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Techno-economic study of a PV-hydrogen-battery hybrid system for off-grid power supply: Impact of performances' ageing on optimal system sizing and competitiveness

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ABSTRACT

The use of intermittent renewable energy sources for power supply to off-grid electricity consumers requires either additional power sources or energy storage solutions, in order to manage the time mismatch between energy production and load requirements.

We investigate in this paper the interest of a hybrid solar energy system, including a lithium-based batteries bank and a hydrogen chain (electrolyser, gas storages and fuel cell), for an off-grid application. This system is compared with two reference cases: PV-diesel generator and PV-Batteries. These different systems have been represented using empirical and semi-empirical models and are simulated with the CEA made ODYSSEY platform.

The originality of our study lies in the simultaneous optimisation of the power management strategy and the components' size, and in the detailed modelling of the components (power consumption of the auxiliaries and ageing approach in the form of performances degradation).

The PV-Batteries-H_2 system is operated by an efficient power management strategy and its optimal sizing is assessed on the basis of technical (e.g. load satisfaction) and economic (e.g. levelized cost of electricity) criteria. The results highlight the important role of the hydrogen chain in reducing the cost of the supplied energy. It is also shown that performances degradation of the hydrogen chain has a limited impact on the system optimal sizing and economic results.

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Introduction

As reported by the International Energy Agency, 1.3 billion people in the world have no access to electricity [1]. However, extending the electricity grid is not always the most cost-effective solution for electrification and stand-alone off-grid power supply installations might prove more profitable for large countries and limited energy requirements [2,3].

The majority of off-grid systems presently rely on conventional electricity generation technologies, mainly diesel generators. Due to the concerns on climate change and dependence on fossil fuels, systems based on photovoltaic (PV) or wind production, and employing diesel generator as a backup solution (in the night time or in the case of cloudy and windless days) are rapidly penetrating the market for small-scale systems in the kW range [2]. However, this solution presents the same drawbacks as the diesel generator alone: increasing and unstable fuel prices, issues with fuel availability and harmful carbon emissions.

An alternative backup of intermittent renewable energy (RE) sources for power supply to off-grid electricity consumers is the use of energy storage technologies. Among them, batteries technologies start to enter the market often hybridized with a diesel generator. However, several studies have shown that the coupling of batteries (for intra-day storage) and hydrogen energy (for seasonal storage) is a good option to ensure a security of supply all year round [4–6].

Designing a hybrid power system is a complicated task that includes two main exercises: the sizing of the different components and the optimisation of their management through an adequate strategy.

Since the recognition by Ulleberg [7] of the significant impact of control strategies on the performance of PV-Hydrogen systems, numerous studies have developed and tested various types of control strategies. In the present paper, we will focus on hybrid systems coupling one intermittent RE source (PV) and energy storage through batteries and hydrogen. In such systems, the power management strategy must define which of the two storages (battery or hydrogen chain) is operated in priority if required (be it for an excess or a deficit of RE production compared to the load).

The main decision parameters that have been implemented so far in power management strategies are the followings:

- SOC (State of Charge) of the battery,
- SOC of the hydrogen storage,
- Level of power to be absorbed (in case of excess) or provided (in case of deficit) by the energy storage.

In the original study by Ulleberg [7], further investigated by other authors [8–11], the power management strategy is based on the SOC of the battery. The level of the battery SOC, compared to fixed SOC levels, indeed determines the on/off switching of the electrolyser and the fuel cell. In most studies, a hysteresis band for the upper SOC level (determining the on/off switching of the electrolyser) and for the lower SOC level (determining the on/off switching of the fuel cell) prevents from frequent start-ups and shutdowns of the electrolyser and the fuel cell (a pattern that could be observed in Refs. [10], where these hysteresis bands were not present), and guarantees a smoother operation of the hydrogen chain. Several modes of operation for the electrolyser and the fuel cell have been tested. Based on energy efficiency considerations, Ulleberg [7] and Zhou [11] have concluded that the electrolyser should be operated in variable power mode, and the fuel cell should be operated in fixed power mode.

Some studies [5,12,6] have included the SOC of the hydrogen storage as a decision parameter in addition to the SOC of the battery bank. Castañeda [6] showed that the inclusion of this indicator in the power management strategy permitted to get better results in terms of energy efficiency of the two storages.

The last decision parameter to appear in some power management strategies is the excess (or deficit) power to be absorbed (or provided) by the storage. Indeed, Dufo-Lopez [13] showed that for low powers, the cost of cycling energy through the battery is lower than the cost of cycling energy through the hydrogen chain (the reverse is observed for high powers). A power level can thus be fixed: for residual powers below this power level, the battery is operated, and for residual powers above this level, the hydrogen chain is operated. Dufo-Lopez [13] claims that the control strategy based on this indicator determines the most economical way to use the spare energy or meet the energy deficit. Several studies have introduced this decision factor in power management strategies, coupled [6,14] or not [13] to the two previously mentioned decision indicators.

Most of the studies presented here above focus on the analysis of the power management strategies for a fixed architecture and size of the system components. The analysis is mainly based on indicators of technical performance of the system (e.g. storage efficiency, solicitation profile of the components, energy balances, number of startups of the components…). In some studies [5,11], the size of the components is optimised based on the power management strategy. In only one study [13], the parameters of the power management strategy are optimised together with the size of the components, in order to minimize an economical criterion.

In our study, we use the CEA made ODYSSEY platform introduced in Ref. [15] to study the operation of a PV-Batteries-H_2 system for a stand-alone application. After developing a power management strategy similar to Ulleberg study [7], we determine the optimal system configuration, by optimising the size of the components and the parameters of the power management strategy. The originality of our study lies in the simultaneous optimisation of the power management strategy and the components' size, and in the detailed modelling of the components. In particular, we take into account the power consumption of the auxiliaries, and the ageing of the components (battery, electrolyser, fuel cell), in the form of performance degradation.

The paper is organized as follows. Section Case study description describes the case studied in the paper and the energy systems considered (PV-Diesel generator, PV-Batteries and PV-Batteries-H_2). For each energy system a description of the different components and their empirical and semi-empirical modelling is provided. The sizing parameters subject to optimisation are then presented. Independently of the