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Analysis of a fuel cell combined heat and power plant under realistic smart management scenarios

Andrea L. Facci*, Stefano Ubertini

School of Engineering (DEIM), University of Tuscia, 01100 Viterbo, Italy

HIGHLIGHTS

- Thorough techno-economic analysis of a CHP plant based on automotive PEM-FCs.
- The control strategy determined minimizing the cost or the energy consumption.
- Economically sustainable and effective FC based power plant.
- In Europe cost minimization might increase the primary energy consumption.

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ABSTRACT

Proton exchange membrane fuel cells are a promising and mature technology for combined heat and power plants. High efficiency (in particular for small size devices), practically zero pollutant emissions, noiseless operation and fast response to transient demand make these energy systems excellent prime movers for residential and commercial application. Nevertheless, due to large capital costs, their utilization and commercialization are still limited to demonstrative projects. In this scenario, we are working on a research project, called AutoRe, which utilizes an automotive derivative fuel cell for a cogeneration plant to create a synergy between two non competitive industries (automotive and stationary plants) and to realize a significant economy of scale that will drastically cut the costs of fuel cell based cogenerative plants. In this paper, we perform a thorough techno-economic analysis of the AutoRe (AUTomotive deRivative Energy system) power plant. A number of realistic energy management scenarios are constructed by varying the energy demand, the climatic condition, the energy cost, and the efficiency of the surrounding energy system. The control strategy is determined on an hourly basis, by minimizing the cost or the primary energy consumption through a graph based methodology. The resulting global parameters are compared to a reference scenario where electricity is acquired from the grid and heat is locally produced through a natural gas boiler. We consider 5 different building types (Office, Apartment district, Clinic, Hotel, Supermarket), 5 different climatic conditions (Hot, Cooling Based, Moderate, Heating based, Cold), and 2 different surrounding energy systems (USA and Europe). The results show that overall the proposed plant is economically sustainable and effective in reducing the energy costs and the primary energy consumption. Nevertheless, the building type and the energy prices impact on the return on investment, while the climatic condition affects the relative cost and energy variations. In the US scenario, the management based on cost and primary energy minimization exhibits similar patterns. On the contrary, in Europe cost minimization might increase the primary energy consumption with respect to the reference scenario.

1. Introduction

Fuel cells (FCs) are a promising technology for satisfying the energy demand for stationary applications, in particular in the residential and commercial sectors [1–5], being particularly suited as prime movers for small cogeneration (CHP) plants [6,5]. In fact, 64% of the micro-cogeneration systems sold in 2012 are based on FCs [3,7,8]. Several features of the FCs, such as high efficiency [9], very low pollutant (NO_x,SO_x, and particulate matter) emissions [10], vibration and noise-free operation [11] determine such a success. Moreover, the efficiency of a FC is only marginally influenced by its size and is generally increased at part load [12], differently from traditional power generation technologies [12]. Depending on the FC technology, different fuels can be used including hydrogen [13], natural gas (NG) [14], methanol [14],

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

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and bio-fuels [15–17]. Hydrogen fueled FCs are also envisaged to promote renewable sources penetration allowing long term electrical energy storage [18,19]. All these positive aspects boost the advantages of combined heat and power that are already widely acknowledged and include: (i) increased overall efficiency compared to separate production [12,20]; (ii) reduction of pollutant and green house gases emissions [20,21]; (iii) deferring expensive investments on large size plants, and on transmission and distribution system [20,21]; (v) reducing losses in the distribution system [21]; (v) providing network support or ancillary services [21]; (vi) promoting the use of alternative technologies and renewable sources especially in smart grids [18,20,22–24].

Similarly, FCs can have a large potential in the automotive industry [25–28] allowing to cut down the environmental impact of the mobility sector [25] and to overcome few of the major issues related to electric vehicles [28].

In the European Union (EU), residential and commercial buildings are responsible for 40% of the energy demand and for 36% of the carbon dioxide emissions [29]. In the United States (US) buildings utilized 41% of the primary energy consumed in 2010 [30,31], 54% of which only for the residential sector [31]. The International Energy Agency (IEA) estimates that CHP systems together with district heating and cooling could save 950 Mton/year of carbon dioxide emissions by 2030 [32]. Thereafter, FC based CHP plants could significantly contribute to reduce the depletion of fossil energy sources and the global environmental footprint.

In the last two decades, different fuel cell technologies have been developed and entered the market of distributed CHP systems. Polymer electrolyte membrane (PEM) fuel cells are the most mature FC technology. At the end of 2012, PEM fuel cells, represented almost the 88% of the total fuel cell market [8]. Table 1 surveys the PEM based energy systems available on the market or in a pre-commercial stage with a nominal power below 500 kW [33–41]. Apparently, no commercial systems are available in the power range [50 kW,100 kW]. The large investment cost is the main obstacle that hinders the market spreading of such a technology. In fact, actual costs, reported in Table 1, are much larger compared to the targets set by the Fuel Cells and Hydrogen Joint Undertaking (FCH-JU) that are between 3500 €/kW and 6500 €/kW for energy systems in a power range between 5 kW and 400 kW [42]. Similarly, in [2] it is evidenced that PEM fuel cells are competitive with internal combustion engines as CHP prime movers for residential applications if the investment cost is below 3000 €/kW. Few relatively large demonstrative projects have been implemented leveraging on public financial support, such as the ENE-FARM project in Japan [43], the residential fuel cell demonstration programme in South Korea [44], the Callux residential project Germany [45], the FC-District Project operating in Spain, Greece and Poland [46], and the ene.Field project under the H2020 European programme [47].

The capital investment required for a PEM based CHP system is largely determined by the FC production volumes [38,48–50]. In this scenario, the AutoRe project [51,52] envisages the possibility of realizing a significant economy of scale by utilizing an automotive derivative PEM-FC as a prime mover for a micro-CHP system with a power of about 100 kW. In fact, even a small series for an automotive industry could already represent a large market for power generation. For example, the sole Toyota plans to produce 40,000 fuel cell commercial vehicles by 2020 and 400,000 vehicles by 2030 [26,27] overselling the ENE-FARM project by an order of magnitude. The AutoRe plant is designed to be connected to the natural gas infrastructure and to produce electricity and heat for residential and commercial demands. The expected investment cost for mass production of such a plant is 2000 €/kW.

Table 1
Examples of PEM Fuel cell energy systems available in the market or in a pre-commercial stage in the power range 0–500 kW.

Model	CHP	Cost [k€]	Power [kW]	Electrical efficiency
Ballard ClearGEN [33]	Yes	NA	500	40%
Ballard ElectraGen [34]	No	17–50	1.7–5	40%
Baxi Gamma Premio [35]	Yes	NA	1	34%
Doosan FC Purocell 5 [36]	Yes	NA	440	43%
Elcore 2400 [35,37]	Yes	9	0.3	33%
Panasonic [35,38]	Yes	20–30	0.75	37%−40%
Inhouse 5000+ [39]	Yes	NA	1.5–5	34%
Toshiba [35]	Yes	20–30	0.7	35%
Tropical NG-5 [40]	NO	NA	5	NA
Viessmann [35,41]	Yes	36	0.75	39%
Eneos [38]	Yes	24.5–28.5	0.7	NA

In this paper we perform a thorough techno-economic analysis of the 100 kW CHP plant that is being developed within the AutoRe project [52] under different energy management scenario. In particular we vary the energy demand by combining 5 different building typologies (an office building, an hotel, a clinic, an apartment district, and a supermarket) and 5 climatic conditions. Moreover, we dissect the impact of the surrounding energy system by considering the different electricity and natural gas costs and primary energy factors (PEF) relative to the American and European energy markets. For each scenario the plant control strategy is determined utilizing an optimization methodology developed by the authors [53–55]. We consider two different management policies: cost minimization and primary energy consumption minimization. The pay back period (PBP) is taken as an indicator of the economic feasibility of the plant. Its impact on the surrounding energy system is evaluated through the relative cost saving and the relative reduction of the primary energy consumption (PEC).

Such an analysis is performed with the twofold objective of assessing the effective performance of PEM based CHP plants under realistic scenarios and of disseminating the applicability of control strategy optimization for different actors of the energy sector. First, the results will identify the technical (i.e. building type), environmental (i.e. climate), and economical (i.e. energy tariffs) conditions that promote the utilization of the proposed technology. The investment analysis, performed utilizing realistic input data for a variety of different scenarios gives relevant information to the technology developers to determine the potential markets for PEM based CHP plants, thus assessing the effectiveness of the investments in such a technology. The comparison between the different optimization criteria could also help policy makers to identify the energy tariffs, supporting mechanisms, and policies that promote the efficient exploitation of advanced systems. Finally, results will demonstrate that design performance are not sufficient to evaluate an energy conversion technology. At the same time we propose an evaluation methodology based on the control strategy optimization that allow dissecting the behavior of complex power plant and facilitates the evaluation of the performance. The profitability of the plant or its energy and environmental advantages ere directly estimated as results of the optimization methodology, rather than relying on concepts such as the levelized cost of electricity or the CAPEX and OPEX.

The paper is organized as follows. The CHP system is briefly described in Section 2. In Section 3 we define the methodology utilized to determine the optimal operating strategy and to perform the techno-economic analysis. The results are presented and discussed in Section 5. Finally, conclusions are drawn in Section 6.

2. The automotive derivative PEM based CHP plant

The prime mover of the CHP plant in study is a 100 kW PEM fuel cell whose schematic representation is given in Fig. 1. The electricity is generated within the FC by the catalytic oxidation of pure hydrogen. The FC operates at a temperature of 80 °C and low grade thermal energy can be generated from the waste heat. Specifically, thermal energy is recovered both from the FC flue gases through a water cooled heat exchanger and from its cooling circuits (see Fig. 1). The high temperature circuit removes heat from the bipolar plates and the low