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# Domestic distributed power generation: Effect of sizing and energy management strategy on the environmental efficiency of a photovoltaic-battery-fuel cell system

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ABSTRACT

The maximum exploitation of local renewable energy sources is a key feature of DG (Distributed Generation) systems: to this aim, HPSs (Hybrid Power Systems), integrating renewable and non-renewable power sources with local energy storage may represent an effective solution, although they may require an optimum utilization of the different sub-systems, for example if including FCs (Fuel Cells).

This work introduces a new definition of system efficiency, which is linked to a class index defined according to the local renewable energy availability. The system efficiency is also demonstrated as a function of two performance parameters describing the effectiveness, respectively, of renewable and fossil energy conversion. The new set of parameters is used to study an experimental DG hybrid system including photovoltaic panels and FCs, representing a detached house. A test facility has been used to validate numerical models. A full year period was then simulated, to single out that the new set of parameters could help evaluate the HPS environmental performance and the effective renewable energy exploitation; the class index also helps evaluating the real system efficiency and environmental performance, which strongly depends on the local renewable energy available. An optimal management strategy is also found respect to the FCs utilization.



## 1. Introduction

The growing energy demand [1], along with the need to reduce carbon dioxide emissions in atmosphere [2], requires an optimal exploitation of RES (Renewable Energy Sources) which often have a distributed potential. These requirements are driving intense research efforts, as energy conversion is moving towards the paradigm of the DG (Distributed Generation), which implies that energy is consumed where produced. This also presupposes a change in the power production and management strategies at national and international levels [3,4].

Under the DG paradigm, HPSs (Hybrid Power Systems) (or micro-grids), integrating power generation from RES with short- and long-term storage options (such as hydrogen, $H_2$), efficient energy conversion systems (such as FCs [fuel cells]) and non-renewable programmable energy sources, are getting greater attention as they allow for an efficient energy utilization where it is produced. For these reasons, HPSs are intensively studied, especially under the assumption that all the energy consumed during a year has to be provided by RES (i.e. in stand-alone configuration) [5,6]. Unfortunately, technical reasons often do not allow the HPS stand-alone configuration, usually because of lack of space for RES exploitation. Some studies, then, have been presented with a configuration including exclusively short-term storage and with an FC proving the interest towards the use of $H_2$ as a long-term storage option. Simultaneously, great research effort has been produced during the last years both in the field of electrical storage [7] and FCs [8–12], in order to overcome technological issues and improve reliability and efficiency of such components. Therefore, HPSs are gaining a more competitive position with regard to traditional technologies and, indeed, although costs are still considerably high [13], some systems are already in their early market stage, as they are intensively studied in simulation environment [14–17], or already at an experimental level [3,18]. In particular, Ipsakis et al. describe an experimental system installed in Greece including PhotoVoltaic (PV) generators, a wind turbine, lead-acid batteries, a diesel generator, an FC and a long-term storage facility including an electrolyser and $H_2$ high pressure storage. Carton and Olabi [3],

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**Nomenclature**

| | |
|---|---|
| $\eta^*$ | reference conversion efficiency |
| $\eta$ | mean conversion efficiency |
| $\psi^*$ | reference performance parameter |
| $\psi$ | mean performance parameter |
| $E$ | energy [kWh] |
| $\eta_{sys}$ | HPS energy efficiency over a year |
| $I_{size}$ | size index |
| $V_{FC}$ | fuel cell mean operation voltage [V] |
| $V_{high}$ | fuel cell stop voltage [V] |
| $V_{low}$ | fuel cell start voltage [V] |
| $V_{max}$ | battery pack charge voltage [V] |

*Subscripts*

| | |
|---|---|
| Diesel | diesel |
| e | electricity |
| FC | fuel cell |
| FES | fossil energy sources |
| Load | load |
| MPP | maximum power point |
| PV | photovoltaic |
| reform | diesel reforming |
| RES | renewable energy sources |

*Acronyms*

| | |
|---|---|
| DG | distributed generation |
| DOD | depth of discharge |
| EL | electronic load |
| FC | fuel cell |
| FES | fossil energy sources |
| $H_2$ | hydrogen |
| HPS | hybrid power system |
| HIL | hardware-in-loop |
| LCC | life cycle cost |
| MPC | model predictive control |
| MPPT | maximum power point tracker |
| OCV | open circuit voltage |
| PEMFC | proton exchange membrane fuel cell |
| PSU | power supply unit |
| PV | photovoltaic |
| RES | renewable energy sources |
| SOC | state of charge |
| SOH | state of health |
| VRLA | valve regulated lead-acid |

instead, refer to an experimental HPS installed in Dundalk, Ireland, including a wind turbine as a conversion technology from RES.

For this type of DG systems, the optimization of system design and control is key to have high performance both in terms of efficiency and lifetime (mainly regarding batteries and FC). The control strategy is particularly important to those aims and several control approaches have been introduced so far including rule-based strategies [19–24], fuzzy logic [19,20], neural networks-based [21,25], or Model Predictive Controls (MPCs) [26–28]. In general in these studies control strategies or components characteristics are defined to the aim of solving the management problem via the optimization of single components behaviour, such as batteries [19,22,23], or the maximization of RES use [17,21,25,26]. Opposite restraints may rise for these activities as in the first case the main goal is to avoid highly transient behaviour of key components, which may reduce their lifetime, while RES maximization may require a very fast adaptability to power generation profiles. In Refs. [27,28], instead, the focus is only on the system cost.

Although new and refined management strategies may seem the best solution in order to face such issues, simple, yet reliable, rule-based control strategies characterized via pre-defined operating conditions as functions of the different environmental variables, still require a deeper understanding of system behaviour by varying operating conditions. In particular, the study of the FC transient operation deserves a special care, as the FC technology still has high capital costs and limited lifetime with respect to other technologies. Good results were obtained, in this sense, by Giaouris et al. [24] in a simulation model of a real installation, assuming a rule-based strategy aimed at maximizing RES exploitation and minimizing FC use.

According to these problems, system costs and reliability are the focus of most of the papers on HPSs, especially in stand-alone configuration. Studies on Life Cycle Cost (LCC) are reported in Refs. [5,6,13,29,30], often taking into account the system reliability by means of optimal system design.

Despite the great effort in the development of effective control techniques, or in the identification of optimal design criteria, especially based on the micro-grid cost, literature on HPSs currently has a lack of comprehensive evaluation parameters, especially regarding operating (i.e. energy conversion) performance. Similarly important parameter, such as equivalent $CO_2$ emissions or as primary energy consumption [31,32], is often disregarded.

This paper then introduces a novel definition of the energy efficiency, which may give a synthetic but complete assessment of the performance of the HPS during its operation. The introduced system efficiency is deeply linked to the system sizing in terms of available RES, and its value also depends on the fossil energy consumption. Moreover, two performance parameters are introduced in order to correlate the system energy efficiency to the subsystems energy conversion efficiency.

To the aim of demonstrating the usefulness of the defined efficiency and of the performance parameters for all kinds of stand-alone HPSs, both in self-sufficient and non-self-sufficient operation, the typical domestic load profile of an off-grid house has been considered equipped with an HPS system: a model of the HPS is validated through a Hardware-In-Loop approach and the system is simulated over a year period. Effects of the management strategy and of the system sizing on system efficiency, fossil energy consumption and FC lifetime are shown in terms of the introduced parameters.

## 2. HPSs efficiency parameters

### 2.1. Definition of energy conversion efficiency for micro-grids

In this work the sustainability performance of HPSs is the focus and, according to that, the purpose of the HPSs is considered to be the reduction of FES (Fossil Energy Sources) utilization, by means of the exploitation of RES available on site. The reference model is a micro-grid composed of a component converting local RES (a PV system and/or wind turbines) into electric power, a short-term energy storage (e.g. battery pack), a component converting FES into electric power (e.g. an FC or a Diesel generator) and a long-