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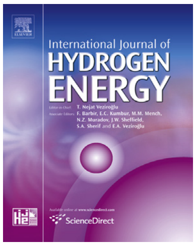

Experimental assessment of hydrogen systems and vanadium-redox-flow-batteries for increasing the self-consumption of photovoltaic energy in buildings

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ABSTRACT

This paper presents a detailed experimental assessment of an alkaline electrolyser, PEM-Fuel cell and Vanadium-Redox-Flow-Battery (VRFB) integrated into building automation system. The aim is to provide an experimental platform to develop operating strategies for building-integrated hybrid renewable energy systems. The first part of this study deals with the design of the test-facility followed by the introduction of the control structure and the implemented energy management strategy. The last part of the paper presents experimental results of the individual energy conversion systems and of the test-facility configured as a grid-connected hybrid storage system, with the control objective to maximise the self-consumption of electricity produced by photovoltaics. Furthermore, the dynamic performance of a hydrogen system (electrolyser and fuel cell) and a VRFB integrated into a building automation system is discussed in detail. The results obtained show that the performance is negatively influenced by the dynamic operation and how system integration aspects limit the capability of the energy storage systems to deal with high transient power variations.

Introduction

The building sector will play an important role in transforming our centralised energy system into a decentralised system, where energy is produced, stored, traded and consumed more locally. It is also a key in decreasing the energy consumption since it is responsible for approximately 40% of the primary energy usage in the EU [1]. Thus, the EU has issued a directive that imposes all new buildings to be nearly zero-energy buildings after the 31st January 2021. This requirement means that the building must reach a very high energy efficiency, an almost zero or at least very low annual energy balance and the energy must preferably supplied by renewable energy sources either generated on-site or nearby [2]. It is expected that buildings will be transformed from passive energy consumers into active energy providers/consumers (so called “prosumers”). Recently, the interest in net

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zero- and positive-energy buildings has increased in the research community [3–5]. Regarding electric energy, there needs to be balance between the electric power generation and the electric load. Imbalances can otherwise lead to grid quality issues, for example over-voltages in times of low demand caused by a high penetration of PV [6]. It is therefore of paramount importance to understand the energy usage within the building and to establish control mechanisms to manage the energy flow either inside the building or between the building and the electric grid [7].

In this context, the introduction of hybrid renewable energy systems (HRES) composed of renewable power sources and electrical storages into the built environment has recently gained more attention in the literature [8–14]. The application of HRES at the low-voltage level seems to be a good solution to effectively manage the energy flow; however, design, control and operational aspects involved with HRES are rather complex. Several parameters need to be considered, such as start-up times, working temperature, response times, minimum and maximum power input/output and the state-of-charge (SOC). A recently started project initiated by the International Energy Agency, has underlined the need for the research to investigate the technical potential and the performance of all kinds of energy storage systems for buildings associated with renewable energy systems [15].

The introduction of electric energy storages is a necessary step towards a low carbon electric energy system and it is believed that its application will be needed at all levels of the electric energy supply system [16]. Various technologies can be applied to store renewable energy. Several studies have compared different energy storage technologies in terms of their performance and functionality [17,18]. However, each technology has its own limitations and no storage technology can currently provide all the desirable characteristics of high energy and high power density [19].

To overcome the limitations of one single storage technology, two or more storage technologies can be combined to form a hybrid storage system, which complement each other. Recently, Bocklisch, Böttinger and Paulischke [20] have presented an experimental study on a test-bed composed of lithium batteries (short-term storage with a high power density) and hydrogen systems (long-term storage with high energy capacity but slower system response times) with focus on domestic application. They highlighted the potential of such systems to significantly reduce the PV power fluctuations and to increase the PV energy utilisation. Another approach which can be applied is the community storage in order to share the storage technologies within the community [21,22]. Parra et al. [21] presented a simulation study on a combination of lithium battery and hydrogen storage for a small community with PV installations. They concluded that the introduction of community energy storage helps balancing the local demand and the volatile PV generation. They further highlighted the option of using the community energy storage as deferrable load to store off-peak renewable generation such as wind energy, which can beneficial to stabilise the regional electricity grid.

In general, the type of electric energy storage that can be deployed depends strongly on the application, operational constraints and spatial requirements. Possible storage technologies applicable within the built-environment are discussed in Ref. [23]. Nowadays typical storage technologies installed in buildings are electrochemical batteries e.g. lead-acid and lithium-ion; however, in Ref. [23] they also discussed emerging technologies such as vanadium-redox-flow-batteries (VRFB) and the usage of hydrogen in the residential sector.

VRFB has the potential to be applied at the distribution and customer level providing energy management services. Compared to traditional battery systems, VRFB has the advantage that the power rate can be independently scaled from the energy capacity and that the entire working range of the state-of-charge (SOC) can be used without reducing its lifetime. Over the last few years, the number of VRFB demonstration projects to store renewable energy has significantly increased [24–27]. At customer level the ongoing research project “Multi-Source Energy Storage System Integrated in Buildings” has published first results about the development and integration of small-scale VRFB [28]. However, VRFB is a relatively new technology which is only recently commercially available. It was found that the commercial production and the availability of such systems have increased faster than fundamental knowledge about the underlying process [29]. Ongoing research is focused on all aspects, for example on new component materials, electrolyte, electrochemical reactions, flow distribution and flow rates optimisation, system integration and costs reduction [30].

Hydrogen can be used, if generated from renewables by water electrolysis, as a clean and sustainable energy carrier. It can play an important role to store surplus renewable energy and it facilitates a link between the electricity, the heat and the transport sectors by offering a flexible usage as fuel [31]. Although, the applicability of hydrogen at customer level is questionable due to the high component costs and low overall efficiency, the energy carrier hydrogen has motivated many researchers to demonstrate the technical feasibility at customer level [20,21,32–43]. It is believed that hydrogen systems have a high potential for the decentralised market if the system reliability can be improved [44]. Despite technological progress there are still research challenges in terms of improving system efficiency, system integration and to reduce the costs of the components [45].

Dynamic performance of fuel cells, electrolysers and VRFBs and their integration into HRES have been experimentally investigated by a number of studies [38,46–49]. All studies reported difficulties to achieve overall controllability of the HRES. The main challenges reported were related to the integration of the different component interfaces into a central data acquisition and control system [38,46], the adjustment of a commercial available electrolyser system to buffer the power output of renewable sources [47], the negative influence of peripheral systems (the balance-of-plant) on the overall controllability [48], and the communication delays between power and measuring devices [49].

Both technologies are already available in suitable sizes for buildings; however, relatively little is known about practical aspects and their performance in building-integrated HRES. System integration issues associated with the development of a building-integrated HRES composed of hydrogen systems or VRFB are not adequately reported or documented in the literature. More importantly, their dynamic performance

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