

Optimising energy storage for domestic household with PV to support the grid

Haitong Zhang, Dave Stone, Dan Gladwin

Department of Electrical and Electronics Engineering, The University of Sheffield, Sheffield, S1 4DE, United Kingdom

Abstract

In this paper, load profile modelling is introduced as the basis of the research, and a practical photovoltaic (PV) profile for a typical UK household with 4kW solar system is presented to couple with the load. An evaluation on the combined profile throughout a year is done to size the required battery, and a smart domestic energy storage system is developed to integrate the domestic energy storage facility with the renewable energy generation system, in order to create a win-win situation for customers and grid. By using PV as an alternative energy resource to power the home appliances, the system can reduce the dependence of household on grid, it can reduce the stress on the grid by managing the loads and exporting excess energy back to grid to balance peak demand. Also it can cut the electricity bill for customers and make profit by selling electricity to grid. Moreover, the electricity tariff is considered in this study for system validation. The payback period of the system is evaluated against different sizes of PV-battery setups.

Keywords: Solar power, Renewable energy, Energy storage and management, Smart grid, PV, Optimisation

1. Introduction

The electricity consumption in the domestic sector can be affected by two factors, the type and number of electrical appliances owned in domestic houses and the user consumption pattern of occupants of the house [1]. The wide range of variation on appliances' power consumption and user pattern cause the difficulty on predicting daily domestic load profile accurately especially for short time steps. A more complex and precise simulation tool is therefore required to be developed for household load profile generation.

In order to meet the target set by the UK Government's Climate Change Bill in 2007 to cut the UK CO₂ emissions by 60% from 1990 levels before 2050 [2], schemes such as energy efficiency measures (e.g. appliance energy labelling and house insulation) [3] and smart metering [4] which designed to affect the households behaviour were considered. Smart meters can provide a series of information including tariffs and usage to encourage households use less electricity. The UK Government's Renewable Energy Strategy sets a legally binding target in 2009 to ensure 15% of the energy produced by renewable sources by 2020 [5], and runs alongside the Government's Low Carbon Buildings Programme providing grants (known as 'Feed-in Tariff (FIT)') for installing small scale renewable energy generation systems [6] such as solar power, wind turbines and hydro technology. Thus the total number of domestic PV system under 4kW installed has increased to 864,836 units in July 2017 [7] compared to the figure at the beginning of 2012 which was 215,292 units [8]. With domestic solar photovoltaic (PV) system installation, customers can save money on electricity bills and get paid for the energy generated by their supplier. However, due to lack of energy storage facilities and control systems, a large amount of energy is not utilised during off-peak hours, and only part of the load at peak hours can be met. This causes load-shedding outage and

* Manuscript received December 6, 2019; revised August 17, 2020

Corresponding author. *E-mail address:* haitong.zhang@sheffield.ac.uk

doi: 10.12720/sgce.9.5.827-842

even a possible energy crisis for the grid. To overcome any mismatch between domestic solar power output and the household electricity load profiles [9], and produce a better path to a smart grid in the UK, energy storage at domestic households with PV rooftop needs to be reviewed and optimized, in order to create a win-win situation for both grid and customers.

The feed-in tariff (FIT) is a UK government scheme launched in April 2010, which aims to encourage the installation of small-scale renewable electricity generation systems [6]. The export tariff is a certain amount of cashback paid by the energy supplier on every unit of surplus energy that export to the grid [10]. Moreover, Economy 7 meters measure day and night electricity usage separately, with the figure measured, the energy supplier will offer customers an economy 7 tariff which has lower energy price at night (nearly 1/3) [11]. This applies for 7 hours each night, depending on the suppliers' timing decision, it could start early from 11pm to 6am the next morning, or later from 1am to 8am. The schemes of FIT and Economy 7 tariffs enhance the potential for domestic energy storage system (ESS) to maximise savings.

Recently, grid connected domestic solar PV with ESS has been studied and the benefits evaluated in multiple papers. Renewable energy generation and energy storage system are introduced as two keys to the smart grid [12], where the battery energy storage system enables the ability to mitigate the intermittency of PV power caused by shading on panels or bad weather condition. An optimisation-based approach was used to evaluate the daily profits for domestic PV system with the battery storage system coupled [13] [14]. The benefits gained from the PV-battery hybrid system under the consideration of different electricity tariffs was analysed and presented for typical summer and winter days [15]. Reference [16] also extended the research in paper [15] by presenting the optimal battery sizes to use in PV-battery hybrid system to achieve the maximum annual revenue with tariff incentives under the unique setup, but without comparing the trade-offs between payback periods, PV sizes and battery sizes.

From the current extent of research, there's no publications examining the optimisation of battery control algorithm under real world tariffs, and the optimal payback of household energy storage system using real world costs. Thus, in this paper, domestic load profiles were modelled using real world data for different types of households, alongside validated PV generation profiles for various sizes of solar PV systems, to examine the optimisation of household payback period. Batteries with different sizes were then engaged to the system with developed control algorithm and payback periods were calculated using average real world costs quoted from battery companies. The results were compared with the [14][15][16] to analyse the improvement.

The main objectives of this paper are as follow:

- Domestic load profile was modelled on an hourly basis for a year using Goldsim simulation tool with real world dataset from government energy survey.
- PV profile was generated using System Advisor Model (SAM), the simulated data was on an hourly basis and validated by comparing with real world measured data. The PV profile was then analysed and added to the optimisation model together with the domestic load profile.
- Battery control algorithms and constraints were developed for energy storage system to increase the system revenue.
- Cost of system and tariffs were included in the model to investigate the system behaviour under multiple setups. The payback periods were evaluated to determine the marginal and optimal battery sizes

2. System Modelling

2.1. Domestic load profile modelling

Goldsim is a simulation tool which can perform Monte Carlo algorithm to the models in order to evaluate the uncertainties. The software is highly graphical and extensible, by dragging and editing graphical objects, the model can be visually created and algorithm are easily performed through linking equations with data blocks in an appropriate manner to automatically indicate their influences. Model users can change the variables of the system on the dashboard interface created for the model.

Real world data is used in Goldsim simulations, the data used can be found on the UK government website [17], on which the Department of Energy & Climate Change has published a survey based on the energy monitoring of a total 250 owner-occupied households across England from 2010 to 2011. In this survey, there are 5 household types in common which are indicative of almost all homes in the UK shown as follow:

- Single pensioner household (65+ years old)
- Single non-pensioner household
- Multiple pensioner household
- Household with children
- Multiple person household with no dependent children

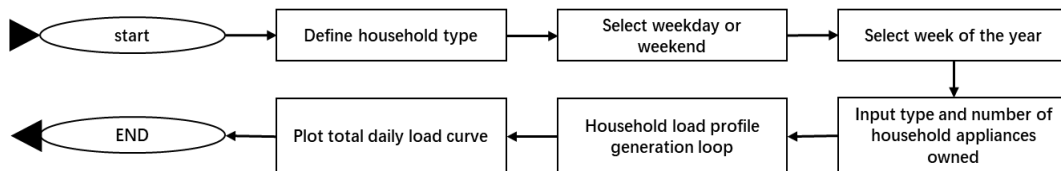


Fig. 1. Bottom-up design flow for domestic load profile modelling

The survey generally divides the household energy consumption into a sum of seven categories of appliance, and through monitoring of appliances in these categories for months, the average hourly load profile for each of them is produced for both weekend and weekday.

A bottom-up approach is also used in this simulation method, Fig.1. shows the diagram of the design flow of Goldsim load profile generation model. According to the flow chart, the basic idea is to first identify the type of household, after letting users select the household type, they also need to select which day is going to be simulated due to the difference between typical weekday energy consumption and weekend consumption. Week of the year is then requested due to seasonal use for all household appliances. Then the type and number of household electric appliances owned is defined by user to couple with real world hourly load profile in order to calculate the total energy consumed by each category of appliances. Finally the load curves for each category of appliances are summed up to produce total household hourly load curve throughout the day.

In order to precisely simulate the hourly energy demand, a dashboard is created. It asks user for several inputs, by selecting and editing in the column and then click on RUN button, the corresponding simulation will run automatically based on the user's real house setup. Then the results are presented in a new window when user simply click on the buttons in outputs selection. The simulated domestic load profiles were validated with real world measured data to evaluate their reliability. Fig. 2 shows the generated load profile of single pensioner household with selected appliances setup and with heavy loads included. Seasonal effects also have been considered for all appliances. From the diagrams, Fig. 2.(a) shows the typical weekday energy demand in winter, compared to Fig. 2.(b) which shows the weekday energy demand in summer, it is obvious that the energy consumption in winter is much higher than that in summer due to lower mean temperature, thus higher demand for heating. The two diagrams at bottom show the typical weekend energy demand in both winter and summer, they show the similar usage pattern as that of weekday. The average total daily electricity consumed in winter is about 25kWh while less than 10 kWh is used daily in summer.

Fig. 3 is a set of measured energy consumption curve in a typical household in hourly basis for both weekend and weekday in different seasons. Such kind of load profiles can be found on the website of ELEXON [18]. From the diagrams, they show the same trend as the simulated results which the energy consumption in winter is much higher than that in summer, however, energy consumed on weekend in both seasons are observed higher than that on weekday. This is because the monitored household type is different with the chosen type for simulation, people who have a job need to go to work during daytime

on weekdays while pensioners don't. The measured total daily consumption in winter is 25.9kWh and 26.6kWh respectively for weekday and weekend, and in summer, the load reduced to 9.6kWh and 9.8kWh respectively.

Generally, the model is validated with measured load profiles, the simulated load profile have the same trend on curves and similar amount, the difference between two sets of profiles can be explained by different type of household monitored and this doesn't have dramatic impact on the system behaviour.

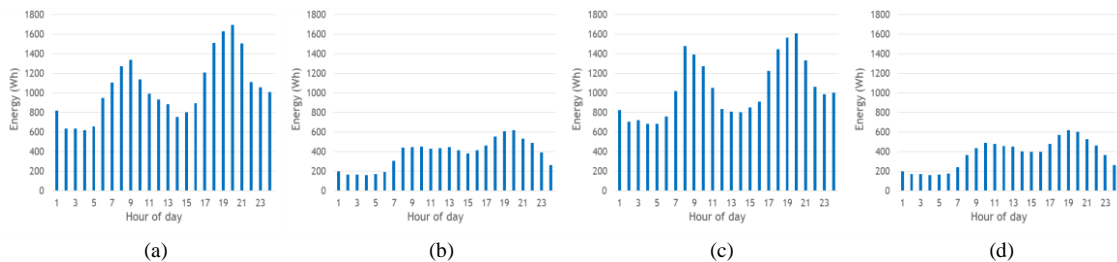


Fig.2. Average hourly load profile on (a) weekday in winter; (b) weekday in summer; (c) weekend in winter; (d) weekend in summer

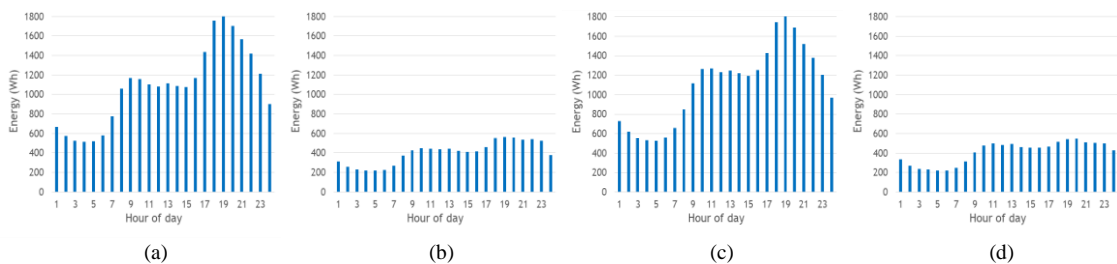


Fig.3. Measured hourly load profile on (a) weekday in winter; (b) weekday in summer; (c) weekend in winter; (d) weekend in summer

2.2. Hourly PV profile simulation

Based on the domestic load profiles provided previously, in order to integrate the load with a domestic renewable energy system, hourly PV profile needs to be generated to compare with the load curve and find the optimum battery size.

To precisely integrate the renewable energy generation with domestic electricity consumption, it requires a higher resolution dataset which tracks the PV generation every hour with weather effects considered.

Thus a tool called System Advisor Model (SAM) is used for data generation. It is a free software created by the National Renewable Energy Laboratory in U.S. [19], with the integration of weather data files and sunlight data files from each meteorological station around the UK, SAM can easily provide the hourly PV profile for selected size of system at targeted location. In this study, weather and solar resources used are from Finningley station which is close to Sheffield. A 4kW solar system is considered for the further research. Fig. 4.(a) shows the generated PV profile, the result is validated by comparing to the practically measured yearly PV generation from 2011 to 2015 shown in Fig. 4.(b). From the diagrams, the generated dataset is validated and can be applied to the following research.

Table 1. lists the typical costs of different sizes PV systems currently on the market, the prices have included the installation and supporting hardware, these prices are used for the following study and payback calculation.

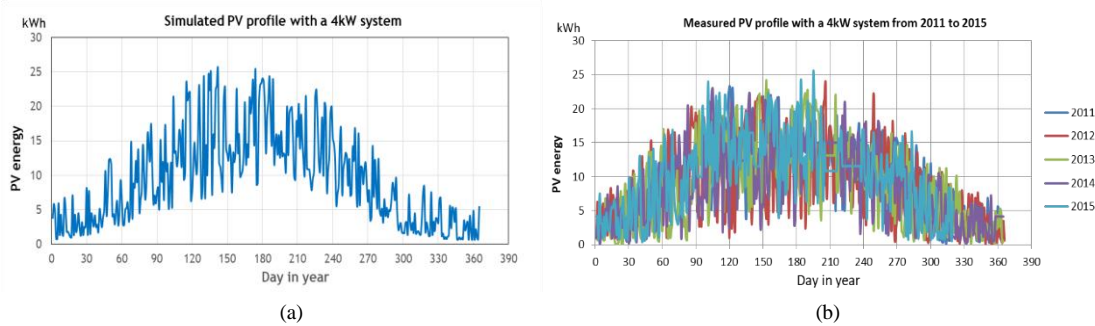


Fig. 4. (a) Simulated and (b) Measured PV profile with 4kW system

Table 1. Costs of PV system for range of sizes

Solar system size	Average price
1kW	£1840
2kW	£3680
3kW	£5520
4kW	£6040

3. Domestic Energy Storage System and Control Algorithm

The basic concept of grid connected PV-battery hybrid system is shown in Fig.5. A merging platform is set as the interface between the load and the different energy sources. The grid provides AC input to the platform while solar panel and battery bank provides DC power. Hence, DC-AC inverters are needed to transfer the DC power into AC to supply the domestic load. A charge controller is a device with a built-in algorithm to control the charging and discharging process for battery banks. The energy used to charge the battery is either imported from the grid or absorbed from excess production of PV system. The optimisation model optimises the battery charging and discharging process in combination with the solar PV system to maximise the annual system revenue and reduce the payback period for the installation. The battery storage system has the opportunity of energy self-sufficiency by storing the maximum solar power output for night and expensive hour usage, to reduce high electricity bills when variable tariffs are implemented.

3.1. Operating theory

The basic operating theory is that the domestic energy storage facility is installed with an energy management system, the smart controller will gain load profiles from household first, then compare against the renewable energy generation. If the renewable energy generation such as solar PV exceeds the load, the controller will stop importing energy from the grid, which means the load will be fully covered by locally generated power. In this situation, the excess energy generated will be used to charge the battery. On the other hand, if the renewable energy generation is lower than the load (e.g. in cloudy or rainy days), the controller will try to use PV energy to supply part of the load, then deliver energy through discharging of battery to try to meet the load. If the demand is too high which cannot be met by this approach, the controller will import electricity from the grid to fully cover the household consumption. In [11], the UK economy 7 and 10 tariffs are benefiting those households with storage heating by setting two-tier tariffs. In this research, the default Economy 7 hours was used as the off-peak hours run from 00:00 to 07:00. The economy 7 tariff used in this study is based on the rate from the EDF energy website, which is 6.99p/kWh at night and 19.46p/kWh at other hours out of the Economy 7 period. Thus, in this study, the optimisation model seeks to make better use of cheap tariff during the night to store energy and cover the rest of the hours of the day which have a higher electricity price.

3.2. Battery sizing

Fig. 6 shows the energy consumption in a single pensioner household with 4 kW solar system installed, for a typical day in the four seasons. The bars marked in blue shows the PV production and the red bars represents the domestic load demand. The solar energy generation appears as the lowest in winter, this is due to shortest daytime. The average daily generation from the simulated dataset for this season is about 3kWh, while during summer period, as shown in Fig. 6(c), the average daily renewable energy generation is typically over 13kWh and it can cover the daily domestic electricity consumption theoretically. Fig. 6(b) and (d) show the load profiles in spring and autumn respectively.

According to the simulated datasets for 5 types of household, the maximum solar energy generation appears for a 4kW system at week 26, from which the average daily generation is 20.5kWh, and the maximum average excess energy is 15.8kWh per day at week 21 in multiple pensioner household. So batteries with less than 15 kWh capacity are unable to absorb the total amount of the excess energy in summer, whilst sizes larger than 16kWh have limited utilisation.

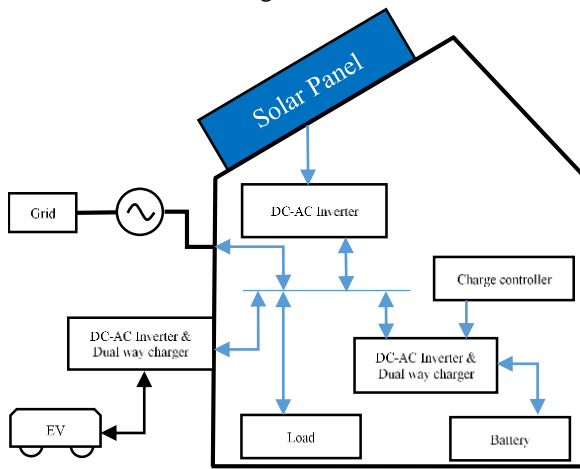


Fig.5. Basic concept of grid connected PV-battery hybrid system

Table 2. Battery prices for the range of capacities

Battery capacity (kWh)	Price
1	£290.16
2	£580.32
3	£870.49
4	£1 160.65
5	£1392.63
6	£1671.30
7	£1949.98
8	£2228.66
9	£2507.34
10	£2785.25
11	£1968.23
12	£3238.49
13	£3507.98
14	£3778.24
15	£4047.73
16	£4317.98
17	£4439.71
18	£4700.78
19	£4961.85
20	£5222.92

Thus the trade-off between system performance and batteries sizes needs to be analysed. Lithium-ion batteries with communication functions, from 1kWh to 20kWh, were quoted for the research purposes. The prices are listed in Table 2. The battery specification from the supplier mentioned the lifetime is 6000 cycles for 90% depth of discharge which means the capacity will lose 20% after 6000 times of charging and discharging. If the battery is set to make a full cycle operation every day, it will last as long as 15 years, as manufacture guaranteed, hence, the battery degradation cost is assumed very low in this study. The maximum power the battery can deliver is over 6kW, due to the inverter choice, hence it is able to support most of the load during the day except high power appliances. Since the system is designed to optimise energy independence, thus the integration of battery with PV and load is valid.

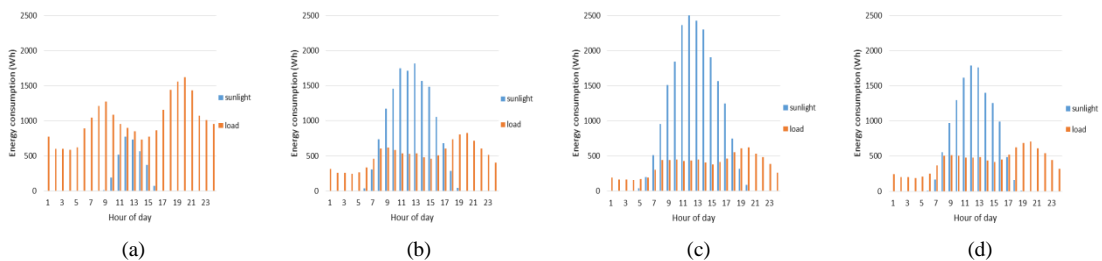


Fig.6. Domestic hourly energy demand and domestic PV generation of a typical day in (a) winter; (b) spring; (c) summer and (d) autumn

3.3. System operating sequence

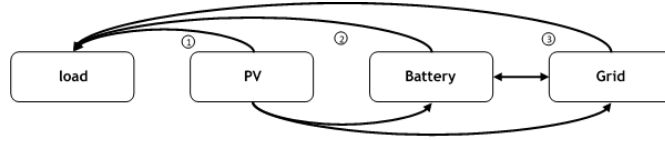


Fig. 7. System operating sequence

Fig.7. illustrates the proposed dispatching mode, the system will first use PV energy to provide load consumption, if more energy is required by the load, then the battery will engage to provide the excess demand. Theoretically, the load should be met by this step, if the battery is not allowed to dispatch or it has already reached the minimum state of charge (SOC), finally, it requires energy imported from the grid. While in charging mode, which typically happens when PV production is over the load usage, the excess energy will be dumped into the battery until it is fully charged, then export the rest to the grid.

3.4. Battery discharging algorithm

In order to fulfil the battery energy dispatching control, the system first needs to perform battery discharging algorithm on the collected information of yesterday to predict today's energy usage and provide a demand profile to manipulate the system operation throughout the day. The load and PV information from yesterday is gained initially, then based on this, an estimate of the total amount of energy required to import from grid between 07:00 to 24:00 (E_{grid_out7}) is calculated:

$$E_{grid_out7} = (E_{load_out7} - E_{sun_out7}) - E_{battery} \quad (1)$$

In this equation, E_{load_out7} is total energy required by load out of Economy 7 hours, E_{sun_out7} is defined as total energy generated by PV system out of Economy 7 hours and $E_{battery}$ represents maximum capacity of battery that can be used. The unit of each element is watt-hour (Wh).

In circumstances where there is low ambient temperature, or unfavourable weather, the PV system cannot provide sufficient energy, which results in the Equation (1) to be positive. Therefore, both PV system and a fully charged battery cannot match the load. Subsequently, the battery use is specifically disabled between 10:00 and 15:00 to preserve energy in order to have better performance on peak demand support. Thus, the battery will fully charge to its maximum capacity within Economy 7 hours, the amount of energy required to charge for each time step (E_{char}) can be calculated by:

$$p = (100\% - E_{SOCend}) \div 7$$

$$E_{char} = p \times 100\% \times E_{battery} \quad (2)$$

where p is the percentage SOC to be charged. The value of p is set a maximum of 0.15 to smooth the demand from grid within each hour. E_{SOCend} is defined as energy left in the battery at the end of the previous day. In this study, each time step is set in hourly basis.

On the other hand, if E_{grid_out7} is negative, it represents load demand of all the hours out of Economy 7 can be covered by the energy from the PV and energy storage facility. Thus different situations need to be considered separately.

If $E_{loadT} - E_{sunT} > 0$ and $E_{load_out7} > 0$, where E_{loadT} is the total energy consumed in the household throughout a day and E_{sunT} is the total PV energy generated during the day. In this situation, solar energy is insufficient to cover the consumption, therefore the battery needs to matching the load between 07:00-24:00. The targeted SOC (E_{SOCest}) required to be stored in the battery at the end of Economy 7 hours is calculated by the equation:

$$E_{SOCest} = E_{battery} \times 10\% + E_{SOCmin} + (E_{load_out7} - E_{sun_out7})$$

$$E_{char} = (E_{SOCest} - E_{SOCend}) \div 7 \quad (3)$$

where E_{SOCmin} is the battery minimum SOC set by the user to prevent deep-cycle events, for example, 10% of the battery capacity is preserved to prevent sudden change in the load demand on the next day which may affect the system behaviour.

The targeted SOC needs to be reached before 7am in the morning to support the energy consumption during the rest of the day, and the battery is allowed to fully cover the load until the minimum SOC is reached.

If $E_{loadT} - E_{sunT} > 0$ but $E_{load_out7} < 0$, the solar energy cannot cover the usage throughout the whole day (24 hour period) but can cover the consumption between 07:00-24:00. So the battery will discharge to its targeted SOC within Economy 7 hours, and then fully cover the load during the rest of the day. In this case,

$$E_{SOCest} = E_{battery} \times 10\% + E_{SOCmin}$$

$$E_{dischar_7} = (E_{SOCend} - E_{SOCest}) \div 7$$

$$E_{dischar_out7} = E_{load} - E_{sun} \quad (4)$$

$E_{dischar_7}$ and $E_{dischar_out7}$ represent the energy required to discharge to the load at each time step during and out of Economy 7 hours respectively, E_{load} is the energy consumption of the household at the current time step, E_{sun} is the energy provided by renewable PV system at current time step.

Moreover, if $E_{loadT} - E_{sunT} < 0$, it means the PV system can provide sufficient energy to the load throughout the day with no electricity needed to import from grid. Hence the battery will discharge throughout the whole day including Economy 7 hours. The system is supposed to export electricity to grid at higher demand time for example 08:00-11:00 in the morning and 17:00-21:00 in the evening. So these 7 hours are chosen for export, the total energy to be export will be divided equally for each hour for delivery instead of all in once. The energy can be exported to grid each hour (E_{export}) is calculated by:

$$E_{export} = [E_{SOCend} - (E_{load_7} + E_{SOCmin})] \div 7 \quad (5)$$

E_{load_7} represents total energy required by load within Economy 7 hours.

3.5. Battery energy dispatching strategy

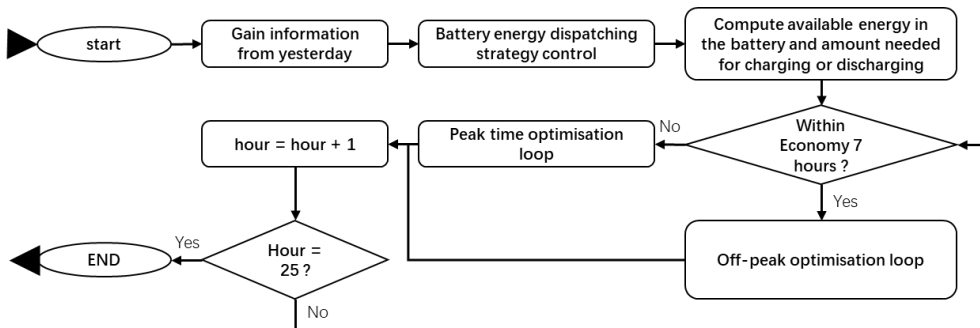


Fig. 8. Diagram of domestic energy storage optimisation procedure with battery dispatching strategy applied

The dispatching strategy is shown in Fig.8. The system first gains historical recorded information of the last 24 hours at the beginning of the first time step. Then the system performs battery dispatching algorithm on this data. The system needs to evaluate how much energy remained in the battery bank at the last time step of the previous period, and how much energy is needed to charge to or discharge from the battery. Then a checking function is used to define whether the current hour is in allowed Economy 7

hours. If current time step is within Economy 7 hours, it is defined as an off-peak hour on which a lower electricity rate is applied. The system will then jump into the off-peak optimisation loop as shown in the diagram. After comparing the PV energy generated with the load demand at current time step, the control signal will manage the battery to charge from the grid or discharge to the load. Both operations are aimed at making the energy stored in the battery equal to the targeted value, the total energy required from grid (E_{grid}) at current time step is:

$$E_{grid} = E_{load} - E_{sun} + E_{char} \quad (6)$$

On the other hand, if the battery is allowed to discharge during Economy 7 hours, the energy required from the grid changes to

$$E_{grid} = E_{load} - E_{sun} - E_{dischar_7} \quad (7)$$

An increment of time function is performed at the last of the each loop, and then feed back to the period check. The battery should have a targeted SOC at the end of Economy 7 hours.

Any hours after 07:00 are defined as peak electricity tariff hours. According to the peak hour optimisation loop, the first procedure is to compare PV energy versus load. Then control signals will be generated for corresponding circumstances as described in the previous section to perform on the system.

If the PV energy generated is insufficient to fully cover the demand, such as in a cloudy or rainy day, or in winter season and battery is allowed to dispatch energy at this time step, the load will be met with energy discharged from the battery. In this situation, battery will discharge to match any demand that solar energy cannot cover, hence there is no need to import the electricity from the grid, $E_{grid} = 0$. If the battery is not allowed to discharge by the control signal, then the amount needed to import from the grid is

$$E_{grid} = E_{load} - E_{sun} \quad (8)$$

If the generated PV energy is sufficient to supply the load, $E_{grid} = 0$, the energy can be fed back into the grid during peak demand hours is described in Equation (5), the amount of excess energy after exportation will dump into the battery storage system for recharging until it is fully charged, then the rest will sell back to grid directly.

3.6. Battery discharging constraints

Few constraints are made for the system as listed below:

- Battery is only allowed to charge from the grid in Economy 7 hours (00:00 to 07:00 was chosen as the default value in this study) in order to minimise the cost to the consumer by using cheaper off-peak rate, and support the domestic consumption and grid at peak hours.
- During charging, a maximum amount of charge per hour is set to equal 15% of the battery capacity, in order to smooth the demand from the grid.
- Battery can only discharge till its minimum SOC set by user, in this case, 10% of its total capacity was set to prevent deep-cycle events which cause excess degradation and shorten the battery life cycle.
- If battery is fully charged (reaches 100% SOC), the excess PV energy will directly export to the grid.
- The battery is allowed to charge from the PV system at any time of the day, but the system will run in the sequence which was described above which to meet the load with PV energy first then use the excess energy to charge the battery.

4. Results and Discussion

4.1. Battery energy dispatching strategy

Few assumptions listed in Table 3 are used for simulation, the datasets generated from Goldsim model and SAM are exported to Excel for analysis. A dashboard is created shown in Fig.9. in Excel by coding in Visual Basic for Application. The dashboard is used to input variables and present results. Users can update their expenditure on PV system, installation costs, FIT eligible periods and electricity tariffs in the tool, then the tool can automatic calculate the outputs. The datasets and the user interface construct a complete tool with comprehensive functions such as load and PV profile modelling, battery system size evaluation, payback periods calculation and comparison.

Take an example of single pensioner household energy storage optimisation, from the result section on the dashboard (Fig.9.(b)), optimised system performance for typical winter and summer day were plotted. From the figure, where the blue bars represent original domestic load profile, yellow bars represent hourly PV energy production, red represents the load profile with smart energy storage system engaged and green bars represent the exported energy to grid. In winter, due to short daytime and lower temperature, it is obvious that the household electricity consumption is relatively high because of higher demand of space heating energy. Performance diagram for winter shows when E_{grid_out7} is positive, where the load out of Economy 7 hours cannot be matched by both PV system and a fully charged battery, hence, battery is not discharging between 10:00-15:00. In this situation, the energy storage system will try to cut the electricity cost for customers by charging the battery at cheaper rate and provide energy to load during daytime, so the daytime usage are mostly shifted to Economy 7 hours. Energy drawn from the grid between 21:00-24:00 is because the battery has reached its minimum SOC, and the house requires energy import. The change of battery SOC throughout the day is shown on the right, the plot shows that the battery is fully charged within the first 7 hours and then discharge to meet the load demand between 07:00-10:00, then the discharge is disabled between 10:00-15:00, after that, the battery starts to dispatching energy again till the minimum SOC is reached.

Table 3. Assumptions made for domestic load profile and PV

Assumptions		
Domestic load profile modelling	PV profile modelling	Installation cost
Appliances setup: 1 refrigerator 1 upright-freezer 3 ICTs 1 LCD TV 1 washing machine 1 clothes dryer 1 dishwasher Storage heater Water heater Kitchen appliances Lighting	Weather data UK Finningley PV module type Standard DC to AC ratio 1.2 Inverter efficiency 96% Array type Fixed roof mount Tilt 20 degrees Azimuth 180 degrees Total system losses 14.08% Degradation of the PV system is not considered	An installation cost including the cost for an electrician to wire the system, the cost for supporting hardware and software which include a DC-AC inverter & dual way charger for battery and a charge controller with control algorithm. The cost is assumed at £300 as an average quotation in total.
Electricity Tariff	Feed-in Tariff	PV cost and battery cost
Economy 7 tariff is assumed applying to the household to maximize the system revenue by properly use the cheap electricity rate to support expensive hours. The day rate is 19.46 p/kWh, night rate is 6.99 p/kWh. The export tariff used in this study is based on recent rate which is 5.24 p/kWh.	The FIT rate used in this study is 3.93 p/kWh which is the latest rate for system installed during 01/07/2018-30/09/2018 [20].	The prices of various sizes of PV system used is listed in Table 1, and that for various sizes of battery is listed in Table 2.

The system performance diagram for summer shows when E_{grid_out7} is negative, the load can be fully provided by renewable energy, the remaining energy in the battery from the last day will support the demand between 00:00-07:00, then the excess energy will charge the battery when load is fully met. The export of energy between 07:00-10:00 is due to the configuration of the last day's information, so part of the excess energy stored yesterday will export to the grid to balance early peak demand. Between 13:00-17:00, when the battery is already fully charged, then the excess energy will be sold back to grid, the

amount is recorded by export meter. After that, the late peak demand appears between 17:00-21:00, thus a constant energy export is allowed for grid support.

According to the data simulated for single pensioner household and with the chosen electricity tariff, the annual profit that the household can achieve can be calculated. The result shows the cost on electricity bill will reduce from £872.89 per year to £231.16 per year with the system installed, and the customer will make £42.62 profit from selling excess energy to grid at 5.24p/kWh. Thus, the domestic users can save £641.73 per year on overall cost of electricity, The payback period of the system can be calculated using the following equation:

$$\text{payback} = \frac{p_{\text{system}}}{p_{\text{profit_tot}}} \quad (9)$$

Where

$$p_{\text{system}} = p_{\text{battery}} + p_{\text{PV}} + p_{\text{install}}$$

$$p_{\text{profit_tot}} = p_{\text{savtot}} + p_{\text{expotot}} + p_{\text{FITtot}} \quad (10)$$

p_{system} is the total system price including the price of battery system (p_{battery}), PV system (p_{PV}) and installation (p_{install}). $p_{\text{profit_tot}}$ is the total profit gained by using the system. p_{savtot} represents the total saving on electricity bills, p_{expotot} is the total return from energy exportation, and since the ESS system is installed on the on the AC side of PV system, so FIT scheme is still eligible for the system to get paid, p_{FITtot} represents the total return on feed-in tariff. The return on FIT in this study for 4kW solar system based on current FIT scheme is unique, which is £134.34 per year.

The payback period of the system is 11.15 years as calculated, from the evaluation of the results, the system performance is proved reliable and the payback period seems reasonable for domestic users. The battery energy storage system was also applied to different types of household for further validation.

Household type

Single pensioner household

Tariff

Economy 7 tariff

Tariff 1	Tariff 2
6.99 p/kWh	19.46 p/kWh

Export tariff

5.24 p/kWh

Battery minimum SOC

10 %

PV Size

4 kW

Installation cost

£ 300

Battery Size

10 kWh

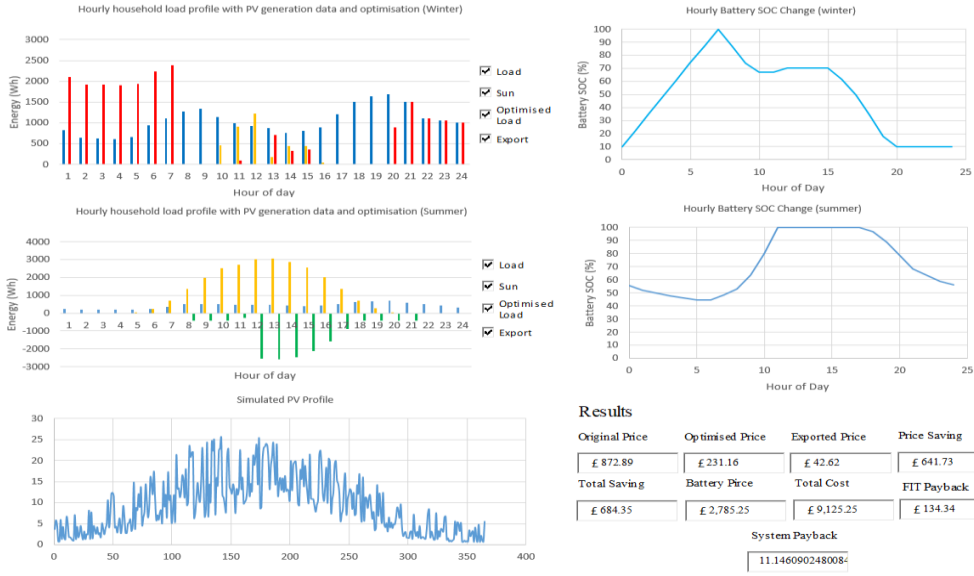
PV Price

£ 6040

Feed-in Tariff

Installation Period	Type of tariff
01/07/2018-30/09/2018	higher rate
Tariff Rate	3.93 p/kWh

(a)



(b)

Fig. 9. Dashboard created in Excel for (a) data input and (b) result presentation

4.2. Sensitivity analysis

The performance of the system is evaluated in the form of payback period. As mentioned before, the system payback can be calculated from Equation (9), the total savings on bill, returns from grid export, and returns from FIT are most likely affected by the PV size and battery size. The total cost of system depends on the cost of solar energy system, battery banks and installation.

Fig.10. shows how battery cost varies with the increasing battery size and how optimal annual benefit varies with the increasing battery size respectively. With the same 4kW PV, According to Fig.10.(a), the x-axis represents the range of battery capacity in kWh, and the y-axis represents the battery price in pounds (£). The curve shows a positive linear increase against battery size, the price increased from £290.16 for 1kWh capacity battery to £5222.92 for 20kWh battery.

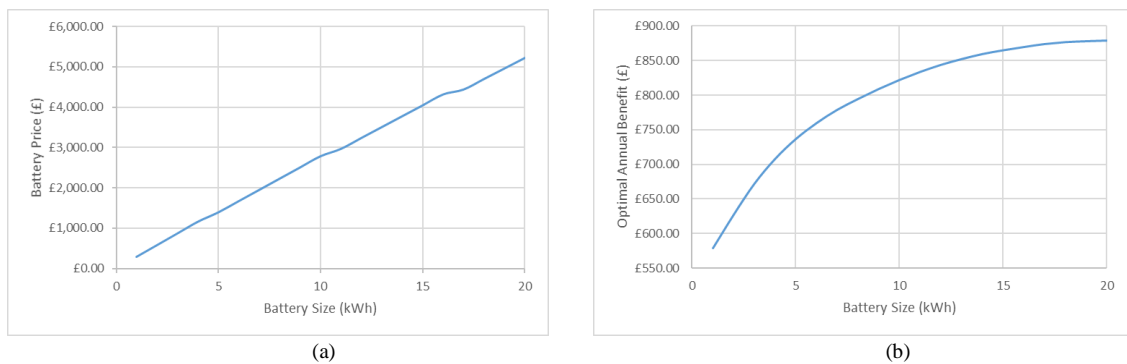


Fig.10. (a) Prices of battery for corresponding sizes and (b) Optimal system annual revenue for different sizes of battery

However, the optimal annual benefit shows a logarithmic growth against battery size. In Fig.10.(b), when a system applied in single pensioner household is analysed as an example, the x-axis represents the range of battery capacity in kWh and the y-axis shows the annual revenue in pounds (£). It shows the revenue increases quickly in the beginning where the battery size increases from 1kWh to 5kWh and the

revenue increases 27%. Then the gains decrease as battery size increases further, the revenue increases 19% from £736.69 for 5kWh battery to £879.02 for 20kWh. The revenue will eventually saturates at £879.02, at which, the increasing battery size will no longer provide any more profits but only increases the system cost. The reason of this curve shape is mainly due to a fully charged 20kWh battery bank (during economy 7 hours) can cover the maximum energy demand from the grid for the household during the rest of the day. Moreover, the maximum excess solar energy from the system modelling shows 15.8kWh on the second day of week 21 for multiple pensioner household with 4kW PV system installed, so batteries with capacity larger than 16kWh will be able to store all of these energy for night usage and peak time export. Thus, the export profits will have advantage for batteries larger than 16kWh. With the fixed amount of FIT returns, according to the Equation (9), no further improvement will be obtained for a battery size beyond 20kWh.

Thus, the bigger size of battery may not bring proportionally higher profits, but is definitely increasing the system cost. The payback periods of system with battery storage for full range of battery sizes were calculated and comparing with the original system payback time without ESS, to evaluate the marginal and optimal battery sizes for each size of PV system installed in different types of household.

The sensitivity analysis is carried out using the algorithm shown in Fig.11. With the setup and assumptions listed in Table 3 and the costs of the range of batteries listed in Table 2, Table 4 shows the calculated system payback periods under different sizes of PV and battery setup for single pensioner household. The original system payback without battery is also listed. The range of battery sizes that can apply to the household are highlighted. It might not be suitable to integrate a battery system into the house if the overall payback period is longer than that without a battery bank. The optimal battery size which can have minimum payback is marked in red. Fig.12. shows the impacts of battery sizes on the system payback for various PV system.

Take the example of single pensioner household, the minimum payback periods for PV system with size 1kW to 4kW are 8.99, 10.20, 11.35 and 10.52 years respectively with respect to 9.74, 11.35, 12.75 and 11.40 years payback periods for system without battery storage. The new energy storage system has 7.7%, 10.1%, 11.0%, 7.7% improvement on payback time for 1 to 4 kW solar systems installed respectively. Other sizes of system have higher payback periods due to limited utilisation of the larger systems or insufficient capacity to make further profits for the smaller systems.

```

Sizepv = 4;
Ebattery = 20;
tableA = zeros (20,4);
tableB = zeros (20,4);

for j = 1:Sizepv
    for i = 1:Ebattery

        payback = psystem/ pprofit_tot
        tableA(i,j) = payback

        if payback < payback_org
            tableB(i,j) = 1
        else
            tableB(i,j) = 0
        end if

    end for
    minpayback = min(tableA)

end for
    
```

Table 4. Payback periods for single pensioner household with various sizes of PV and battery system

	1kW	2kW	3kW	4kW
No battery	9.74 yrs.	11.35 yrs.	12.75 yrs.	11.40 yrs.
1kWh	10.51 yrs.	11.60 yrs.	12.75 yrs.	11.49 yrs.
2kWh	9.99 yrs.	11.04 yrs.	12.16 yrs.	11.04 yrs.
3kWh	9.58 yrs.	10.60 yrs.	11.72 yrs.	10.74 yrs.
4kWh	9.29 yrs.	10.35 yrs.	11.49 yrs.	10.61 yrs.
5kWh	9.02 yrs.	10.20 yrs.	11.35 yrs.	10.52 yrs.
6kWh	9.00 yrs.	10.25 yrs.	11.38 yrs.	10.58 yrs.
7kWh	9.07 yrs.	10.36 yrs.	11.45 yrs.	10.68 yrs.
8kWh	9.19 yrs.	10.49 yrs.	11.57 yrs.	10.83 yrs.
9kWh	9.36 yrs.	10.63 yrs.	11.72 yrs.	10.98 yrs.
10kWh	9.53 yrs.	10.82 yrs.	11.88 yrs.	11.15 yrs.
11kWh	9.58 yrs.	10.86 yrs.	11.92 yrs.	11.21 yrs.
12kWh	9.80 yrs.	11.04 yrs.	12.10 yrs.	11.40 yrs.
13kWh	10.04 yrs.	11.25 yrs.	12.30 yrs.	11.61 yrs.
14kWh	10.30 yrs.	11.50 yrs.	12.53 yrs.	11.83 yrs.
15kWh	10.62 yrs.	11.78 yrs.	12.78 yrs.	12.07 yrs.
16kWh	10.93 yrs.	12.05 yrs.	13.03 yrs.	12.32 yrs.
17kWh	11.00 yrs.	12.12 yrs.	13.11 yrs.	12.41 yrs.
18kWh	11.33 yrs.	12.42 yrs.	13.39 yrs.	12.67 yrs.
19kWh	11.69 yrs.	12.75 yrs.	13.69 yrs.	12.95 yrs.
20kWh	12.07 yrs.	13.10 yrs.	14.01 yrs.	13.24 yrs.

Fig.11. System payback evaluation algorithm

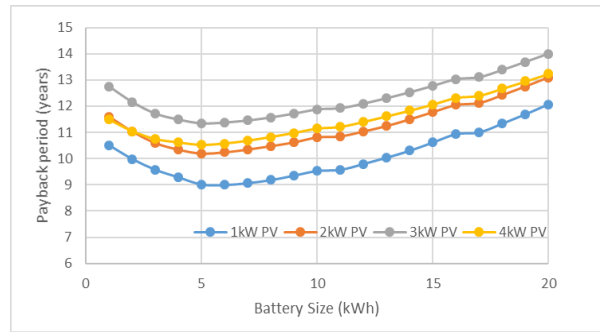


Fig.12. Payback periods of various battery sizes for different sizes of PV system installed in Single pensioner household

Table 5. Minimum system payback period and optimal battery size for different household types with different sizes of PV system coupled.

	PV size	1kW	2kW	3kW	4kW
Household type					
Single pensioner household		9.00 yrs. (6kWh)	10.20 yrs. (5kWh)	11.35 yrs. (5kWh)	10.52 yrs. (5kWh)
Single non-pensioner household		8.98 yrs. (6kWh)	10.18 yrs. (5kWh)	11.32 yrs. (5kWh)	10.50 yrs. (5kWh)
Multiple pensioner household		9.09 yrs. (6kWh)	10.35 yrs. (5kWh)	11.53 yrs. (5kWh)	10.69 yrs. (5kWh)
Household with children		8.93 yrs. (6kWh)	10.14 yrs. (5kWh)	11.28 yrs. (6kWh)	10.46 yrs. (5kWh)
Multiple person household with no dependent children		8.88 yrs. (6kWh)	10.03 yrs. (5kWh)	11.14 yrs. (5kWh)	10.34 yrs. (5kWh)

Same simulation applied to different types of household provides similar results as shown in Table 5. Due to the dramatic impact of battery price on the system performance, the shortest payback periods for various sizes of PV system in different households are showing between integrating with 5kWh and 6kWh battery systems. The cost of lithium-ion battery packs is reducing 25% from 2009 level to 2014 [21] according to the research, hence the results will improve due to lower battery price with passing time, the system payback time will reduce and the optimal system size will increase. Thus, the customers will tend to buy larger size of battery systems in the future for better energy self-sufficient.

4.3. Contributions and future work

This paper introduced an accurate approach to simulate domestic load profiles. Battery discharging algorithm was developed for the energy storage system, optimal battery sizes for different sizes of PV system in different types of household were evaluated with tariff incentives.

With the benefit of battery discharging algorithm, the system can lower the users' expenditure on electricity bills, and also make money from energy exportations. Energy self-sufficiency achieved by applying this system can effectively support the peak demand of the grid. System behaviour in practice will be monitored for further validation and development.

According to the results presented, the system was validated for all types of households in the UK with different sizes of PV-battery setups. Thus, with more households installing this system in a typical area, a large scale energy storage system can be integrated by connecting those household battery systems. Then it can be used for electric vehicle charging and grid reserve services. Moreover, communication and control of systems within a community is another research topic in order to achieve higher efficiency on energy utilisation.

5. Conclusion

Previous sections illustrate the work have done on solving challenges outlined in section 2. First, domestic load profile modelling was introduced to simulate hourly energy consumption throughout a day

in typical residential household. Goldsim simulation is realistic since it uses real world hourly load profile for each appliance. A dashboard was created in Goldsim, by entering information such as household type, week of the year, which day of the week and the type and number of appliances owned in the house, the system can precisely generate hourly electricity consumption for different situations. Thus Goldsim simulation was used to produce domestic load profile for this study. Then PV profile was generated to couple with load profile, in order to size the battery. An optimised smart energy storage system and its control algorithm have developed to manage domestic energy usage and improve grid stability by exporting excess energy back to grid during high demand hours. The results were validated to show the system can reduce the cost on electricity bills. The payback periods of installing such a system were evaluated under different sizes structures. The optimal battery size was found for each size of PV system installed in each type of household, the marginal sizes of battery were found to ensure the acceptable improvement in total system payback periods. The shortest payback periods appear between 5kWh battery and 6kWh battery systems. Due to logarithmic growth on system revenue, the system has a higher payback periods due to limited utilisation of larger systems and insufficient capacity to make further profits for smaller system.

Conflict of Interest

The author declares no conflict of interest.

References

- [1] Firth S, Lomas K, Wright A, Wall R. Identifying trends in the use of domestic appliances from household electricity consumption measurements. *Energy & Buildings*, 2008; 40(5):926-936.
- [2] Gov.uk. (March 2007), Draft Climate Change Bill. [Online]. Available: <https://www.gov.uk/government/publications/draft-climate-change-bill>
- [3] Parashar U, "Phase2: Exploring the relationship between environmental regulation and competitiveness: A case study on the Renewable Obligations. A report to the Department for Environment, Food and Rural Affairs", SQW consulting, 2007.
- [4] Ofgem.gov.uk. (2017). Transition to smart meters. [Online]. Available: <https://www.ofgem.gov.uk/gas/retail-market/metering/transition-smart-meters>
- [5] Gov.uk. (2017). The UK renewable energy strategy. [Online]. Available: <https://www.gov.uk/government/publications/the-uk-renewable-energy-strategy>
- [6] Gov.uk. (2017). Evaluation of the Low Carbon Buildings Programme. [Online]. Available: <https://www.gov.uk/government/publications/evaluation-of-the-low-carbon-buildings-programme>
- [7] Gov.uk. Solar photovoltaics deployment. [Online]. Available: <https://www.gov.uk/government/statistics/solar-photovoltaics-deployment>
- [8] Gov.uk. (2017). Weekly solar PV installation & capacity based on registration date. [Online]. Available: <https://www.gov.uk/government/statistical-data-sets/weekly-solar-pv-installation-and-capacity-based-on-registration-date>
- [9] Jacquet B, X Yang, X Niu, Y Zhou. Operation and investment optimization of energy storage system in distributed PV generation. Presented at: 2015 ICEE Proceedings.
- [10] Fitariffs.co.uk. Export tariffs | FI Tariffs. [Online]. Available: <https://www.fitariffs.co.uk/FITs/principles/export/>
- [11] uSwitch. (August 2017). What Is An Economy 7 Electricity Tariff And How Does It Work? [Online]. Available: <https://www.uswitch.com/gas-electricity/guides/economy-7/#step2>
- [12] Liu X, Aichhorn A, Liu L, Li H. Coordinated control of distributed energy storage system with tap changer transformers for voltage rise mitigation under high photovoltaic penetration. *IEEE Trans. Smart Grid*, 2012; 3(2):897-906.
- [13] Ratnam EL, Weller SR, Kellett CM. An optimization-based approach to scheduling residential battery storage with solar PV: Assessing customer benefit. *Renewable Energy*, 2015; 75:123-134.
- [14] Jayawardana H, Agalgaonkar A, Robinson D. Novel control strategy for operation of energy storage in a renewable energy-based microgrid. In: *2015 Australasian Universities Power Engineering Conference*, 2015:1-6.
- [15] Wu Z, Tazvinga H, Xia X. Demand side management of photovoltaic-battery hybrid system. *Applied Energy*, 2015; 148:294-304.
- [16] Abubakar S, Liana C, Nick J. Optimal battery storage operation for PV systems with tariff incentives. *Applied Energy*, 2017; 203:422-441.

- [17] Intertek Testing & Certification Ltd (May 2012). Household Electricity Survey - A study of domestic electrical product usage. [Online]. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/208097/10043_R66141HouseholdElectricitySurveyFinalReportissue4.pdf
- [18] ELEXON. (2017). Profiling - ELEXON. [Online]. Available: <https://www.elexon.co.uk/operations-settlement/profiling/>
- [19] NREL. (2017). System Advisor Model (SAM). [Online]. Available: <https://sam.nrel.gov/>
- [20] Ofgem (April 2018). Feed-in Tariff (FIT): Tariff Table 1 April 2018. [Online]. Available: <https://www.ofgem.gov.uk/publications-and-updates/feed-tariff-fit-tariff-table-1-april-2018>
- [21] Muenzel V, Mareels I, de Hoog J, Vishwanath A, Kalyanaraman S, Gort A. PV generation and demand mismatch: Evaluating the potential of residential storage. Presented at: 2015 IEEE Power & Energy Society Innovative Smart Grid Technologies conference (ISGT).

Copyright © 2020 by the authors. This is an open access article distributed under the Creative Commons Attribution License (CC BY-NC-ND 4.0), which permits use, distribution and reproduction in any medium, provided that the article is properly cited, the use is non-commercial and no modifications or adaptations are made.