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Technical and economic assessment of a SOFC-based energy system for combined cooling, heating and power

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HIGHLIGHTS

- Assessment of the performances of a SOFC based CHCP plant for residential applications.
- Optimal plant design as a function of investment cost and control strategy.
- Optimized control strategies to minimize the costs and primary energy consumption.

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ABSTRACT

Here we present the technical and economical performances of a small scale trigeneration power plant based on solid oxide fuel cells and designed for a small residential cluster (i.e. 10 apartments). The energy system features a natural gas solid oxide fuel cell, a boiler, a refrigerator, and a thermal storage system. We compare different power plant configurations varying the size of the fuel cell and the refrigeration technology to satisfy the chilling demand (i.e. absorption or mechanical chiller). Given that the ability to meet the power demand is crucial in this kind of applications, the plant performances are assessed following an optimal control strategy, as a function of different energy demand profiles and electricity prices, and of rated and part load efficiencies of each energy converter. The optimization of the energy system operating strategy is performed through a graph theory-based methodology. Results are provided in terms of electrical and thermal efficiency, operating strategy, as well as economic saving, primary energy consumption reduction, and pay back period, considering different capital costs of the fuel cell.

1. Introduction

Increasing the energy efficiency and reducing the environmental impact of buildings is a key aspect for developed countries [1–3]. In fact, buildings are responsible for 40% of the energy demand and 36% of the carbon dioxide emissions in the European Union (EU) [4]. In particular, households cause 25% of the total greenhouse gases emission related to fossil fuel combustion in the EU [5]. Similarly, in 2010, buildings used about 41% of the primary energy consumption of the United States (US) [6,7], 54% of which only for the residential sector [7]. In this scenario, both US and EU undertook actions to reduce the buildings energy waste [3,4]. The US Department of Energy envisages the possibility of reducing the energy consumption of buildings by 50% compared to 2010 [3]. The EU requires that all new buildings must be "nearly-zero-energy" by 31 December 2020 [4], and all new public buildings must be "nearly-zero-energy" by 2018 [8] as a determinant measure to meet the objective of reducing the primary energy consumption by 20% with respect to the business as usual projection.

Cogeneration, or combined heat and power (CHP), and trigeneration or combined heat cooling and power (CHCP) are reliable technologies that are already contributing to the global energy demand [9]. According to the International Energy Agency (IEA), CHP coupled with district heating and cooling could save 950 Mton/year of carbon dioxide emissions by 2030 [9]. Although the main driver for large CHP investments is economic [9], cogeneration and distributed generation (DG) offer several other opportunities, such as: (i) increased overall efficiency compared to separate production [10,11]; (ii) reduction of pollutant and green house gases emissions [11,12]; (iii) deferring expensive

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investments on large size plants [11], and on transmission and distribution system [12]; (iv) reducing losses in the distribution system [12]; (v) providing grid support or ancillary services [12]; (vi) promoting the use of alternative technologies and renewable sources [11,13,14]. Several case studies related to the performances of CHP systems can be found in literature [15–21], also coupled with renewable sources [13,15–17,22–24].

Solid oxide fuel cells (SOFC) are a promising technology for high-efficiency and sustainable energy conversion [25–27], and are expected to play an important role in future distributed energy generation [28]. SOFCs have many advantages over conventional power plants including: (i) high efficiency [25]; (ii) fuel adaptability [29]; (iii) very low NO_x, SO_x and particulate matter emissions, and reduced CO_2 emissions [30]; (iv) vibration-free operation [31]. Theoretically, the electrical efficiency of a SOFC may be larger than 70% [32]. On the other hand, commercially available SOFC systems have a net electrical efficiency in the range 40–60% [32]. SOFC systems can produce an electrical power from few W up to several hundreds of kW [25,32] and their efficiency is only slightly influenced by the system scale [32]. SOFC plants with an electrical power of 1 kW and an efficiency of 60% have been demonstrated in [32]. The high working temperature facilitates the integration of SOFCs within CHCP plants [32]. Therefore SOFCs, are becoming a promising prime mover for CHCP applications [25–28,33,34].

After decades of research and development, SOFCs are now close to commercialization [32], and there are already several SOFC high-efficiency micro-cogenerators conceived primarily for residential use or small-scale commercial applications. More than 1000 CHP installations of polymer electrolyte fuel cells (PEMFC) and SOFC have been realized starting from the late 2014, mainly within the European project ENE.FIELD [35]. The ENE-FARM is the most successful project on micro CHP [35]. It has been realized in Japan from 2008 until the end of 2015, whith more than 150,000 CHP units (both PEMFC and SOFC) installed in residential areas [35]. Typical applications are those with high power and heat demands, like office buildings, swimming pools, and small and medium enterprises [36].

The control strategy determines the performances of DG plants [10,37] as much as the technological level of the components [38–40]. Therefore, realistic working conditions must be considered for their economical and environmental evaluation [38,39,41–43]. Determining the set-point is critical for CHP and CHCP, as each of the energy vectors simultaneously produced represents a constraint for the plant [27,38,44]. Optimized control strategies emphasize the strengths of DG plants, compared to predetermined strategies (i.e. thermal tracking or electrical tracking), impacting the return on investment and the environmental benefit [43].

In this paper we evaluate the potential of a SOFC-based CHCP plant in terms of economic, energy, and environmental performances. We hypothesize that such a plant satisfies the energy demand of a small residential cluster (i.e. 10 apartments) and we compare different configurations varying the SOFC electrical power and the refrigerator machine technology (i.e. absorption or mechanical chiller). Two control strategies are considered for each configuration: an economically optimized strategy that minimizes the total daily cost, and an energy consumption optimized strategy that minimizes the daily primary energy consumption (PEC). Both strategies are determined through the methodology presented in [45–47] that accounts for hourly energy demand and costs, and for the efficiency of the energy system components as a function of their set-point.

The paper is organized as follows. In Section 2 we describe the methodology utilized to determine the total energy cost. The case study is presented in Section 3, with particular reference to the plant configurations, the energy demand, and the energy tariffs. Results are dissected in Section 4 and conclusions are drawn in Section 5.

2. Methodology

We dissect the performances of a SOFC-based CHCP plant in a realistic energy management scenario. In particular, we concentrate on the annual energy cost and on the primary energy consumption. We compare different configurations, varying the equipment size and the refrigerator technology (further details are given in 3.3).

The operating efficiency of such a plant is largely determined by its control strategy as highlighted in [10,37,38,45,46,48]. Thereafter, we compare the performances of the different configurations assuming two possible management policies: cost minimization and PEC minimization. Both control strategies are determined through the optimization methodology introduced in [45], and further developed in [46,47]. Such a methodology minimizes a prescribed objective function on a daily basis accounting for: (i) the design performances of all the subsystems; (ii) the derating of the performances at part load; (iii) the effects of environmental conditions; (iv) energy demand and costs as functions of time; (v) maintenance, and cold start costs; (vi) constraints related to the dynamic behavior of the equipment, such as the minimum time interval between two consecutive starts or shutdowns. All the energy converters are modeled as black-boxes, through their efficiency curves as functions of the set-point and environmental conditions.

The prescribed objective function for cost minimization is:

$$G_{\text{Cost}} = \sum_{h=1}^{24} C_f(h, s(h)) + C_m(h, s(h)) + C_s(h, s(h)) - R(h, s(h)), \qquad (1)$$

being h the time interval, C_f the cost of fuel, C_m the maintenance cost, C_s the cold-start cost, and R the revenue/cost yielding from the electricity exchanged with the grid. Costs are functions of the time interval and the plant state (i.e. the set-point of the subsystems) $s(h)$.

PEC minimization requires the following objective function reported in Eq. (2)

$$G_{\text{PEC}} = \sum_{h=1}^{24} E_f(h, s(h))\text{PEF}_f + E_{\text{grid}}\text{PEF}_{\text{grid}}, \qquad (2)$$

where E_f is the energy content of the fuel, PEF_f is the primary energy factor of the fuel [49], E_{grid} is the electricity exchanged with the grid, and PEF_{grid} is the primary energy factor of electricity [49].

Eqs. (1) and (2) are discretized with respect to the plant state and in time, and the problem is represented as a weighted and oriented graph. The optimal control strategy is determined seeking for the shortest path across the graph.

We combine two energy demand profiles, one typical of summer and one representative of winter (see Section 3.1), and two electricity cost profiles (see Section 3.2), one for working days and one for non-working days, to obtain four sample combinations. The control strategy is optimized for the four days, and the daily results are projected on the whole year to compare the performances of the different plant configurations.

3. Case study

In this paper we evaluate the performances of the CHCP plant described in Section 3.3 to comply the energy demand of a relatively small residential unit.

The prime mover is a cogenerative SOFC. A natural gas boiler is included as a back-up and to satisfy peak thermal energy demand. Both absorption and mechanical chillers are considered for the production of chilling energy.