Energy xxx (2015) 1–10

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Proton exchange membrane fuel cell for cooperating households: A convenient combined heat and power solution for residential applications

Francesco Cappa [a, b], Andrea Luigi Facci [a, *], Stefano Ubertini [a]

[a] School of Engineering (DEIM), Univesity of Tuscia, 01100 Viterbo, Italy
[b] Department of Business and Management, LUISS University "Guido Carli", 00198 Rome, Italy

ARTICLE INFO

Article history:
Received 28 April 2015
Accepted 22 June 2015
Available online xxx

Keywords:
Combined heat and power
Control strategy optimization
Investment analysis
Fuel cell
Energy efficiency
Social innovation

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 cooperating 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.

1. Introduction

Cogeneration, referred also as CHP (combined heat and power), 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 to 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 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 EU (European Union) stimulates its members to promote the development of CHP systems, that are characterized by high efficiency and low environmental impact [19].

FC (fuel cells) 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

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* Corresponding author.
E-mail addresses: francesco.cappa@unitus.it (F. Cappa), andrea.facci@unitus.it (A.L. Facci), stefano.ubertini@unitus.it (S. Ubertini).

http://dx.doi.org/10.1016/j.energy.2015.06.092
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Please cite this article in press as: Cappa F, et al., Proton exchange membrane fuel cell for cooperating households: A convenient combined heat and power solution for residential applications, Energy (2015), http://dx.doi.org/10.1016/j.energy.2015.06.092

been made in Japan up to 2013 (about 50,000 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 IEA (International Energy Agency) foresees a production volume above 70,000 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 SGIP (self-generation incentive program) 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 (Proton Exchange Membrane) 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]. HT PEM-FC (high temperature PEM fuel cells) 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 Ref. [16], concluding that fuel cells do 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]) evidence 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 NPV (net present value) 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 our 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, through the control strategy optimization we determine 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 for 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 Ref. [3] and further developed in Ref. [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

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

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

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