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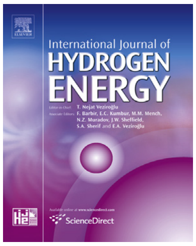

Combined micro-cogeneration and electric vehicle system for household application: An energy and economic analysis in a Northern European climate

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ABSTRACT

In recent years, Denmark boosted investments in renewable energy and electrification of transportation. The Danish Agenda proposed that all primary energy consumption will be covered by renewable sources such as wind, biomass and solar by 2050. These changes require significant investment and re-thinking of entire energy infrastructures and types of consumption. The Agenda also suggested, among other things, improving the efficiency of energy systems.

In this paper, the interactions between charging an electric car and an innovative cogeneration system for household application (micro-solid oxide fuel cell with an integrated heating system) are investigated. The charge of the electric car by the cogenerator produces waste heat that can be used to partially cover the heat demand of the house. In this way it may be possible to increase overall efficiency and decrease total energy costs. Different innovative strategies are proposed and analyzed to manage charging an electric car and efficiently using the waste heat available. The aims of this study are to make the system grid-independent, to decrease the thermal stress of SOFCs and to determine the nominal power of an integrated heating system. The results show energy efficiency and economic profitability of the system, even if subsidies are not included.

Introduction

Electric cars and electrical mobility are open topics of research [1] with the aim of decreasing the environmental impact of transport. For example, traditional cars powered by traditional fuels (chemical energy such as petrol) could be replaced with electric ones. Different studies show that electrical mobility has an environmental impact that is strictly related to the energy sources used to produce electricity [2–5]. For example, greenhouse gas emissions can be avoided only if renewable energy sources are used [6,7]. Electrical mobility has been already studied in relation to the possibility of domestic charging [8]. Also analyzed was the possibility of using electric cars and their batteries as energy storage systems to stabilize electric systems in scenarios where the majority of

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the total energy demand is supplied by renewable energy [9,10].

One of the main drawbacks of electrical mobility is related to low energy storage density of batteries with respect to hydrocarbon fuels. One possible solution for the transition from traditional to electrical mobility is the use of bio-fuel. Different types of fuels have been investigated and developed to decrease greenhouse emissions [1]. The main advantages are the higher power density and the possibility of using traditional internal combustion engines with a mixture of fossil fuels and bio-fuel [1]. The disadvantages are the high cost, the low efficiency of the refinery/production process and the use of food to produce fuels (for example, corn-based methanol). The last point could be morally unacceptable [11].

Meanwhile, energy systems are moving to distributed generation, improving electrical transmission efficiency and infrastructure [1]. One solution for household applications is micro-cogeneration, which allows a better match between energy demand and production as well as lower transmission losses with respect to a traditional electrical system. Different cogeneration systems have been proposed, analyzed and studied, such as internal combustions engines [12,13], Stirling engines [14–16], fuel cells [16–28], micro-Rankine [29,30] and micro-gas turbines [31–34], and photovoltaic cogeneration modules [35–37]. In some cases, systems set up with a cogenerator and an integrated heating system have been proposed in order to face both electrical and heat demand in a more effective way [38,39].

Even though electric mobility has been analyzed for years [1], studies on micro-cogeneration combined with electric cars are not so plentiful. In Refs. [39–42], micro-cogeneration systems based on internal combustion engines coupled to natural gas boilers are proposed for household application: the results prove higher efficiencies than those of traditional systems. In Ref. [43], a proton exchange membrane fuel cell is proposed as a micro-cogenerator, while in Refs. [44,45], solid oxide fuel cells (SOFCs) are used. Further [46], proposed instead a PV system. In the authors' opinion, innovative systems require innovative operation strategies. From this point of view, the only example found in the literature is reported in Ref. [43], where an innovative strategy based on multi-linear programming is proposed.

In this study, a system composed of an SOFC and a heat pump is presented. In addition, an electric car that is charged from the electricity produced by an SOFC is also considered. An innovative approach is thus followed to boost efficiency of the system, to realize grid independence and to achieve the maximum economic benefit. The aim of the research is to analyze both thermodynamic and economic advantages with respect to a traditional solution for household application.

Overview of the system

Equipment and design strategy

The innovative system considered here is based on a previous study by the authors [47]. As proposed, it will satisfy energy demands in terms of electricity, space heating and domestic hot water (DHW) for a residential building located in Denmark. The system is represented in Fig. 1, which is a setup consisting of an SOFC system integrated with a ground source heat pump (GSHP). SOFC is the high efficiency micro-cogenerator that provides both electricity and heat, while the GSHP is used to meet part of the heating and DHW demands with a higher efficiency than those of traditional boilers or electric heaters. The electrical energy produced by the SOFC (fueled by natural gas [NG]) is used to cover the user electricity demand, mainly at night, and to charge an electric vehicle (EV). In the case of a mismatch between electrical demand and production, the system exchanges energy with the grid. However, the operation strategies implemented here (Section "Operation strategies") have the aim of maximizing the electrical demand covered by the SOFC in order to be as grid independent as possible.

The main part of the system is the SOFC micro-cogenerator that provides electricity, while its waste heat is used to meet part of the heat demand for the building. Fig. 2 shows the main components of the SOFC system, which includes all necessary components, such as an air compressor (to supply air at the correct pressure and to cool the stacks), an inverter (which is used to convert current from direct to alternate current – DC to AC), a catalytic partial fuel reformer (to crack the heavy hydrocarbons), a desulfurizer (to remove sulfur and thus avoid sulfur poisoning for the cells) and a catalytic burner (to burn the unreacted fuels that remain). In this study, a 2 kW nominal electric power SOFC is adopted for covering the electrical demand, while the heat produced by the fuel cell is used to cover space heating and domestic hot water demands as much as possible, thus maximizing the overall system efficiency.

Due to the different heat-to-power ratios of the fuel cell and user demands, the heat recovered by an SOFC is not sufficient to cover the heat demand, and therefore, a ground source heat pump is proposed as an additional integrated heating system. Note that the GSHP nominal power is related to the design strategy, and therefore, no other devices for the heating system will be used. For example, in Ref. [38], two different integrated systems (condensing boiler and electric heater) were analyzed to cover peak heat demands with the aim of decreasing the nominal power of the heat pump and its purchase cost.

In the current study, an innovative strategy related to electric car charging is also proposed in which batteries are

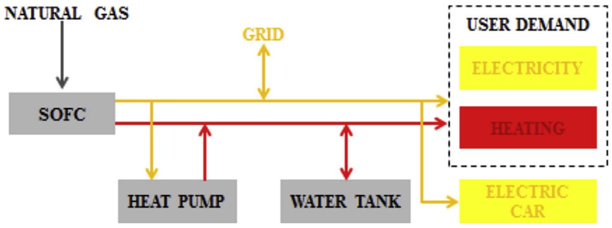

Fig. 1 – Representation of system energy fluxes (yellow represents electricity, and red represents heat). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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