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Design, testing and evaluation of a community hydrogen storage system for end user applications

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ABSTRACT

A hydrogen community energy storage (H-CES) system including a PEM electrolyser, metal hydride tank and PEMFC unit was designed, built and tested for a low carbon community. The H-CES performs end user applications including PV energy time-shift and demand load shifting. The system proved to have good flexibility and capability for mid-term and long term energy storage, with a round trip efficiency of 52%. Mid-term energy storage was demonstrated when the H-CES performed demand load shifting and hydrogen was stored for use one day later. Additionally, when PV energy time-shift was added to demand load shifting the operational hours of the electrolyser increased by 116%. Some improvements for future H-CES systems are also discussed in this study, the consideration of the optimum electronic equipment for the technology and rating being considered a key factor to maximize the discharge rating, round trip efficiency and reliability.

Introduction

There is strong interest in the role that smart communities can play to facilitate greater renewable energy (RE) generation [1] and the use of microgrid technologies to effectively manage the community demand load [2], whilst increasing user awareness of energy [3]. Research has previously identified the potential of communities to catalyse the transformation of our society by introducing “grassroots” innovations in terms of construction supply chain, reducing ecological footprint, community-building and enabling collective action [4]. Additionally, several programs have been developed worldwide in order to promote low carbon technologies and engagement activities in communities, for example the Low Carbon Communities Challenge in the UK [5], the Smart Communities Programme at the Maryland Smart Energy Communities in USA [6] and the Smart Community project in Japan [7]. From a technical point of view, the benefits of having several RE sources with different generation patterns which complement each other has already been addressed for grid [1] and off-grid communities [8].

Hydrogen storage in single homes has been studied both technically and economically, more often for off-grid houses. In these studies, the energy storage system was sized to guarantee the electricity supply to the autonomous house. In order to achieve it, the local microgeneration and energy storage installations on-site were designed to meet all demand requirements even in a period (typically several consecutive days) with low RE resource, i.e. worst supply

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conditions. Therefore, the energy storage capacity was calculated based on an analysis of the demand load and RE supply making use of simulations [9,10]. The use of hydrogen storage connected to solar energy for achieving autonomous electricity supply was demonstrated in Germany in 1993 [11] and in the USA (New York) in 2008 [12]. A hybrid system comprising a 2 kW_e PEMFC unit and lead acid batteries in combination with wind (1 kW) and PV (0.8 kW) generators for a mobile house in Turkey (Istanbul), was designed according to the peak (2.4 kW) and annual (1550 kWh) demand load requirement and the available solar resources [9]. Surplus RE generation was stored in eight 200 Ah at 12 V lead-acid batteries (19.2 kWh) with a depth-of-discharge of 60% and pressurized cylinders (up to 160 bar) with an equivalent capacity of 8.2 kWh using a 0.4 kW PEM electrolyser. In a later work, different strategies were compared in order to quantify the performance of the battery bank as a function of the operation of the PEMFC unit and it was experimentally demonstrated that the highest battery efficiency, equal to 85%, was achieved when the battery and the hydrogen storage system charged and discharged simultaneously instead of in sequence [13]. However, the number of start-ups performed by the electrolyser and PEMFC unit were not included in the analysis despite the fact that they can drastically reduce the lifespan of these technologies [14]. Work also focussing on autonomous houses by Santarelli et al. simulated the performance of a hydrogen storage system connected to different RE plants (hydro, wind and solar generators) in the north of Italy [10]. The hydrogen storage system comprised an alkaline electrolyser with a rating fixed by the total rating of the RE generators, a pressurized storage tank and a 3 kW_e PEMFC unit. Seasonal storage was necessary to meet the demand load, especially in the case of solar and hydro energy which offer high seasonal patterns. Therefore, hydrogen storage was more suitable than batteries for this specific application despite a seasonal round trip efficiency of only 38%.

Some recent studies also analysed a hydrogen storage system for grid-connected homes. If assuring electricity supply was the objective in the case hydrogen storage systems installed for autonomous houses, some examples of economic benefits introduced by a hydrogen storage system to individual grid-connected homes (or communities) are increased PV energy self-consumption [15] and reducing electricity import [16]. These economic benefits are driven by higher retail electricity prices than export tariffs and the reduction of electricity bills respectively. Focussing on a grid-connected house at Nottingham (UK) using simulation-modelling, a hydrogen storage system was compared with lead-acid battery technology [15]. This showed that hydrogen storage increased the self-consumption by 132%, which meant an additional income of £ 102 in 2012 in the UK. Alternatively, a 4.5 kWh metal hydride storage tank was integrated in a hydrogen storage system for a grid-connected house reducing the annual electricity import by 76% [17]. Regarding the type of hydrogen tank technology, the advantage of a low-pressure hydrogen storage system through metal hydrides regarding compressed gas is that it enhances system safety in the built environment. The techno-economic benefits of using energy storage in communities (in contrast to being used in single dwellings) were assessed for lead-acid and lithium-ion batteries. The levelised cost of meeting the demand load using PV energy generated locally could be reduced by 37% and 66% regarding a single dwelling for a 10-home and 100-home communities respectively [18]. In the case of hydrogen storage systems for communities, it was quantified that a 6 kW PEM electrolyser could only supply 19% of the annual hydrogen needs of a 1.2 kW SOFC unit which supplied 128% more electricity to a 7-home community than to a single home due to better match with the community demand load, i.e. better self-consumption [16].

According to this literature review, most previous studies on hydrogen storage systems have focused on off-grid single homes instead of grid-connected communities, especially those including experimental results. Therefore, PV energy was the main electricity source to run the electrolyser without making use of cheap electricity (related to retail electricity tariffs which make a difference on the electricity price depending on the time of the day), i.e. shifting local demand to off-peak periods. As a consequence, there is need for demonstrations of hydrogen community energy storage (H-CES) systems performing PV and demand management in grid-connected communities in order to understand the technical and economic benefits of hydrogen storage, this research gap being emphasized when the H-CES system performs both applications simultaneously. Also, learnings and research outputs from the design, building, testing and appraisal phases of such systems are also interesting for future designs. Additionally, most previous hydrogen storage systems used compressed gas technology therefore the performance of metal hydrides storage tanks coupled with an electrolyser and FC unit needs to be explored further. The content of this paper has the following structure. The next section introduces end user applications performed by the H-CES system. Sections 3 and 4 present the H-CES system at the University of Nottingham and the experimental results respectively. Finally Section 5 discusses further the results and the practical implications of the design, construction and testing phases while Section 6 concludes this paper.

End user applications

End user applications are those which satisfy end user needs by managing their local community energy, i.e. RE generation and demand [19]. RE time-shift and demand load shifting have been considered key end user applications because they occur on a daily basis instead of “power applications”, e.g. voltage control and power quality which are more related to punctual events or problems derived with the network performance [20]. Also, both domestic RE generation (supply) and demand management are covered. RE time-shift, and PV energy time-shift (PVts) in particular, consists of shifting PV generation to meet the demand load later. The economic driver for this application is the higher price to import in comparison to export electricity since the latter does not account for transport and other ancillary costs.

Demand load-shifting (LS) consists of shifting the electricity imported by a home or community to take advantage of tariffs with valley and peak prices. In terms of the H-CES management, it consists of generating hydrogen and storing