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Hybrid energy fuel cell based system for household applications in a Mediterranean climate

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ABSTRACT

In this paper, a specific hybrid energy system was proposed for household applications. The hybrid energy system was assembled from a HT-PEM fuel cell stack supplied by hydrogen via a steam reformer, where finally the majority of produced electricity is used to drive a modified split heat pump system with heat recovery (that is enabled via standard modified accumulation boilers). The system is able to produce both high and low temperature heat output (in the form of hot water), cooling thermal output and electricity. Performance analysis was conducted and the specific hybrid energy system showed high value for overall energy efficiency, for the specific case examined it reached 250%. Levelized Cost of Energy (LCOE) analysis was also carried out and the proposed hybrid energy system's cost is expected to be between 0.09 €/kW h and 0.16 €/kW h, which is certainly competitive with the current retail electricity price for households on the EU market. Additionally, the system also has environmental benefits in relation to reduced CO_2 emissions, as estimated CO_2 emissions from the proposed hybrid energy system are expected to be at around 9.0 gCO_2/kW h or 2.6 times less than the emissions released from the utilization of grid electricity.

1. Introduction

Global energy and environmental issues are forcing the research community to elaborate, analyze and eventually propose new energy solutions, as viable options for commercial applications, [1]. Hybrid energy systems are especially attractive as they often utilize the application of renewable energy technologies [2]. On a global level the building sector accounts for some 40% of the overall primary energy consumption with carbon dioxide emissions being respectively high. The residential sector alone accounts for approximately half of this amount, therefore 20% of the primary energy consumption, whilst the commercial sector accounts for the other half [3]. On a European level the residential sector accounts for approximately 26% and the commercial for 15%, the sum being in line with the global figures; the values obviously varying from country to country [4]. Hence, different energy strategies have been analyzed and discussed for buildings, in order to reduce energy consumption, to improve energy efficiency and to increase the utilization of renewable energy sources to cope with the thermal and electrical loads [5,6]. All those efforts have yielded results and the energy requirements of buildings that comply to contemporary European national regulations are reduced by more than 70% compared to buildings designed before the 1970s. However, there is still significant potential for improvement, particularly with respect to improving the energy efficiency of the existing building stock [7,8]. In recent years, fuel cell hybrid energy systems are in the focus of research efforts, as hydrogen represents an attractive and environmental friendly energy storage medium. However, the feasibility of the fuel cell based energy systems is crucial in order to ensure its commercial success. In order to cover the electrical and thermal requirements of household, different energy technologies have been used. In isolated and remote electrical systems, like insular one, the need for securing the energy supply is a major argument for such hybrid systems, whilst in stable systems, like the continental European one, it is the need to use cleaner energy sources as well as the need to reduce energy costs which drive developments [9]. However, our efforts should be focused on the development of hybrid energy options that are totally renewable ones. The idea of this paper was to use a gas option in an as much as possible efficient manner although fossil fuel is used.

The objective of this paper is to elaborate the proposed fuel cell based hybrid energy system for applications in residential or commercial building applications for geographical locations with a Mediterranean climate (or in general for locations with mild

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Nomenclature

AC	total life cycle cost, €
C_{gas}	monthly cost for consumed natural gas in the reformer, €/month
CRF	capital recovery factor
d_m	number of days in the specific month, days/month
EO	average annual overall energy output from the hybrid energy system, kW h/year
E_{el}	engaged electric power from the HT-PEM fuel cell stack system, kW
$\dot{E}_{gas}$	energy input from natural gas into the hybrid energy system, kW h/month
IC	installation cost (overall investment), €
n	amortization period, years
$\dot{N}_{gas}$	amount of natural gas consumed in the reformer, m^3/month
OM	operation and maintenance cost, €
p	interest rate, % p.a.
$\overline{P}_{comp}$	mean engaged compressor power for the modified split heat pump system, kW
$\dot{Q}_{s\_H/C}$	heating/cooling thermal output from the modified split heat pump system, kW h/month
$\dot{Q}_{w\_HT}$	high temperature heat released from the HT-PEM fuel cell stack system, kW h/month
$\dot{Q}_{w\_LT}$	low temperature heat released from the modified split heat pump system, kW h/month
COP_{av}	mean coefficient of performance for entire season (heating/cooling)

Greek symbols

η_{ef_H}	overall energy efficiency rate from the hybrid energy system
η_{ge}	rated system electricity generation efficiency (LHV based)
η_{hr}	rated heat recovery efficiency
τ_d	average working time of the hybrid energy system, hours/day

climates). In general, a techno-economic (feasibility) aspect for the proposed hybrid energy system will also be analyzed. A hybrid energy system would be capable to produce heating/cooling thermal output and hot water simultaneously for domestic needs, and due to this fact, it would have a potential to cover more than 70% of energy demands for the average household.

2. Review of latest research findings

An Innovative household system based on solid oxide fuel cells for northern European climatic conditions was elaborated and discussed in [10]. According to the provided thermodynamic simulations and the feasibility study analysis, the system showed high primary energy savings and a sound economic viability. Dynamic simulations of hybrid energy systems in a load sharing application have been analyzed in [11], where one system was a ground source heat pump (GSHP), coupled with a fuel cell (FC), and another analyzed hybrid energy system was a combination of GSHP and photovoltaic thermal (PV/T) system. The latter hybrid energy option turned out to be economically more effective and also to produce less carbon dioxide emissions compared to the GSHP-FC system. Different energy management strategies have been presented in [12] to provide efficient operation of hybrid power systems with renewable energy sources based on polymeric electrolyte membrane fuel cells. It found that reformer-fuel cells increase the robustness of the hybrid system and that loss of power supply probability can be reduced significantly (up to 88%). Authors in [13] proposed and analyzed energy control strategies for the standalone Renewable/Fuel Cell Hybrid Power Source (RES/FC HPS) and a simulation model was developed using MATLAB-Simulink to check different possible scenarios and load profiles. The study performed in [14] focused on the evaluation of cost and of reliability for the standalone hybrid renewable energy systems in building applications, as a combination of PV, fuel cell, wind turbine and battery bank system. The key finding in the previously mentioned paper was one that the combination of wind turbines, solar PV system and battery bank gives the most cost effective hybrid system. Exergy analysis of an EFC/PV/Battery-based hybrid power generation system was obtained in [15] and possible operation scenarios were discussed. A new heat recovery design was elaborated and it was found that the specific design improves exergy efficiency. Different alternative energy scenarios for Bozcaada Island in Turkey were discussed in [16], where implementation of a fuel cell system was also elaborated using the HOMER simulation system. Results showed that the most suitable grid connected system is grid/wind in relation to electricity price. Authors in [17] provided thermodynamic analysis of a combined PV/T-fuel cell system that is capable to produce electricity, heat, fresh water and hydrogen. A parametric study was also carried out and discussed, so as to determine that system's efficiency for different scenarios. A novel hybrid PEMFC power system was presented in [18], where simulation results were compared to experimental ones, discussion also the impact of different management strategies on the system's efficiency. The authors developed their own simulation model to simulate experimental response and the simulation model was compared to experimental results with high accuracy. Hybrid photovoltaic/wind/fuel cell power system modeling was obtained in [19], controlling strategies were also discussed as well as some practical issues. The considered controlling strategies were experimentally implemented and they caused increase in energy efficiency of the proposed hybrid energy system. A techno-economic analysis was elaborated for a wind turbine-PEM (polymer electrolyte membrane) fuel cell hybrid system for possible standalone application; the results were discussed in [20]. The previous study was obtained for two cities in Iran and results showed that the wind turbine size is bigger in stand-alone application than the on-grid supply (for full load consumption) which means that stand-alone application is not economically attractive. Authors in [21] provided techno-economic analysis of a hybrid renewable micro-generation system, suitable for residential or small office building facilities. The previously mentioned hybrid energy system showed economic viability, but only for specific boundary conditions of energy pricing and operational patterns. Energy and exergy analysis of a combined renewable energy system for residential applications was conducted in [22] and the analysis showed potential spots for improvement in the overall system energy efficiency. A hybrid fuel cell-photovoltaic generator development suitable for stand-alone applications in remote areas was elaborated in [23], where different topologies were also compared to an obtained optimal design for hybrid photovoltaic–elec trolyzer–fuel cell system.

A review paper for the current status of fuel cell based combined heat and power systems for a residential sector was provided in [24], where all proposed hybrid energy solutions were analyzed