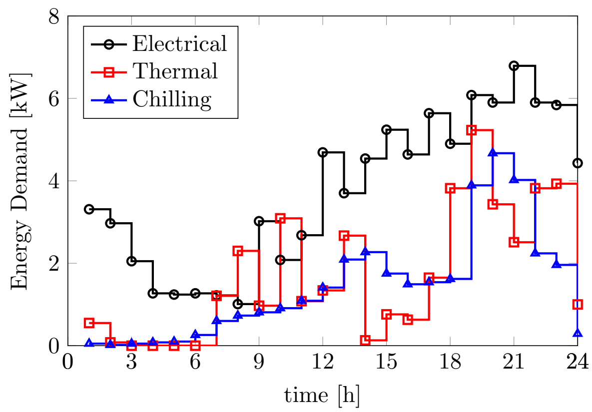


Figure 1: Summer energy demand time series. Data elaborated from [58].

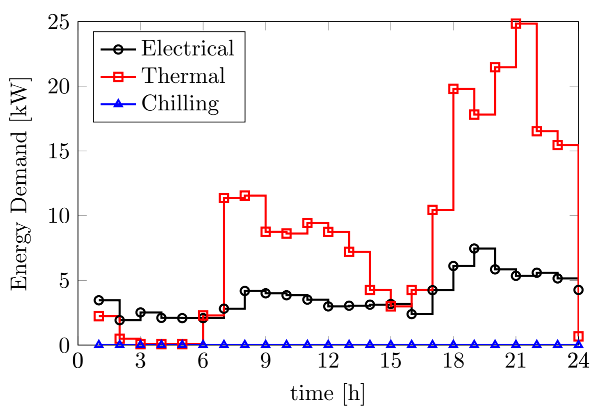


Figure 2: Winter energy demand time series. Data elaborated from [58].

The cost of the electricity bought from the national grid for a small consumer, in the Italian market is in the range of $[220, 223]$ €/MWh after taxes (Fig. 3) and varies only twice per day [1]. Daylight hours have slightly higher costs compared to the night and the off-peak hours. The hourly prices of energy sold

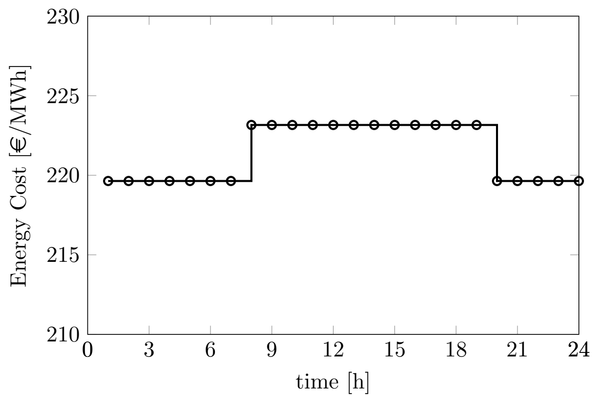


Figure 3: Time series of the unit cost of the electricity purchased from the national grid. Data from [1].

to the grid are retrieved from [31]. Specifically, the prices of six selected days, one per month, per season are averaged to obtain a representative seasonal value (Fig. 4). The peak unit cost of bought electricity is 2.5 times greater than the maximum selling price, and the average buying cost is 3.5 times higher than the average selling price. Comparing Fig. 1 and Fig. 2 with Fig. 4 it is possible to see that the peaks in the energy demand are associated with those of the energy sales prices. In particular prices and demands are locally maximized between 8 and 10 o'clock in the morning and between 18 and 21 o'clock in the evening, and the maximum selling price doubles its minimum value.

On the other hand, bought electricity is more expensive during the central hours of the day (Fig. 3), and the span between maximum and minimum unit cost is 1.5%.

3.2. Plant description

The power plant serving such a residential facility is a complex system made up of different components (i.e. primary movers, boilers, cooling machines) that

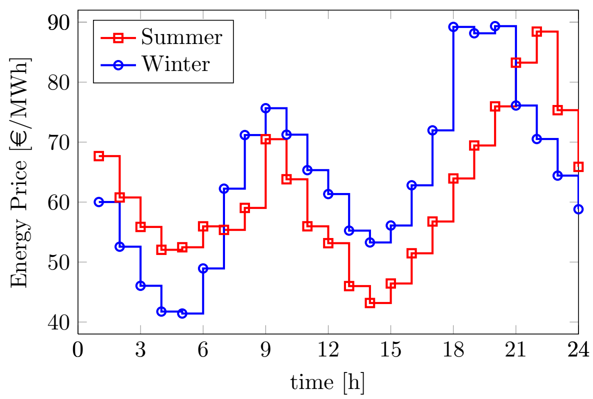


Figure 4: Time series of the unit price of electricity sold to the national grid. Data from [31].

has to satisfy the energy requirements in terms of heat, electricity and cooling. The efficiency of such a power plant is determined by the mutually dependent efficiencies of the single components. Therefore, an evaluation of the potential of fuel cell energy systems for combined heat and power can not ignore the analysis of their behavior in a complete energy system. Thus, the comparison between an HT PEM-FC and an ICE is performed by comparing their behavior within the same power plant. Without loosing generality, the sizing $\mathcal{S}$ of the primary mover analyzed in this case study is based on the peak value of the electricity demand. At 9 pm during summer we register the highest value of electrical request equal to about 7.7 kW. This value is given by the sum of the pure electricity demand, E_l, and the electrical power needed to satisfy the chilling demand, E_c/COP, calculated as follows.

$$\mathcal{S} = \frac{E_l + E_c}{\mathrm{COP}} = 7.7\,\mathrm{kW}\,. \tag{6}$$

It is worth to note that reciprocating internal combustion engine is widely recognized as a leading technology for CHP with capacities ranging from 100 kW to 30 MW, thanks to its high efficiency, reliability and flexibility and to a large diffusion of maintenance infrastructures. In fact, typical applications are of the order of 1 MW and feature multiple 200-500 kW natural gas engine gensets. On the other hand, reciprocating engines of small power, that would fit such a peak electricity demand, are available for applications other than CHP. Given that natural gas engines of such a small power would have a very low efficiency, the comparative analysis is carried out with respect to a 10 kW diesel engine, which is widespread in the market for a nominal power below 30 kW with a relatively high electrical efficiency.

The power plant, schematically depicted in Fig.5, is completed with a 25 kW complementary natural gas boiler, and a 5 kW mechanical chiller, sized on the thermal and cooling peak power demand, respectively. For the fuel cell case, natural gas is the preferred fuel in particular for stationary/decentralized applications, because it is abundant and available. However, it requires a fuel processing system, which becomes particularly critical for PEM-FC, due to the intolerance of the catalysts to carbon monoxide, thus requiring further purification of hydrogen-rich reformate gas obtained by processing available fossil fuels. The plant is grid connected so that the electricity can be acquired or sold to the grid in case of shortage or excess of production. A thermal storage with a maximum capacity of 67.5 kWh and a rated power of 23 kW can cover the peak thermal energy demand for about three hours. The capacity of the thermal storage is selected according to the conclusions in [25]. The charging and discharging efficiencies of the thermal storage are both set to 95% [39].

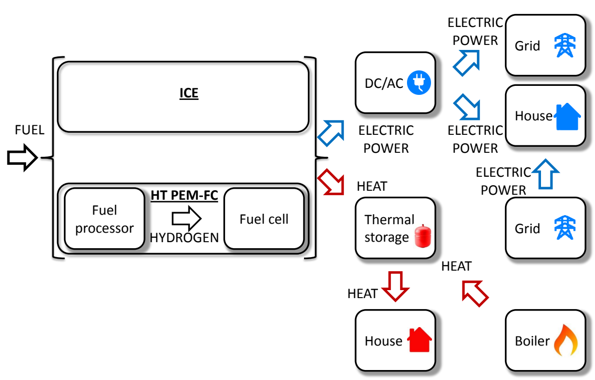


Figure 5: Scheme of a CHP system for residential applications.

The nominal and part load efficiencies of the natural gas boiler are retrieved from [20] and reported in Fig. 6. A Daikin FTXZ50N chiller [12] satisfies the chilling energy demand. The nominal Coefficient Of Performance is COP = 4.47 [12], and its efficiency curve as a function of the effective load is reported in Fig. 7 and is retrieved from [20].

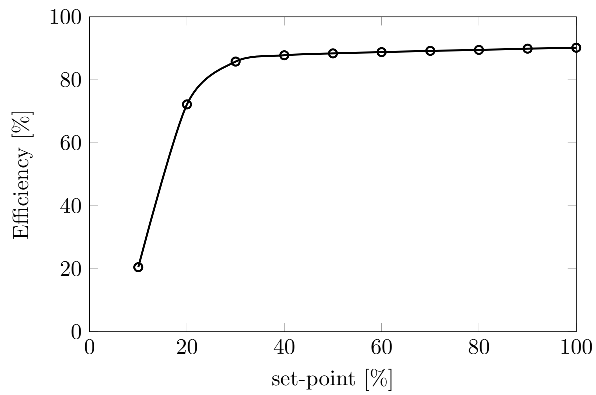


Figure 6: Boiler efficiency as a function of the set-point.

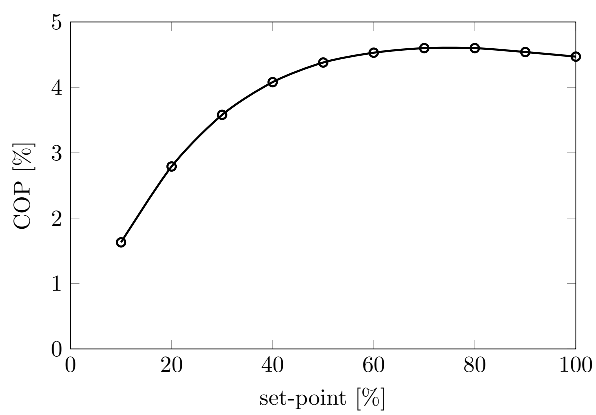


Figure 7: COP of the mechanical chiller as a function of the set-point.

The two different CHP technologies, i.e. an HT PEM-FC based plant and an ICE based plant, are described in the following subsections.

3.2.1. High temperature fuel cell

Domestic CHP needs to be directly connected to the natural gas infrastructure. Therefore, in the fuel cell based plant, natural gas is first converted by a fuel processor (e.g. a reformer with one or more water gas shift reactors) into a hydrogen rich syngas, that, in turn, is oxidized inside the FC producing electricity and thermal energy. Thus, the overall electrical efficiency (η_{el}) of the plant is defined as the product of the efficiencies of the fuel processor (η_{fp}) and of the fuel cell (η_{FC}) as follows:

$$\eta_{el} = \eta_{\mathrm{fp}} \eta_{\mathrm{FC}} \tag{7}$$

The main reforming technologies are based on Partial Oxidation (POX), Steam reforming (SR) and Autothermal Reforming (ATR). From a purely chemical point of view, the highest fuel processing efficiency (i.e. chemical energy output per unit chemical energy input) is obtained with a steam reforming process (around 98%) and decreases for autothermal reforming and partial oxidation (85% and 75% respectively) [17]. On the other hand, POX and ATR have intrinsically faster transient responses. Here we chose a steam reformer with one or more shift reactors to set the CO content below 4%, which is the tolerance limit of HT PEM-FC fuel cells [26].

The operation of a natural gas steam reformer at different set points is studied in [42]. Therein the reformer efficiency is evaluated as a function of the higher heating values of hydrogen (HHV_{H_2}) and of natural gas (HHV_{NG}). The reformer in [42] included also the Preferential Oxidation Reactor (PROX), in order to reduce the CO concentration in the syngas below 10 ppm, which is the tolerance limit of a low temperature PEM fuel cell. According to the gas compositions reported in [42] the CO concentration before the preferential oxidation is 0.9%. Thus PROX is not required for the application in study. The fuel processor efficiency, reported in Fig. 8, is then calculated as,

$$\eta_{\mathrm{fp}} = \eta^{*}_{\mathrm{ref}} \frac{LHV_{H_2}}{LHV_{\mathrm{NG}}} \frac{HHV_{\mathrm{NG}}}{HHV_{H_2}} \frac{1}{\eta_{\mathrm{prox}}} \, , \tag{8}$$

where η^{*}_{ref} is the value of the fuel processor in [42], LHV_{H_2}, and LHV_{NG} are the lower heating values of hydrogen and natural gas, respectively, and the PROX efficiency $\eta_{\text{prox}} = 0.97$ according to [56].

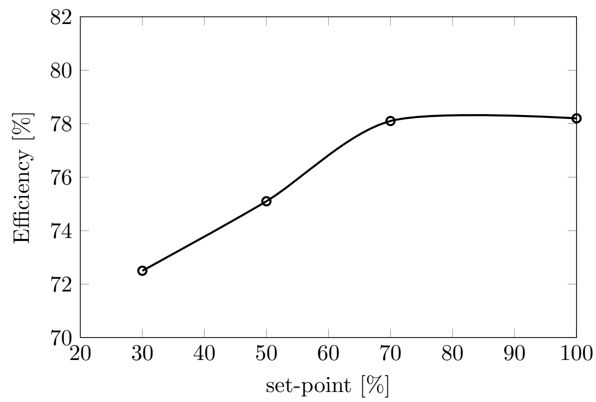


Figure 8: Fuel processor efficiency as a function of the set point.

The electrical efficiency of an HT PEM-FC is measured in [26], for CO concentrations of 0.2% and 2%. Since in the previously mentioned study, η_{prox} refers to a CO concentration equal to 0.9%, we linearly interpolate the data in [26] to obtain the η_{FC} relative to a CO concentration of 0.9%, required in Eq. 7. The overall electrical efficiency of the HT PEM-FC based CHP is reported in Fig. 9.

Thermal efficiency, reported in Fig. 9, is calculated as

$$\eta_{th} = (1 - \eta_{el})\eta_{\text{hr}} \tag{9}$$

where $\eta_{\text{hr}} = 0.8$ is an efficiency term that takes into account the heat losses related to the thermal energy recovery from the fuel cell exhaust gas [47].

The lifetime of fuel cell based CHP is affected by the degradation of the stack [11, 35, 66]. In our analysis the cost for stack substitution is included in the maintenance costs assumed to be equal to 2.43×10^{-2} €/kWh [53].Under this assumption it is reasonable to consider the lifetime of our HT PEM-FC equal to 10 years.

CHP plants based on fuel cells are still on a pre-commercial development status, and only few units are being produced [61]. In this scenario, the initial

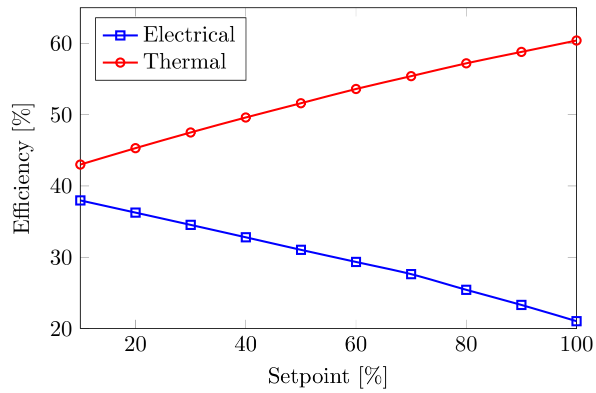


Figure 9: HT PEM-FC electric and thermal efficiencies as a function of the set-point.

investment depends heavily on the number of units produced [62]. As a consequence a precise evaluation of their capital cost is not feasible. In fact, the cost of an FC based cogeneration plant is significantly influenced by both its electrical power (P_e) and by the number of units effectively installed as demonstrated in [41] through a design for manufacturing and assembly methodology. According to their estimations, reported in Table 1, the capital cost of a 10 kW CHP plant based on an HT PEM-FC would be approximately in the range $[1800 - 3000]$ \$/kW. Similarly, according to [61], the cost of a low temperature PEM-FC CHP ranges between 2300 \$/kW and 4000 \$/kW having assumed a production of 50000 units per year. In contrast, a capital cost of 22000 \$/kW for a 0.7 kW HT PEM-FC residential CHP is reported in [14], based on current installed plant and retail prices, and a capital cost equal to 9100 \$/kW for an 25 kW HT PEM -FC plant is assumed in [7].

The cost of natural gas required by the fuel processor is assumed to be 0.5 €/Sm^3, according to actual European prices [18].

3.2.2. Internal combustion engine

The "Lombardini' LDW" Diesel engine, commonly used in generator sets, has been selected as the prime mover for the ICE based CHP. The thermal and electrical efficiencies of the ICE are reported in Fig. 10, [45]. The initial

Plants per year	Capital cost [$/kW] $P_e =$ 1 kW	$P_e =$ 5 kW	$P_e =$ 25 kW	$P_e =$ 100 kW
100	10130	3483	1363	1062
1000	7895	2840	1181	867
10000	6699	2448	941	680
50000	6101	2132	816	606

Table 1: Capital cost estimation for a CHP plant based on HT PEM-FC as function of the installed size and of the number of units produced. Data from [41].

investment required for the ICE is set to 1100 €/kW [54] while maintenance cost is assumed to be 10^{-2} €/kWh [53] and the fuel cost is set to 0.918 €/kg according to common Italian industrial prices.

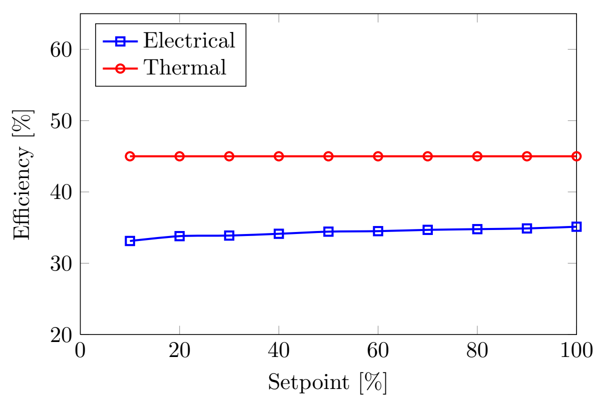


Figure 10: ICE electric and thermal efficiencies as a function of the set-point.

4. Results and discussion

4.1. Analysis of the CHP control strategy

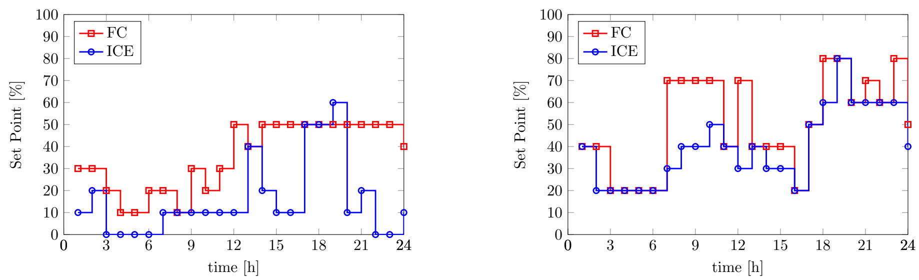
Here we discuss the optimized control strategy comparing its economical results and set-points with those of thermal tracking management, that strictly follows the thermal demand and is a commonly used control policy for CHP solutions.

	Optimized control strategy		
	Reference	HT PEM-FC	ICE
$\mathcal{C}$[€]	13137	7381	11025
$\mathcal{R}$[€]	0	411	90
$\mathcal{E}$[€]	13137	6970	10935
	Thermal tracking strategy		
	Reference	HT PEM-FC	ICE
$\mathcal{C}$[€]	13137	8372	12667
$\mathcal{R}$[€]	0	540	807
$\mathcal{E}$[€]	13137	7832	11860

Table 2: Annual economical results as functions of the plant technology and control strategy.

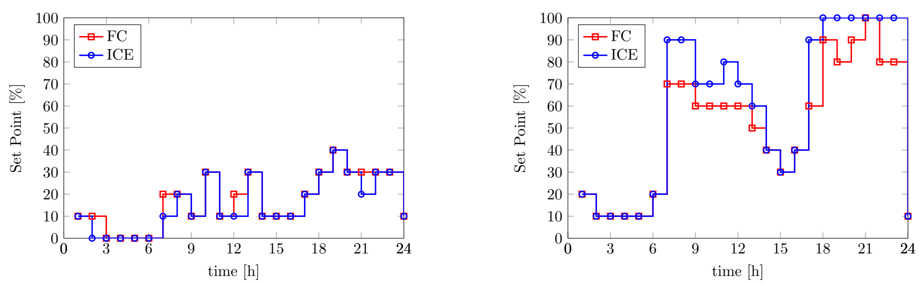
Economical results reported in Table 2 demonstrate that the adoption of the optimized strategy significantly decreases the annual net expenditures $\mathcal{E} = \mathcal{C} - \mathcal{R}$. In fact, using the optimized strategy rather than thermal tracking, $\mathcal{E}$ is reduced by 11% for the PEM-FC based plant and by 7.8% for the ICE based CHP.

Moreover, in Figs. 11 and, 12, the two control strategies are compared in terms of the prime mover set-point. As a consequence of the higher thermal energy demand, the winter is always characterized by a larger value of the CHP utilization factor, compared to the summer, irrespective of the selected control strategy and generator technology. In particular, with the optimized control strategy the utilization of the HT PEM-FC and of the ICE are 43% and 28% respectively. The higher utilization of the fuel cell based plant is related to its inherent flexibility. In fact, the fuel cell electrical efficiency increases as its load is decreased (see Fig. 9), and, contemporary its thermal efficiency is reduced. Consequently, the HT PEM-FC is characterized by a favorable behavior at part load, and, as highlighted in Fig. 11 the fuel cell is never turned off, differently from the ICE. On the other hand, following the thermal tracking strategy the average usage of the HT PEM-FC and the ICE generators are almost equal (i.e. respectively 34% and 37%) since the prime mover is forced to strictly follow the thermal demand. Thus, the fuel cell experiences a larger variation in the utilization factor compared to the ICE, explaining why the FC plant annual net expenditure is more affected by the variation of the control strategy compared to the one of the ICE.



(a) Summer (b) Winter

Figure 11: Fuel cell and internal combustion engine set-points with the optimized strategy.



(a) Summer (b) Winter

Figure 12: Fuel cell and internal combustion engine set-points with the thermal tracking operating strategy.

Both CHP systems are characterized by a lower primary energy consumption (PEC) compared to the reference scenario (see Table 3). For the HT PEM-FC based plant the PEC is reduced by 7% utilizing the optimized control strategy and by 12% through the thermal tracking, with respect to the reference scenario. Moreover, for the ICE based CHP, the optimized control strategy allows a 13% reduction of the primary energy consumption, while the thermal tracking yields a 15% decrease of the PEC, compared to the reference scenario. Notably, the HT PEM-FC yields a larger PEC, with respect to the ICE, despite having a lower $\mathcal{E}$. This entails that the economical convenience previously found is due to the flexibility of the plant, especially at lower set points, that allow a tighter coupling between the energy production and demand. Moreover, using the thermal tracking strategy the primary energy consumption results to be lower for both the CHP systems. Such a behavior reflects the fact that economical optimization does not enforce the maximization of the plant efficiency.

	Optimized control strategy		
	Reference	HT PEM-FC	ICE
PEC [GJ]	513	475	446
	Thermal tracking		
	Reference	HT PEM-FC	ICE
PEC [GJ]	513	450	436

Table 3: Primary energy consumption as a function of the plant technology and control strategy.

4.2. Investment analysis

In this section we evaluate the investments into the different CHP technologies, through the NPV analysis described in section 2. In order to perform this analysis we substitute the annual costs and revenues reported in Tab. 2 into the Eq. (3), together with the initial capital investment reported in section 3.2.

Using CHP the annual energy expense is always reduced with respect to the reference scenario which separately purchases electrical power from the grid and produces the thermal energy through a standard boiler. In fact, $\mathcal{E}$ is reduced by 47% using the HT PEM-FC, and by 17% through the ICE when the plants are operated according to the economically optimal strategy. Moreover, using the thermal tracking the annual saving are equal to 40% and 10% of the reference expenditure for the HT PEM-FC and the ICE respectively, as reported in Tab. 2. As expected, the most relevant savings are allowed by the fuel cell based plant, with an $\mathcal{E}$ relative variation in the range $[-47\%, -40\%]$ as a function of the control strategy. Note that, these results are consistent with the findings in [48].

For the ICE based CHP the NPV becomes positive during the 6'th year, after investment and the overall value at the end of the plant life is about 9400 €, as shown in Fig. 13.

As already pointed out in section 3, the technological maturity and market penetration of fuel cell based CHP plants does not allow a precise estimation of the capital cost for the NPV analysis. Thus, to compare the PEM-HT with the internal combustion engine we first determine the initial cost of the PEM-HT based plant that would lead the same discounted return on investment of the ICE plant, and then compare the economical and financial results of the two technologies varying the plant control strategy.

For an initial investment of 2950 €/kW the NPV of the fuel cell plant becomes positive during year 6, as for the ICE, and is about 24000 € at the end of the plant technical life. Note that, having assumed the same discounted payback period, the FC can have a larger initial cost compared to the ICE, as it yield larger annual savings. As a consequence, the residual value of the investment of the end of the CHP plant life is larger compared to the ICE plant.

These results demonstrates that under the current Italian energy market conditions CHP is a favorable investment for residential applications, if the plants are regulated following an economically optimal control strategy. In fact both the ICE and the FC based plants yield a discounted pay back period significantly lower than their expected technical life, and, thus a positive residual NPV. Moreover, PEM-FC, though requiring a higher initial investment, is characterized by a larger NPV at the end of the plant technical life. Thereof, the HT PEM-FC outreaches the ICE in terms of long term economical results.

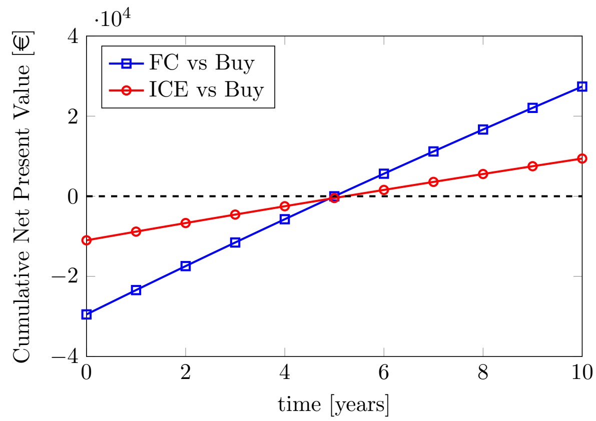


Figure 13: Cumulative Net Present Value for the fuel cell and the internal combustion engine with the optimized operating strategy

The I_0 previously obtained for the HT PEM-FC CHP plant is well in line with the cost estimate for fuel cell based plants reported in [41, 61], and is even larger compared to the cost targets established by the American Department of Energy for year 2015 and 2020 (i.e. between 1700 €/kW and 1900 €/kW). Thus, small size HT PEM-FC based cogeneration plants can be technologically mature for residential applications according to the Italian energy market requirement, and could be profitably exploited to reduce the energy costs for buildings.

NPV analysis is also performed assuming that the CHP power is regulated according to a thermal tracking strategy, see Fig. 14, in order to assess the relevance of the plant management on the investment evaluation. Moving from the optimal control strategy is particularly detrimental for the ICE based plant. In fact, with a NPV equal to -580 € at the end of its technical life, the ICE CHP becomes economically unprofitable. The I_0 of the HT PEM-FC is fixed to 2950 €/kW to be consistent with the previous analysis. Under this assumption, the fuel cell based plant remains a convenient solution with respect to the reference scenario but reduces its economical performance. In fact, the NPV turns positive during year 6 but, at year 10, NPV= 19014 € . These results demonstrate the importance of a proper control strategy in terms of plant profitability.

As a consequence, the investment analysis should always be performed considering the actual CHP control policy, and the utilization of the optimal strategies could boost the diffusion of distributed generation plants, as also highlighted in [23, 24]. Moreover, the HT PEM-FC is more robust with respect to the variation of the control strategy. In fact, despite a 22% reduction in the NPV, the fuel cell plant remains a convenient investment also when its power is regulated according to the thermal tracking strategy. This result is obtained thanks the higher flexibility of the fuel cell in working at partial load. Therefore the fuel cell based plant represents a convenient solution in respect to the reference scenario, also running with the standard thermal tracking control strategy.

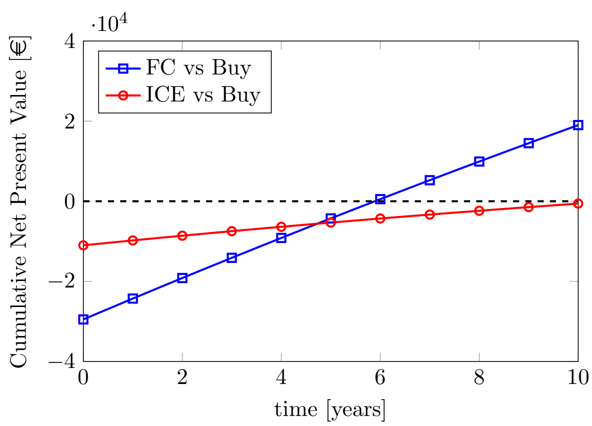


Figure 14: Cumulative Net Present Value for the fuel cell and the internal combustion engine with the thermal tracking operating strategy

A further analysis is performed by hypothesizing to finance the entire initial investment with debt. Instead of the initial capital investment, families will pay for ten years an yearly mortgage of 4056€ in the case of HT PEM-FC and of 1512 € in the case of ICE. Under this condition the NPV lowers to 15227€ and 4955€ , for the HT PEM-FC and for the ICE respectively, both using the optimized control strategy. If instead the plants are controlled with thermal tracking the NPV of the HT PEM-FC remains positive but decreases (i.e.8658€) and the one of the ICE becomes negative (i.e. -1996€). Thereafter the CHP solutions proposed in this paper are more effectively for families that have the capital investment needed available at the beginning of the project. However these plant configurations remain convenient also for those who have to start a loan to finance it. As before the control strategy adopted is fundamental for the economical considerations. If thermal tracking is adopted, also in this case the ICE based plant is not more viable, while the HT PEM-FC remains a convenient solution.

5. Conclusions

In this work we study the technical and economical performances of an HT PEM fuel cell for a residential CHP application, representing a group of collaborating households. The analysis is carried out in two representative days, one in the summer and one in the winter, and with an optimized and a thermal tracking operating strategy of the energy system. A detailed NPV analysis is carried out, distinguishing the discount rates related to the additional revenues and reduced costs obtained by the CHP unit, that is crucial for a precise estimation of the economical benefit.

Our findings highlight the economical convenience of the fuel cell solution, with respect to the use of an ICE and to the separate production of electricity and heat, which is taken as the reference scenario. Specifically, with respect to the reference scenario we calculate that the use of the fuel cell allows a reduction of the annual net expenditure of 47% with the optimized strategy and of 40% with the thermal tracking. Using the ICE, the annual savings with respect to the separate production are -17% and -10% with the optimal and the thermal tracking operating strategy, respectively. The NPV analysis also supports the importance of a proper control strategy of the power plant, that has a significant impact on the magnitude of the economical convenience of any CHP residential application. We also highlight that the ICE CHP system is more sensible to the control strategy, given the better part-load operation of the fuel cell. In fact, the NPV of the HT PEM-FC CHP application is positive with both operating strategies and it is maximum with the optimal one, while the NPV of the ICE with the thermal tracking turns negative. On the other hand, thanks to the higher peak efficiency, the ICE presents a better primary energy consumption (PEC) compared to the fuel cell, even if both CHP systems improve the PEC with respect to the separate production. It is thus evidenced that the adoption of the innovative HT PEM-FC cogenerative solutions allows collaborative families to achieve the social goals of reducing energy costs sharing the CHP plant.

Further research also is needed to extend the analysis to other countries, characterized by a different energy market and financial structure, and to thoroughly understand the effects of the plant control strategy on the economical convenience and on the financial evaluation of innovative CHP plants.

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