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# Techno-economic analysis of the viability of residential photovoltaic systems using lithium-ion batteries for energy storage in the United Kingdom

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## HIGHLIGHTS

- Commercially available PV-battery system is installed in mid-sized UK home.
- PV generation and household electricity demand recorded for one year.
- More than fifty long-term ageing experiments on commercial batteries undertaken.
- Comprehensive battery degradation model based on long-term ageing data validated.
- PV-Battery system is shown not be economically viable.

## ARTICLE INFO

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## ABSTRACT

Rooftop photovoltaic systems integrated with lithium-ion battery storage are a promising route for the decarbonisation of the UK's power sector. From a consumer perspective, the financial benefits of lower utility costs and the potential of a financial return through providing grid services is a strong incentive to invest in PV-battery systems. Although battery storage is generally considered an effective means for reducing the energy mismatch between photovoltaic supply and building demand, it remains unclear when and under which conditions battery storage can be profitably operated within residential photovoltaic systems. This fact is particularly pertinent when battery degradation is considered within the decision framework. In this work, a commercially available coupled photovoltaic lithium-ion battery system is installed within a mid-sized UK family home. Photovoltaic energy generation and household electricity demand is recorded for more than one year. A comprehensive battery degradation model based on long-term ageing data collected from more than fifty long-term degradation experiments on commercial Lithium-ion batteries is developed. The comprehensive model accounts for all established modes of degradation including calendar ageing, capacity throughput, ambient temperature, state of charge, depth of discharge and current rate. The model is validated using cycling data and exhibited an average maximum transient error of 7.4% in capacity loss estimates and 7.3% in resistance rise estimates for over a year of cycling. The battery ageing model is used to estimate the cost of battery degradation associated with cycling the battery according to the power profile logged from the residential property. A detailed cost-benefit analysis using the data collected from the property and the battery degradation model shows that, in terms of utility savings and export revenue, the integration of a battery yields no added benefit. This result was, in-part, attributed to the relatively basic control strategy and efficiency of the system. Furthermore, when the cost of battery degradation is included, the homeowner is subject to a significant financial loss.

## 1. Introduction

The United Kingdom (UK) Government set a carbon dioxide ($CO_2$) emission reduction target of at least 80% by 2050 from 1990 levels [1] which became legally binding through The Climate Change Act [2]. Given that the UK power sector accounts for one-fifth of the total final energy demand, contributing 35% of total $CO_2$ emissions [3], with demand projected to increase under many scenarios [4] it is identified

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as the single most important route for decarbonisation [3]. Since 55% of electricity, within the UK, is generated from fossil fuels (with 21% Nuclear and 25% renewable) [5], the obvious route to decarbonisation is by reducing energy consumption. However, the possible negative impacts on economic growth and living standards arising from cutting back energy demand, means that many authors advocate the greater deployment of more environmentally clean alternative energy resources [6].

Renewable energy technologies are expected to play a major role in the decarbonisation of the UK power sector [7], while contributing to domestic energy security. Among the many options available, solar photovoltaic (PV) power is found to have substantial potential for electricity generation [8]. A challenge with PV generated electrical power is the flexibility needed to match demand and supply such that supply needs to match at each time point [9]. Electrical energy storage is one option to mitigate the supply/demand mismatches.

Recent developments that reduce the cost of solar PV panels [10,11] combined with a 59–70% (per kWh) reduction in the cost of lithium ion batteries in the last decade [12,13] have acted as catalysts in stimulating interest in solar home systems (SHS). Significant uptake of combined PV-battery units is now increasingly seen as a possible future, which would lead to increased decentralised generation and higher self-consumption levels [14]. If current battery cost reduction trends persist, it is predicted that these systems could ultimately disconnect from the grid and lead to autonomous homes or micro-grids [14].

In assessing the economic viability of solar home systems, PV-battery storage systems were shown to be profitable for small residential PV systems in Germany [8], although the assumption for battery costs in that study were deemed to be extremely ambitions (EUR 171/kWh). Other studies, also focussing on the German market, found that the profitability of PV-battery systems are dependent on significant reductions in battery price and the favourable German regulatory framework [15]. Corroborating the results of Ref. [15], Truong et al. [16] conclude that the viability of SHS is dependent on both an increasing retail price of electricity and financial subsidies. Such subsidies include, for example, feed-in-tariffs, green certificates or favourable net metering schemes [17]. The economic benefits of SHS is also correlated with the increased usage of on-site solar energy within the home, a practice termed self-consumption [14–16].

A limitation of such previous studies however, is that their assessment of economic viability did not consider the impact of battery degradation. Within the context of this study, battery degradation is characterised by a reduction in the useable energy capacity of the battery (e.g. capacity fade) and a reduction in the ability of the battery to deliver sustained power (e.g. power fade) resulting from an increase in battery impedance. For example, although studies such as [8] considered numerous forward-looking electricity pricing scenarios and the impact of subsidies, their work neglected the cost associated with battery degradation. Given that the daily capacity throughput for a battery in an SHS is almost twice the battery rated capacity [14] – approximately ten times larger than a typical electric vehicle, assuming daily recharging [18] – the impact of battery degradation is expected to be significant [19–21].

In this work therefore, we address the economic viability of solar home systems within the UK considering battery degradation. For this, we develop and employ a comprehensive battery degradation model based on long-term ageing data collected from more than fifty degradation experiments conducted on commercially available lithium ion batteries. This comprehensive model accounts for all established modes of degradation including calendar ageing, capacity throughput, ambient temperature ($T$), state of charge ($SoC$), depth of discharge ($DoD$) and the applied current ($I$) [21]. The model is validated using highly transient real-world usage cycles for various environmental conditions corresponding to different geographical regions of the UK.

Original data for PV generation and electricity consumption in an occupied UK family home is collected for an entire year. Previous studies which have reported consumption data have either been synthetic, i.e., modelled consumption estimates [22] or did not consider on-site generation [23–26]. Using this typical domestic electricity profile for a household in the UK and the detailed battery degradation model, the economic viability for PV battery systems in the UK is addressed.

This paper is outlined as follows: In Section 2, the PV-battery system is introduced and electricity profiles for an occupied family home is presented. The development and validation of the battery degradation model is presented in Section 3. Cost benefit analysis of SHS, considering battery degradation, is presented in Section 4. Analysis and discussion including the impact of future policy and pricing scenarios are presented in Section 5. Finally, conclusion and further work is presented in Section 6.

## 2. PV generation and electricity demand for a mid-size UK family household

### 2.1. Data collection

The domestic property explored here is based in Loughborough, Leicestershire, UK and is a three bedroomed, detached property in a domestic district of the town. Occupancy is a young family of four, with two children under the age of six and an approximate building size of 83 m$^2$. A number of low carbon and energy saving measures are installed in the property, including LED lighting, solar PV, battery storage and the family also own an electric vehicle (EV) which is regularly charged at the property. Based on the properties Energy Performance Certificate (EPC – which is an assessment of key items such as loft insulation, and the operating efficiency of household appliances, such as: the domestic boiler, hot water tank, radiators and windows, etc. The assessment provides a single number for the rating of energy efficiency, and a recommended value of the potential for improvement) the house is placed in band C, with an efficiency rating of 69–80% which is above the England and Wales average of band D [27]. The specifications for the commercially available PV and battery storage system installed in the property are given in Table 1 and a system schematic for the property is given in Fig. 1. Data collection has a 5-min sample period for all of the systems installed in the property, with the EV demand included in the total building demand value which is measured by a current sensor integrated within the supply meter.

### 2.2. Electricity demand and PV generation

The average annual electricity consumption for UK domestic properties is 3100 kWh for standard customers and 4300 kWh for customers on an Economy 7 tariff [28,29] (which is a differential tariff provided

**Table 1**
Technology and data collection specification for the domestic property in Loughborough.

| Item | Specification | Data collected | Units | Frequency |
|---|---|---|---|---|
| PV array | 4 kW monocrystalline PV array (20.4% efficiency, 327 W nominal power rating) | Solar generation<br>Solar export to the grid<br>House import<br>House usage | kWh | 5-min |
| Battery storage | 2 kWh rated (1.6 kWh actual); 400 W inverter; lithium-ion battery | SoC over time<br>Energy flow in/out | %<br>kWh | 5-min |
| Electric vehicle | 2015 Nissan Leaf; 24 kWh lithium-ion battery | N/A | N/A | N/A |
| Building demand | | Energy flow in/out | kWh | 5-min |
| Charge point | 13 Amp plug | Included as part of building energy demand | kWh | 5-min |