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Modeling of PV generation, battery and hydrogen storage to investigate the benefits of energy storage for single dwelling

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ABSTRACT

This work presents the results of simulation of battery and hydrogen technologies for renewable energy management, load-leveling and peak-shaving in a single grid-connected house in Nottingham United Kingdom where three people live. The house has a PV installation of 4.5 kW_p. A stochastic model which takes active occupancy into account is used for simulating the electricity demand. A 10-kWh lead-acid battery and a 1-kW fuel cell together, with a 600-l hydrogen (gas) storage tank at 15 bar (31.3 kWh) are used for these simulations for short (daily cycles) and mid-term (3-day cycles) storage, respectively. Energy balances on a representative summer and winter day for both storage technologies are presented, along with annual balances. The battery increases the local use of PV energy generated on-site by 171%, while the hydrogen increases it by 159%. According to the current feed-in tariff legislation in the UK, the increase of the local use of PV energy means an additional annual income of at least £112 and £102 for the battery and hydrogen storage, respectively.

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1. Introduction

Greater renewable energy penetration is occurring due to environmental concerns and other issues related to fossil fuels at this moment. However, most renewable energy technologies are intermittent because they depend on weather conditions (Freris & Infield, 2008) and as a result energy storage technologies will be essential to increase the availability and reliability of distributed renewable energies. Micro-renewable generation can play a significant role to reduce emissions in the domestic sector (Bergman & Eyre, 2011). In the UK, energy use in the domestic sector accounts for the 30% of the total energy consumption and it has risen by 23% over the last 35 years (Utley & Shorrock, 2010), this trend being comparable to that of many other countries. Storage technologies are essential to ensure continuous energy supply in stand-alone applications (Santarelli & Macagno, 2004) and in grid-connected buildings, energy storage can reduce power losses and increase the reliability of a more distributed electrical system (Nair & Garimella, 2010). Another driver for the use of energy storage close to consumer points is the necessary decarbonization of the heating and transport sectors using either electricity or hydrogen as energy vectors. Energy storage can also add flexibility to the electricity system and help to manage increasing peaks in demand instead of upgrading the electrical network which is the traditional approach usually taken. In fact, energy storage technologies can be integrated into smart grids and micro-grids to match new distributed and variable generation and demand.

Energy storage at the domestic level can also introduce other technical benefits to the electricity network. As renewable energy technologies and other types of distributed generation such as CHP units become more widespread in residential areas, power quality and end-user voltages could be negatively affected (Paatero & Lund, 2007). As a consequence, storing surplus energy and using it on-site later will help to reduce the negative impact of variable generation at consumption level. At the generation level, the electricity system would be less dependent on generators with high carbon intensity based on coal and natural gas which are used to meet peaks in the demand caused by the domestic sector because of their ramping capability. As a consequence, Germany has already legislated a self-consumption bonus to give incentives to PV owners who use the PV power generated on-site, as opposed to exporting it into the grid (Braun, Büdenbender, Magnor, & Jossen, 2009). The addition of the self-consumption bonus (0.2501€/kWh) plus the cost of the electricity (19.4501c€/kWh) is higher than the export tariff (43.01c€/kWh). In the UK, all electricity generated by PV installations with a peak power lower than 4 kW_p is paid 0.218£/kWh, reducing to 0.168£/kWh for installations between 4 and 10 kW_p from March 2012. The user can consume electricity on-site or export it into the grid with a reimbursement equal to 0.031£/kWh, which is significantly lower than the cost of the electricity (around 0.13£/kWh) (Ltd, 2012). As a result, the use of PV energy on-site is valued (August 2012) at 0.348£/kWh or 0.298£/kWh reducing to 0.249£/kWh or 0.199£/kWh when exporting to the grid depending on the size of the installation.

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Several authors have compared different electricity storage technologies available in the market and suggested possible applications for every technology depending on the power rate and discharging duration time, among other characteristics (Hall & Bain, 2008; Ibrahim, Ilinca, & Perron, 2008). Likewise, there have been many researchers (McDowall, 2007; Mohd, Ortjohann, Schmelter, Hamsic, & Morton, 2008; Wade, Taylor, Lang, & Jones, 2010) who have suggested the possible advantages of implementing energy storage at the distribution level, typically linked with the penetration of renewable energy technologies and the related regulation of the electrical system. In general, they discussed battery, supercapacitors and flywheels technologies. The benefits of energy storage very close to consumer points, namely at a residential level were described by Nourai, Sastry, & Walker (2010) and Roberts and Sandberg (2011). The authors suggested incorporating batteries such as lead-acid and lithium-ion to the secondary of distribution transformers, hence providing storage at the grid edge. They introduced the concept of community energy storage (CES) which refers to energy storage systems able to carry out several tasks such as renewable energy support, demand shifting, peak-shaving and system regulation.

When considering introducing energy storage at a community level, a single house approach should be the reference and basic case to study. As a consequence, integrated models of different micro generation sources (PV, wind and combined heating and power units CHPs) were integrated with a lead-acid battery to investigate the optimum size of battery storage for onsite energy capture (D.P. Jenkins et al., 2008). The authors included battery lifetime and grid export considerations as key factors in battery's size. The research obtained the optimum battery size for a given onsite generation profile considering the battery life, cost and the generation profile. Real demand and PV generation in seven houses in Belgium were used to obtain the optimums battery size for daily cycles and peak demand (Mulder, Ridder, & Six, 2010). Other work focuses on different battery technologies (Nair & Garimella, 2010) and the authors argued that batteries are the most mature technology for a single dwelling. Therefore, they focused on voltage characteristics of different battery technologies available in the market using simulation modeling and experimental research. The research concluded that lithium-ion technology offers the most stable voltage plateau and this technology will be the most cost competitive because of low operating costs compared to lead-acid technology when the capital cost of lithium-ion battery is around four times higher than lead-acid battery. Finally, grid parity between the cost of generating electricity from PV and the cost of purchasing from the grid price is expected for some European countries by 2013–2014 (Castillo-Cagigal et al., 2011). Then, using energy generated on-site will be more profitable than exporting to the grid even without incentives. The authors used demand side management (DSM) together with battery storage to increase the amount of PV energy consumed on-site in a house in Madrid and they concluded that DSM techniques can reduce the required battery capacity.

The work presented here compares the technological and economic performance of a lead-acid battery and hydrogen storage installations for a single house in the UK with PV generation when considering the current British feed-in tariffs legislation. It has been found in the literature that research work which describes the technological performance of energy storage technologies in detail does not include the economic aspects, and linking both aspects is considered a key factor for finding a business case for energy storage for end user applications in the domestic sector. This work emphasizes the daily performance of the PV installation, the storage technologies and the grid to understand the seasonal performance of the storage installation. This work is the starting point to obtain the optimum size of energy storage for end user customer applications in the domestic sector within smart grids when considering different technologies. The answer to this will be a key consideration for any business case looking at the economic role out of energy storage technologies.

2. Electricity storage technologies for a domestic property in the UK

The purpose of a storage unit is to balance the electric load and PV generation by increasing PV generation use on-site. When comparing PV generation and electric demand on a daily basis, the mismatch between generation and demand is defined and the storage requirements for the house can be obtained. Then, considering the range of storage technologies available in the market, the most suitable technologies are selected.

2.1. Photovoltaic model

Horizontal irradiance (W/m^2) was measured using a weather station which incorporates a pyrometer with a resolution time of 1 min over a year at the University of Nottingham. The 4.5 kW_p solar array consists of 25 m^2 monocrystalline silicon panels with a maximum panel efficiency of 18%. This area is necessary because solar resource is limited in winter at high latitude areas. Two different tilts of the PV array are utilized considering that building integrated photovoltaics allows more flexibility in the integration of PV panels and arrays taking advantage of different surface areas (Hagemann, 2004). For the battery storage, the PV array is tilted at 60° and solar generation is maximized during the winter period when less solar radiation is available. For the hydrogen storage, the PV array is tilted at 30°, obtaining a higher yield during the summer period to take advantage of the bigger capacity of the hydrogen system (Villalva, Gazoli, & Filho, 2009). Also, a maximum power point tracker (MPPT) is used to make PV performance independent of the irradiance, temperature and load as much as possible. Eq. (1) represents the single diode model including temperature dependence and with series and parallel resistances which is used to obtain the PV output

$$I = I_{PV} - I_0 \times \left[\exp\left(\frac{V + R_s \times I}{V_t \times a} \right) - 1 \right] - \frac{V + R_s \times I}{R_p} \quad (1)$$

In Eq. (1) I, I_{PV} and I_0 are the current output, photovoltaic and saturation currents, respectively; V_t is the thermal voltage of the PV panel; R_s and R_p are the equivalent series and parallel resistance of the PV panel. All the different models presented in this work and simulations have been implemented in the Matlab environment.

2.2. Demand model

The electricity demand model generates the electricity demand for a three person dwelling in Nottingham. A stochastic model which takes active occupancy into account and its seasonal variation is used for simulating the domestic electricity demand (Fazeli, Gillott, Johnson, Sumner, & Parra, 2011). This model is a refined bottom-up model which uses time-use survey (TUS) data, appliance consumption specification and annual temperature and irradiance profiles. At high latitudes, domestic demand in winter is much larger than demand in summer because there are less solar hours in winter but also electrical chillers are not utilized in the summer.

As an example of a basic energy storage application, PV generation and electricity demand in a single dwelling have been simulated using the above models. Fig. 1 represents a typical day in which PV generation from the 4.5 kW_p array tilted at 30° mismatches electricity demand (17th March). As a consequence, most generated energy is exported to the grid on this day (72%). Annual results were obtained by considering all the daily results along the

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