Domestic Energy System Operation with PV and V2G, to Minimise Running Cost, and Provide Passive Grid Support

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Abstract

Today, the number of installed domestic PV systems is increasing, and more efficient appliances are used in households. This trend is a good signal for the UK Government, which has set a target to cut the UK CO_2 emissions by 80% from 1990 levels before 2050. Further legislation was passed in 2019 to amend the target to 100% by 2050, to reach net zero emissions. However, with the increasing PV penetration, the level and direction of power flow on the UK electricity grid is less predictable, which brings challenges to current power grid and energy suppliers. Smart grid technology can solve the drawbacks of the PV penetration, and is the subject of significant investigation. In this thesis, hourly load profile modelling is introduced as the basis of the research, then a PV generation profile is determined for each typical size of PV system installed in the UK. An evaluation of the combined load and PV profiles throughout a year is carried out to address the sizing of an additional battery energy storage system. This facilitates an integrated domestic energy storage facility with renewable energy source, in order to create a win-win situation for both the customers and the grid. By using PV as an alternative energy source to power the home appliances, the system can reduce the dependence of household on grid energy, and it can shave the peak grid demand by managing the loads and exporting PV overproduction back to grid. Hence, the system can cut the electricity bill for customers and make profit by selling electricity to grid. The electricity tariff is considered when calculating the annual profit available, and conducting the system payback period for performance analysis.

EV integration to the household in the form of vehicle to grid (V2G) is then examined based on the models developed. The complete domestic energy system model, including photovoltaic (PV) panels, battery energy storage system (BESS) and electric vehicle (EV) is updated to evaluate the impact of the V2G on the payback periods for a consumer. With a series of control algorithms applied, along with possible electricity tariffs, minimum energy usage and relative payback period for each variation of PV and BESS sizes within a proposed system are calculated. A battery ageing model is then developed to consider the annual battery degradation cost. It is shown that an EV can be used as extended stationary energy storage, together with a household BESS, to enhance the overall system performance.

Declaration

I, the author, confirm that the Thesis is my own work. I am aware of the University's Guidance on the Use of Unfair Means. This work has not been previously been presented for an award at this, or any other, university.

Zhang Haitong

15/01/2021

Publications

Part of the work contained in this thesis have been disseminated in the listed internationally published papers:

Journal publications

H Zhang, D Stone and D Gladwin, '*Optimising energy storage for domestic household with PV to support the grid*', International Journal of Smart Grid and Clean Energy 9, (5), September 2020, pp. 827-842

Conference publications

H Zhang, D Stone and D Gladwin, *'Managing domestic energy storage with PV to reduce household cost and support the grid'.* 2nd International Conference on Smart Grid and Energy, Singapore, April 2019

H Zhang, D Stone and D Gladwin, *'Study into Payback Periods for Domestic Energy Systems including PV, Battery Storage and V2G',* All-energy Exhibition and Conference, Glasgow, 2020 (Accepted but conference deferred to 2022 due to COVID-19)

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Nomenclature

a	Li-ion cell life constant
D	Distance travelled (miles)
d	Current day
$d-1$	Previous day
DoD	Depth of discharge (%)
$E_{battery}$	Energy stored in the battery at rated full capacity (Wh)
$E_{BESS\_available}$	Available energy in BESS that allow to recharge the EV (Wh)
E_{BESS_EV}	Energy stored in BESS at the time when EV is plugged in (Wh)
E_{charge}	Capacity of charge (Wh)
$E_{chest\_freezer}$	Hourly load profile for chest freezer (Wh)
$E_{cold\_appliance}$	Hourly load profile for cold appliances (Wh)
$E_{computer}$	Hourly load profile for computers (Wh)
$E_{discharop}$	Energy discharge from the BESS at each Economy 7 off-peak hour (Wh)
$E_{discharpk}$	Energy discharge from the BESS at each Economy 7 peak hour (Wh)
$E_{discharge}$	Capacity of discharge (Wh)
$E_{dishwasher}$	Hourly load profile for dishwasher (Wh)
$E_{expoort}$	Energy export to the grid (Wh)
E_{EV}	Total energy consumed by EV for trips made in a day (kWh)
E_{EVmin}	Energy stored in the EV battery at the minimum state of charge (kWh)
$E_{EVtarget}$	Targeted energy stored in the EV battery (kWh)
E_{grid}	Energy required to import from the grid (Wh)
E_{gridpk}	Total energy imported from the grid within Economy 7 peak hours (Wh)
E_{gridT}	Total energy imported from the grid throughout the day (Wh)
$E_{heating\_appliance}$	Hourly load profile for heating appliances (Wh)
E_{ICT}	Hourly load profile for ICT appliances (Wh)
E_{kettle}	Hourly load profile for kettle (Wh)
$E_{kitchen\_appliance}$	Hourly load profile for kitchen appliances (Wh)
$E_{lighting}$	Hourly load profile for lighting (Wh)
$E_{lighting\_appliance}$	Hourly load profile for lighting appliances (Wh)
E_{load}	Household hourly load profile (Wh)
E_{loadpk}	Total energy required by the load within Economy 7 peak hours (Wh)
E_{loadop}	Total energy required by the load within Economy 7 off-peak hours (Wh)
E_{loadT}	Total energy required by the load throughout the day (Wh)
E_{loss}	Battery capacity loss (Wh)
$E_{microwave}$	Hourly load profile for microwave (Wh)
E_{netT}	Daily non-renewable energy required from sources exclude PV
E_{netpk}	Non-renewable energy required within Economy 7 peak hours
$E_{refrigerator}$	Hourly load profile for refrigerator (Wh)
E_{remain}	Remaining capacity of the battery

$E_{SOC(END)}$	Energy left in the battery at the end of the previous day (Wh)
$E_{space\_heating}$	Hourly load profile for space heating (Wh)
E_{sun}	Household hourly PV profile (Wh)
E_{sunpk}	Total energy generated by PV system within Economy 7 peak hours (Wh)
E_{sunT}	Total energy generated by PV system throughout the day (Wh)
$E_{surplus}$	Total available surplus energy produced by the PV from the time the EV plugs in
E_{trip}	Energy consumption of a trip (Wh)
E_{tumble_dryer}	Hourly load profile for tumble dryer (Wh)
E_{TV}	Hourly load profile for TVs (Wh)
E_{TV_crt}	Hourly load profile for CRT TV (Wh)
E_{TV_lcd}	Hourly load profile for LCD TV (Wh)
E_{TV_plasma}	Hourly load profile for plasma TV (Wh)
$E_{upright\_freezer}$	Hourly load profile for upright freezer (Wh)
E_{washer_dryer}	Hourly load profile for washer dryer (Wh)
$E_{washing\_machine}$	Hourly load profile for washing machine (Wh)
$E_{water\_heating}$	Hourly load profile for water heating (Wh)
$E_{wet\_appliance}$	Hourly load profile for wet appliances (Wh)
H	Household type
h	Current time step in hourly basis (h)
$h-1$	Previous time step in hourly basis (h)
N	Number of cycles
N_{cycle}	Cycle life
$n_{chest\_freezer}$	Number of chest freezers owned by the household
$n_{computer}$	Number of computers owned by the household
$n_{fridge\_freezer}$	Number of fridge freezers owned by the household
$n_{refrigerator}$	Number of refrigerators owned by the household
n_{TV_crt}	Number of CRT TVs owned by the household
n_{TV_lcd}	Number of LCD TVs owned by the household
n_{TV_plasma}	Number of plasma TVs owned by the household
$n_{upright\_freezer}$	Number of upright freezers owned by the household
$P_{battery}$	Price of battery (£)
$P_{charger}$	Cost of EV charger (£)
$P_{degradation}$	Battery degradation cost (£)
P_{degrad_total}	Total battery degradation cost (£)
$P_{expotot}$	Total profit made by exporting energy to the grid (£)
$P_{install}$	Installation labour cost (£)
P_{E7op}	Economy 7 off-peak hour tariff rate (p/kWh)
P_{E7pk}	Economy 7 peak hour tariff rate (p/kWh)
P_{FIT}	Total return on feed-in tariff (p/kWh)
P_{profit_tot}	Total annual profit made by using the domestic energy system (£)
P_{PV}	Price of PV system (including fitting) (£)
P_{savtot}	Total cost saving on electricity bill (£)

P_{systot}	Total system cost (£)
$p_{charging}$	Power rating of the EV charger
$S_{chest\_freezer}$	Ownership of chest freezers
$S_{dishwasher}$	Ownership of dishwashers
$S_{fridge\_freezer}$	Ownership of fridge freezers
SOC	Battery state-of-charge (%)
SOC_{min}	Minimum state-of-charge (%)
SOC_{tar}	Targeted state-of-charge (%)
$S_{refrigerator}$	Ownership of refrigerators
S_{TV_crt}	Ownership of CRT TVs
S_{TV_lcd}	Ownership of LCD TVs
S_{TV_plasma}	Ownership of plasma TVs
$S_{upright\_freezer}$	Ownership of upright freezers
S_{tumble_dryer}	Ownership of tumble dryers
S_{washer_dryer}	Ownership of washer dryers
$S_{washing\_machine}$	Ownership of washing machines
$T_{charging}$	EV battery charging time (h)
$T_{charging\_start}$	Time when EV starts to charge
T_{end}	Time when EV should finish charging
U_{EV}	EV energy consumption figure (miles/kWh)
E_{EVavg}	The average of measured EV consumption (kWh)
W	Week number of the year
W_d	Weekday
W_e	Weekend
$Y_{cold\_appliance}$	Seasonality of cold appliances
$Y_{heating\_appliance}$	Seasonality of heating appliances
$Y_{kitchen\_appliance}$	Seasonality of kitchen appliances
$Y_{lighting\_appliance}$	Seasonality of lighting appliances
$Y_{wet\_appliance}$	Seasonality of wet appliances
η_{CE}	Coulombic efficiency (%)
η_{CI}	Coulombic inefficiency (%)

Abbreviations

AC	Alternating current
$BEMS$	Building energy management system
$BESS$	Battery energy storage system
BEV	Battery electric vehicle
DOD	Depth of discharge
ESS	Energy storage system
EMS	Energy management system
EV	Electric vehicle
$EVSE$	Electric vehicle supply equipment
FIT	Feed-in Tariff
HEV	Hybrid electric vehicle
IBKs	Inverter backups
ICE	Internal combustion engine
PHS	Pumped hydro storage
$PHEV$	Plug-in hybrid electric vehicle
PV	Photovoltaic
$REEV$	Range-extended electric vehicle
RES	Renewable energy source
ROI	Return on investment
RLC	Residential load control
SAM	System advisor model
$S-ESS$	Stationary energy storage system
SOC	State of charge
$V2B$	Vehicle to building
$V2G$	Vehicle to grid
$V2H$	Vehicle to home
VBA	Visual basic for application

Chapter I.

Introduction

This Chapter introduces the background and motivation for the presented research, it explains the drawbacks in the current UK grid system, and the challenges in the domestic sector under grid evolution. The structure of the thesis is outlined at the end of this chapter.

1.1 Background and motivation

The government recently published an annual report of energy consumption in the UK [1]. The total energy consumption has increased by 1.1% to 143 million tonnes of oil equivalent (mtoe) in 2018, which is the highest level since 2013, Figure 1 shows the energy consumption change in different sectors from 1970 to 2018, domestic and transport sectors represent the majority of energy usage in the last 3 decades.

Figure 2 shows the annual energy consumption in the UK domestic sector from 2002. Generally, the annual average temperature in 2018 remains stable and commensurate with 2017, however, a surge in energy consumption happened in the first quarter under the influence of the ‘Beast from the East’, which results in in a dramatic increase of 4.8% in the domestic energy consumption in 2018 when compare with 2017.

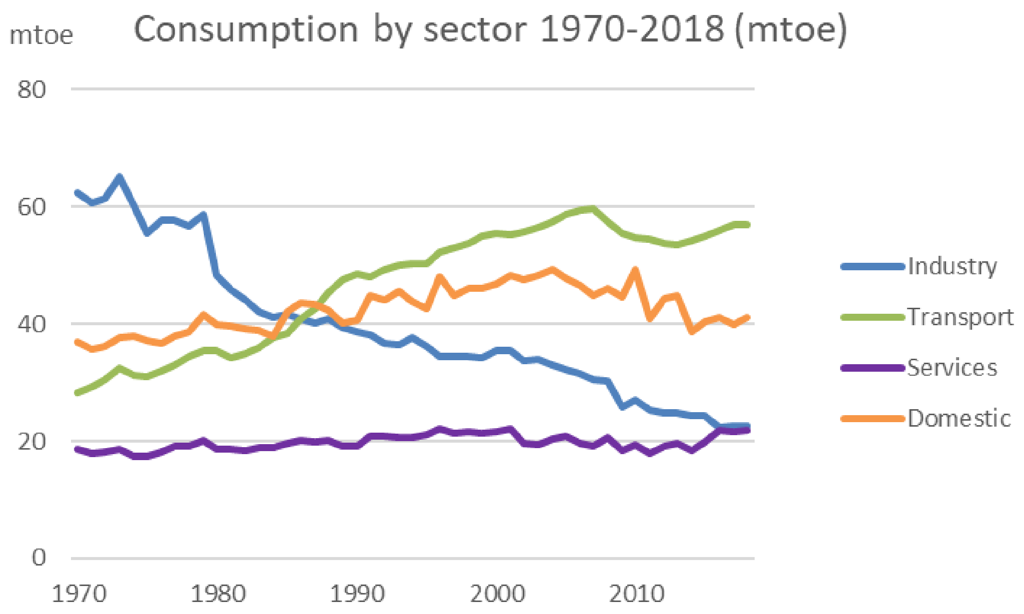


Figure 1. Energy consumption in sectors from 1970 to 2018 [1]

Since the domestic sector is highly responsive to fluctuations in temperatures, the increase is mainly due to households needing more energy for space and water heating, as the winter period was colder leading into 2018, which results in higher average heating degree days[1] (increased from 5.2 to 5.5) [2]. 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 the occupants of the house [3]. These wide variations in domestic appliances' power consumption, and usage patterns, cause significant difficulty with predicting daily domestic load profiles accurately, especially for short time steps.

[1] Heating degree days (HDD) is defined as a measurement to quantify how much energy is needed to heat a building, to calculate HDD, subtract the average daily ambient temperature from a base temperature. In the UK, the base temperature is set at 15.5℃ by the department of energy & climate change, which represents buildings need to be heated below this temperature. The HDD's is summed for a year, and a daily average HDD of 5.5 is derived for 2018. Further details can be found at: https://www.statista.com/statistics/422863/monthly-average-of-heating-degree-days-compared-to-mean-uk/

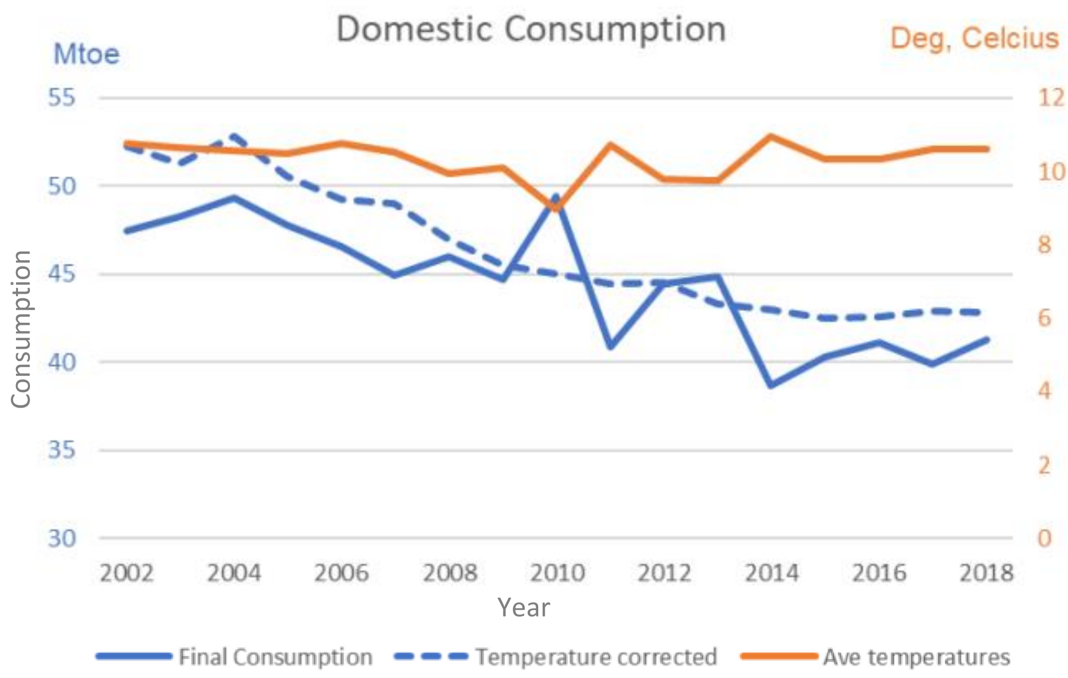


Figure 2. Domestic energy consumption over the period from 2002 to 2018 [1]

In order to meet the target set by the UK Government's Climate Change Bill in 2007 to cut the UK greenhouse gas emissions by 100% from 1990 levels before 2050 [4], schemes such as energy efficiency measures (e.g. appliance energy labelling and house insulation) [5] and smart metering [6], which are designed to affect the households behaviour, were considered. Smart meters attempt to provide a variety of information to the householder, including tariffs and usage to encourage households use less electricity. The most up-to-date figure [7] shows due to the COVID-19 pandemic, although the CO_2 emissions from residential sector have seen a slight increase because more people stayed at home during nationwide lockdowns, less use of road transport and reduced business activities, together with reduced fossil fuel use for energy supply result in the total greenhouse gas emissions produced in the UK in 2020 drops to 414.1 million tonnes carbon dioxide equivalent ($MtCO_2e$) which is 48.8% lower than the 1990's level, it is almost half way towards the goal.

The UK Government's Renewable Energy Strategy set a legally binding target in 2009 to ensure 15% of the energy produced is from renewable sources by 2020 [8], according to the UK Energy In Brief published in July 2020, this target was met with 37% of electricity was generated by renewable sources in 2019 [9] due to the penetration of PV and wind power systems. Additionally, the Government's Low Carbon Buildings Programme provide grants (known as 'Feed-in Tariffs') for installing small scale renewable energy generation systems [10] such as solar power, wind turbines and hydro technology. Among those renewable sources, solar photovoltaic (PV) systems are the most attractive energy generators as to they are easy to set up on houses, and have relatively low maintenance cost [11].

The international renewable energy agency has predicted the cost reduction potential for PV and wind power systems between 2015 to 2025 [12]. It suggests the cost for a typical PV installation will reduce from $1810/kW in 2015, to $790/kW by 2025, therefore, domestic PV penetration levels are expected to grow in the foreseeable future. The cumulative number of domestic PV systems installed in the UK up until June 2018 was 892,378 units, as reported in national statistics [13]. However, there are now concerns with voltage fluctuations and reverse power flows, when the households sell surplus PV energy back to the grid, which is a large problem from the utility company's point of view. Thus, the rapid uptake of green energy generation together with the targeting of usage reduction, promoted an evolution in grid system[2].

The transport sector is responsible for a contribution of 57 mtoe to the total energy consumption in 2018. This is the largest sector for emissions, that produced 123 million tonnes carbon dioxide equivalent (MtCO_2e), and accounts for 28% of all greenhouse gas emissions in the UK [14]. The main source of the overall emissions is from using fossil fuels. In addition, the transport sector has the highest oil demand when compared with other sectors, and has a noticeable contribution to the decline in air quality. Due to limited reserves of fossil fuels, and the desire to reduce pollutants emission, electric vehicles (EVs) have been developed, and are commercially available for daily use in recent years [15]. EVs are to play an important role in achieving government goals on reaching zero net emissions [16], especially for those recharged by renewable energy sources, as they shift the energy demand from fossil fuels to other 'greener' generation.

[2] Details about the grid evolution are illustrated in Chapter 2.

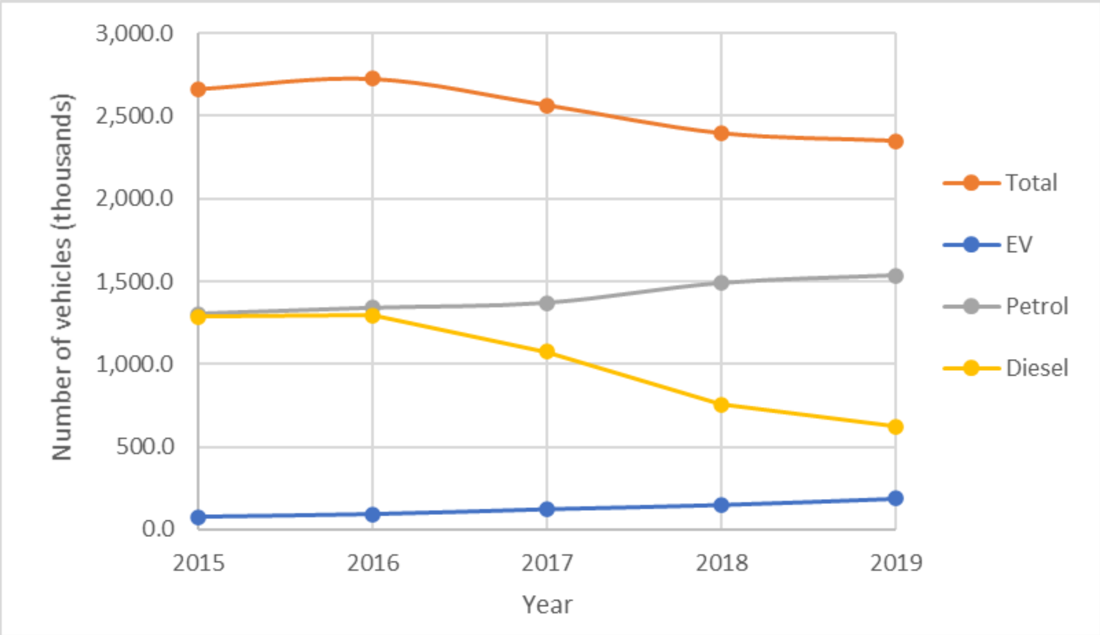


Figure 3. Thousands of cars registered for the first time in UK

Figure 3 shows cars registered for the first time in the UK in from 2015 to 2019, according to the statistical data published by DVLA [17]. It shows total number of new vehicles registered is decreased from 2.66 million to 2.35 million in 4 years. Although the EV market is increasing year on year, unfortunately, due to no government grants provided on purchasing electric vehicles, the higher capital cost (mainly on the EV's battery) and relatively shorter range compared with traditional internal combustion engine vehicles, EV's market penetration is still difficult and slow [18].

Mandating the sale of more energy efficient consumer electronic products to households, and taking more comprehensive technical measures are subject to governmental policies. The development of better performing housing insulation is in the realm of material and civil engineers, and thus electrical engineers focus more attention on the development of smart grids, which is more likely to be an electrical technology-based solution to help produce a better environment and to meet the government's target of energy consumption reduction.

With domestic PV system installation, customers can save money on their electricity bills, and get paid for the energy they generate, by their supplier. However, due to lack of energy storage facilities and control systems, large amount of energy demand is not met by this generation during off-peak hours, and only part of the load at peak hours can be covered. This causes possible load-shedding outages, and in the limit, an energy crisis for the utility grid.

Currently, the cost for installing an energy storage system alongside with PV is still high, this includes the battery cost and the installation cost of hiring a certified electrician. Without the government support and convincing figures on payback time, customers are hesitating to make further investment on the energy storage systems.

Hence, energy storage at domestic households with PV rooftop needs to be reviewed and developed. The developed system can overcome the mismatch between self-generation and load, and produce the better path to a ‘smart grid’, which result in an improvement on bill savings and the potential to help inform and shape the government policy. The outstanding system performance will encourage more installations by customers.

Households with an EV can potentially use the capacity of the on-board battery as distributed stationary storage to support the household load consumption, in a similar way to using a household battery energy storage system (BESS). A vehicle-to-grid (V2G) enabled EV can help cutting electricity bill costs by moving towards domestic energy self-sufficiency, as its battery can be used to fully exploit local PV generation.

Moreover, as the progress is made on battery manufacturing technologies, lithium-ion batteries are now widely used in the automotive industries, consumer electronic products and energy storage systems. Although Li-ion batteries have a series of advantages such as: high energy density, long life-cycle and no memory effects [19], understanding the characteristics of battery capacity and power fade are necessary, especially when applying to frequent charging/discharging operations.

1.2 Contributions of this thesis

Current efforts on renewable distributed generation and energy storage penetration, aim to promote an approach towards domestic energy self-sufficiency. The decreasing costs of PV generation systems and BESS installations, point towards the need for a more holistic approach to designing the domestic energy environment. This thesis aims to address this by holistically modelling a domestic energy system with BESS and V2G, using different scenarios for dwelling occupancy, vehicle use, and electricity tariffs. From the results of the modelling, trade-offs can be identified to achieve the best performance for a domestic energy system.

Prior to designing the system, models to simulate domestic load and PV profiles are created as the foundation of later research. Domestic load profiles are created using the 'Goldsim' software package and government published real world consumption data. This data was generated by appliance monitored in 250 UK households, the data is available on an hourly basis for different types of household. By selecting relative appliances in a specific household environment, the model developed in this work attempts to create the corresponding load profile based on the real-world data. PV profiles are generated using the 'System Advisor Model (SAM)' software package created by the National Renewable Energy Laboratory (NREL) [20], which retrieves local weather data from the closest meteorological station in combination with solar irradiation information, to simulate the household PV generation on an hourly basis for different sizes of installation. Simulated data files from both models are then exported to Excel to create a Household Energy System Tool which contains a user interface with various input selections and an output section for presenting results.

A household with PV generation and a BESS is then modelled using the tool, the BESS being able to absorb PV overproduction for later use, or storing grid energy at low tariff and CO_2 emission period to cover the solar intermittency or support load within high tariff period. With the developed battery control strategy and algorithm, the cost of electricity over a year for typical domestic household is dramatically decreased. Energy self-consumption and self-sufficiency can typically be achieved in the summer when PV production is sufficient to cover all load demand.

An EV is then further integrated to the above system to apply vehicle-to-home (V2H)/ vehicle-to-grid (V2G) operation. The operation proposed is that when the EV is parked at home, it can enlarge the domestic energy storage capacity, which in-turn enhances the domestic energy self-sufficiency and further reduces the annual energy bill cost still further. Additionally, an EV that is fed by renewable energy helps reduce CO_2 emissions, which can potentially accelerate the progress on reaching the 'net zero' target in the UK.

Battery degradation, cost and total system investment are evaluated, annual profit of using the system based on market electricity tariffs is calculated, and through this, system payback periods are derived to analyse the system performance for various scenarios.

Hence, the summarised objectives of the research are listed below:

- Domestic load and PV profile modelling are developed
- Household Energy System Tool is developed to model domestic energy system, household with PV generation and BESS is evaluated under different scenario and the performance on cost saving and system payback time is analysed
- EV is integrated into Household Energy System Tool and different scenario are evaluated
- Battery degradation modelling for both BESS and EV battery is developed and integrated into Household Energy System Tool.

1.3 Thesis structure

The organisation of each chapter in this thesis is shown below, a brief description states the contents included for each chapter.

Chapter 1 is an introduction of the research background, summarising the drives and challenges for the presented thesis.

Chapter 2 reviews the basic system components and definitions in a domestic PV system, together with the basic principle of vehicle to grid (V2G) technology. The review summarises the challenges raised in managing domestic renewable generation and battery storage, and the difficulties on applying V2G, which will be studied in the later chapters.

Chapter 3 introduces a newly developed domestic energy system with PV and battery energy storage system included. Modelling of domestic load profile and PV generation profile are proposed, a control system is designed under the battery dispatching strategy. Additionally, a tool with various of functions is constructed and results are evaluated.

Chapter 4 further develops the tool created in Chapter 3 with the integration of an electric vehicle (EV). A battery aging model is also proposed in this chapter. System payback time for different configurations in a typical case study are calculated to analyse the system performance by deriving overall payback time. In addition, overall CO_2 reduction by using the system was evaluated.

Chapter 5 concludes the work and illustrates the contributions of this thesis. Future works which have the potential to improve the work presented in this thesis are recommended.

Chapter II.

Literature Review

In the last chapter, the environmental concerns and government targets are described which underpin the aims of this project. This chapter further reviews the basic schemes and principles of smart grids, Feed-in tariffs, vehicle to grid (V2G) technology etc, all of which are key to the understanding of the domestic energy system and its interaction with the utility supply. Also, the state of the art in home automation and load remote management, using BESS to support the household and the grid, and the integration of EVs to provide support the grid are discussed. This chapter therefore provides the reader with the fundamental knowledge to understand the work presented in later chapters.

2.1 Basic schemes and principles

Prior to addressing the way in which domestic PV installations can be selected based on cost, and effect the installation has on energy bills, it is useful to examine some of the basic system components and definitions, including the opportunities for income generation and metering. Additionally, some of the basics surround in the definition of a PV system will be addressed in the following sections.

2.1.1 Distributed PV applications and large-scale PV applications

The PV market in the UK comprises two major system types, distributed installations, and large-scale installations. Distributed PV systems are generally those installed for residential, commercial and industrial uses. Usually, this type of systems is rooftop-mounted and primarily feeds into the grid via the building supply connection. The larger-scale, stand-alone, PV installations are typically ground-mounted for utility scale applications, with their own grid-scale connections [21]. PV systems with power ratings within 1-20kW are generally classified as residential, while industrial and commercial PV systems are usually larger than 20 kW. Stand-alone installation sizes greater than 100kW are defined as centralized large-scale PV systems. Typically, 4kW PV systems are the most common rooftop-mounted domestic installations in the UK. In this application, the available roof area is the important factor for sizing the PV system, as typically at least 28.8 m^2 is required for a standard 4kW PV system, given that PV panel sizes vary from 1.3 m^2 to 1.7 m^2 [22].

2.1.2 Feed-in tariffs

The feed-in tariff (FIT) is a UK government scheme launched in April 2010 which aimed to encourage the installation of small-scale renewable electricity generation systems such as solar PV, wind turbines and micro hydro technology [23]. Users who have eligible systems installed will get paid for the decentralized electricity generation. FITs include two elements of direct financial benefit, which are the generation tariff and the export tariff, in addition to the energy bill savings seen by the installation [24]. The generation tariff is paid by the energy supplier for each unit (kWh) of electricity generated, at a fixed rate. It is the main payment from the FITs, and is paid on the total amount of electricity generated by the eligible renewable energy system, whether the energy is fed back into the grid or self-used [25].

There are two types of PV installation, new build and retrofit. It always brings challenges when retrofitting the house with a rooftop mounted PV system, for example the cost of wiring and the safety of retrofitting. Those challenges made customers hesitate to install solar panels. On the other hand, new build PV system can be integrated into the roof which reduces the cost of roof covering and improves the safety. The wiring of solar panels can be done before the decoration, this removes all the complexity and inconvenience of retrofitting. Therefore, the government announced a generous feed-in tariff rate at 56.03 p/kWh for a retrofit PV system of under 4 kW, and 48.87p/kWh for a new build PV system prior to March 2012 [26], which achieved the aim of encouraging numerous households to install domestic renewable system.

The UK national statistics on solar photovoltaics deployment counts the registered new-build PV systems from 2011 to 2020 [27], with the annual installed number of domestic PV systems rated under 4kW summarised in Figure 4. The numbers of systems installed per year peaked at 198,602 units in 2011 since the FIT scheme was first introduced. Then the tariff rate was reduced to 25.91 p/kWh and the difference in tariff rate between retrofit and new build system were removed since 3rd of March 2012, this results in a decrease in the number of PV installations, customers were not sure the effects by reduced FIT rate and started to take a wait-and-see attitude.

However, the benefits of small-scale PV system rekindled customers' interest after 2013, the number of installations went up each year while FIT rate experienced a periodical reduction until January 2016, when FIT deployment caps were introduced [28].

The publication of FIT deployment cap scheme resulted in that the FIT rate dropping from 13.47p/kWh to 4.92p/kWh in early 2016, and further cutbacks on the FIT to date have made some investors lost their interest in installing further domestic PV systems. Therefore, the yearly PV deployment dropped by 69% in 2016, and subsequently less than 50,000 systems are installed annually. The cumulative number of small-scale PV systems installed in the UK is currently 981,145 units, up until 2021 [29].

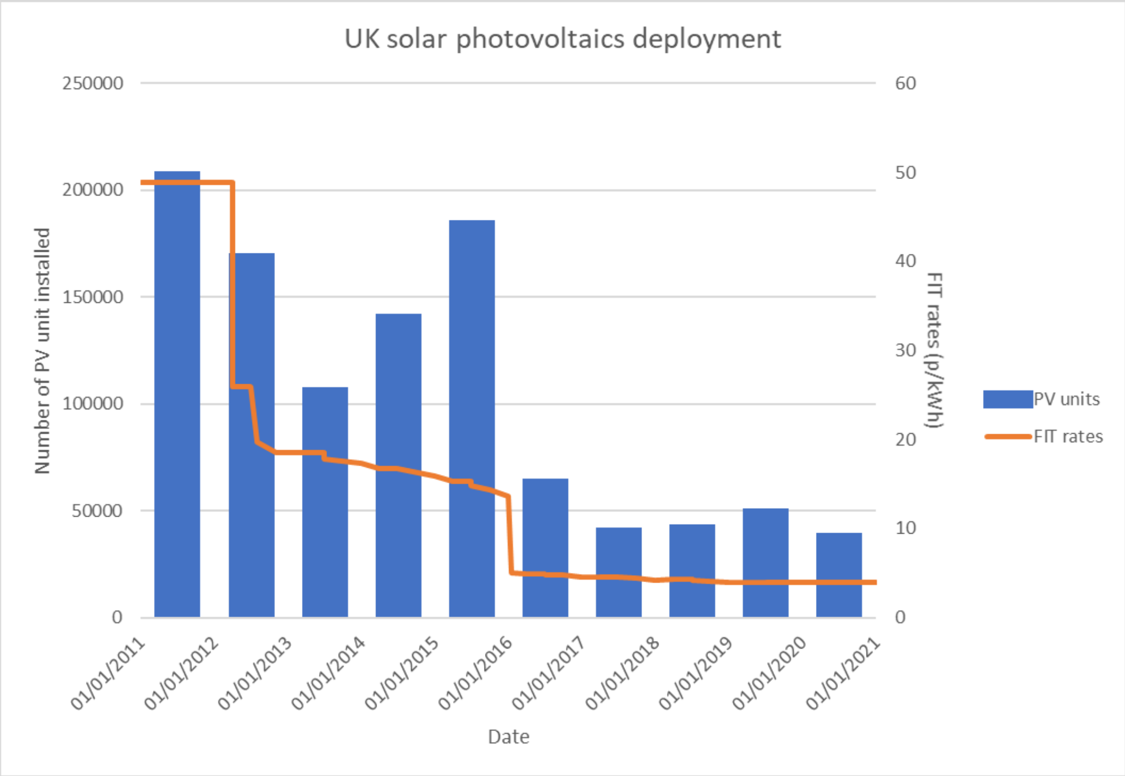


Figure 4. UK solar photovoltaics deployment statistics from 2011 to 2020

Further to the generation component of the FIT, the export tariff is a certain amount of cashback paid by the energy supplier on every unit of surplus energy that is exported to the grid [30]. Before the widespread use of smart meters, the amount of electricity exported was deemed to be 50% of the total energy generation, for a domestic system. However, smart meters are able to measure the exact amount of export to the utility supply. Additionally, the generated energy will lower the electricity bill for the installation, since less energy import is required from the grid to power the appliances in the property.

2.1.3 Economy 7 metering and tariff

There are various types of energy tariffs. The standard variable tariff is a default tariff set by the energy supplier, and it is usually the most expensive rate because the supplier can change the unit price at any time. While fixed price energy tariff is usually the cheapest type, energy is supplied in a domestic setting at a set rate per unit of electricity used (kWh) for a fixed duration [31]. Customers are protected from price rises on this type of tariff, however, if the electricity price fell, there's no cut on the fixed plan. This tariff P_{fixed} is quoted at 15.56 p/kWh [32] and will be used for later analysis.

Moreover, it is possible to have a contract with an electricity supplier which measures the energy used in both peak, and off-peak periods. The off-peak period is typically 7 hours long, and hence these tariffs are termed Economy 7 tariffs. To be eligible for an economy 7 tariff, a consumer requires a suitable energy meter. Economy 7 meters measure day and night electricity usage separately, and under an economy 7 tariff, night-time energy use is costed at a lower, or off-peak rate [33]. This applies for 7 hours each night, and depending on the suppliers' contract, this period could start early from 11 pm to 6 am the next morning, or later, from 1 am to 8 am. The off-peak tariff is typically 1/3 lower cost than the peak hours electricity costs, and in this study the tariff rate used in later chapters was based on the local electricity price from the EDF energy website in August 2017, which 6.99 p/kWh for off-peak hours (P_{E7op}), and 19.46 p/kWh for peak hours (P_{E7pk}) [32]. In this thesis, a default off-peak period is taken as being from 00:00 to 07:00, household energy usage during off-peak hours is defined as E_{loadop}, while the rest hours of the day is defined as peak hours, thus the household energy usage during peak hours is defined as E_{loadpk}.

This thesis focuses on how developed system performs under Economy 7 tariff scheme. Although the peak rate is higher than fixed rate tariff, however, the integration of battery energy storage system is able to utilise the energy pre-charged at cheap rate to cover the PV intermittency or high demand, which reduces the bill cost indirectly. In addition, Economy 7 tariff scheme has significant benefits for customers with electric vehicles that are most likely recharged overnight.

2.2 Previous research

With the increase in the penetration of PV generation into power systems, the adverse effects on the traditional grid system have become more serious. A review of grid-tied PV systems within traditional power grids [34] summarises the effects as follow:

- Real and reactive power fluctuations
- Large reverse power flow
- Interaction with capacitor banks and voltage regulators
- Voltage variations
- Potential effects for overcurrent and overvoltage protection systems
- Increased losses and power factor modification
- Voltage unbalance
- Harmonics

To overcome these adverse effects, and allow further PV penetration, an evolution of traditional power systems has to occur. Smart grid technology is a promising and upcoming approach that was recently introduced to the public. In a smart grid, load consumption control is not the only factor that needs to be considered, energy management systems (EMS) development is a more complicated topic, attracting much recent research [36]-[39][47]-[51]. Modern smart grids include green energy generation, which uses alternative renewable resources such as solar PV, small wind turbine or hydro electricity generation. These generation technologies are often accompanied by distributed energy storage to tackle the intermittency of the green generation, and are starting to expand to include the introduction of vehicle to grid (V2G) technology allowing electric vehicles (EVs) to complement the stationary storage on the grid when the EVs are not in use. Smarter controllers, and similar energy saving devices, are also important in the formation of a smart grid.

2.2.1 Smart meter and smart grid

Smart meters are the new generation of gas and electricity measuring equipment, measuring and recording how much gas and electricity is being used in real time. In addition, they can show the exact cost of the used energy synchronously on an in-home display [35]. A smart meter can also display more intelligent features such as energy usage in the previous time intervals (day/week month etc.), and the balance of the customer's account. With the installation of smart meters, customers are no longer required to send meter readings to their suppliers, and bills are always accurate. Household will also have better understanding of their consumption pattern and visually know their tariff and spend. On the utility side, smart meters save labour cost for gathering meter readings as they are fully digitised and can be accessed easily, also utilities can use them to instantly detect faults or a power outage. Besides, different from analogue meters, smart meters provide real-time information which can be used by utilities to implement dynamic pricing. Normally, consumers are paying a flat rate of electricity, but in fact the cost of generation varies based on the demand and time. Utility companies have to start up more generators or power plants to meet peak demand which can be so inefficient and costly. Therefore, dynamic pricing is introduced to have variable electricity prices over short intervals (typically an hour), this gives customers more control over their bills while energy suppliers can optimise the use of existing resources and get compensated for extra generation.

The government expects every household in the UK will get smart meter installed by 2020 [36] this is termed the smart meter 'rollout'. However, due to delays in connectivity and issues arising with the installed meters, the deadline has been delayed until 2024 [37]. Until January 2021, there are in total about 23 millions of smart meter have been installed, which accounts for 45% of all domestic households [38]. Since the widespread deployment of domestic renewable generators such as wind turbines and solar PV, the amount and direction of power flows within the grid are less predictable [39]. Typically, energy suppliers and grid system operators want to balance the load and generation to produce a stable supply, without overload which can cause loss of supply. The introduction of smart meters, as the foundation of smart grid technology, is an opportunity to transfer the current power grid into a new system with higher reliability, availability and efficiency providing benefits in terms of economics and environmental health [40]. The government is expecting the UK smart grid will be fully implemented around 2030. At this point, the grid will be able to seamlessly integrate large and small scale renewable energy systems to produce a safe, stable and efficient supply environment which, as a result, reduces the peak demand on the grid, and the cost for both the utilities, and the consumer.

2.2.2 Home automation and appliance remote control

The idea of load consumption control has been around for a long time, and is the basis for linking domestic households with a smart grid. The main aim of this approach is to manage appliance operation to occur out of the period where peak demand occurs for grid, where possible. The work studied in [41] introduces a theory based on the aim of being enable to remote-control the distributed household appliances to reduce their energy consumption during peak periods. The European SMART-A project discusses and compares potential changes to appliance operation, alongside local energy generation, to work out options for peak-shaving on the grid load through distributed appliance control, in order to develop a smarter management of supply and demand [42]. A residential load control (RLC) system is developed in [43] with real energy pricing correction. The authors focus on producing an automatic controller for household appliances which is able to predict the price of electricity during a specific time period, and output an optimum delay time for the device operation, based on the predicted cost to control the ON/OFF status of appliances. In [44], a practical control system has also been developed. It consists of several module blocks integrated with programmed wireless Arduino Uno microcontroller boards, the wireless transceiver modules that allows communication between receiver and the control unit to feed power consumption limit information from the transmitter to receiver. Current and voltage sensors are used to measure real time load data while a four-channel relay module is used to control appliances’ ON/OFF state. From these projects, it has been shown that home automation methodologies can manage the energy consumption in a home, on a real time basis, and improve the efficiency of energy use.

2.2.3 Energy storage for grid support

Distributed energy storage is another key to the implementation of smart grids. Generally, it represents the process of storing excess generated energy from the grid at low demand periods, or periods of excess domestic renewable generation, to support high demand from the grid or household use at some later time. There are number of approaches to energy storage, such as pumped hydro storage (PHS), Battery energy storage systems (BESS), Flywheels, super-capacitor, etc. PHS is mostly used for storing large amount of excess energy usually in the 'megawatt-hours' by elevating water from a lower reservoir to an upper reservoir as a charging process, while discharging the water down through a turbine to release the energy as required [45]. Typically, PHS has a reasonable round-trip efficiency of 70%-80%, but it suffers from high capital cost of construction and the capacity is constrained by terrain conditions.

The principle of flywheel energy storage is the energy conversion from electrical to kinetic energy [46], excess energy is used to accelerate the rotation of flywheel which increases the energy content. To discharge the energy back to load, simply convert the kinetic energy back to electric energy via the generator that driven by the flywheel. This technology has the benefit of less maintenance cost, rapid response and high efficiency. However, due to the mechanical characteristic of flywheels, their high self-discharge rates make them only suitable for short timescale storage.

Another method of energy storage is to use electric double-layer capacitor, energy stored by a capacitor can be calculated using Equation (1), where C is the capacitance and V is the voltage applied [47].

$$E = \frac{1}{2} C V^2 \tag{1}$$

Supercapacitors consist two electrodes connected by an electrolyte, an ion permeable membrane (separator) in between allows ions to flow through, to create current. It is known that the capacitance equation of a capacitor as:

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d} \tag{2}$$

Where ε_0 is the permittivity of free space, ε_r is the relative permittivity, A is the area of plates and d is the distance between the plates. Thus, supercapacitors have much higher energy capacity than ordinary capacitors due to their high capacitance as a result of large effective area and small distance between plates [48]. On the other hand, high self-discharge rate makes supercapacitors unsuitable for long-term energy storage, as gradual voltage loss limits their application. Also, supercapacitors have a comparatively very high cost when compared with conventional capacitors and rechargeable batteries with same energy capacity [49] [50].

BESS is introduced to use rechargeable batteries to provide a small amount of energy storage. However, good scalability makes BESS's suitable for wide range of applications. Lead-acid and lithium-ion batteries are the two most common battery technologies used on the market today, mainly due to the overall system costs dropping dramatically in the last decade [51]. Since other methods of energy storage described above are either expensive to operate or limiting to certain applications. In this thesis, a battery energy storage system (BESS) is considered, to be integrated within a domestic household to reduce the energy charges, and additionally, to provide possible grid support. To this end, the next section will describe previous work on BESS based systems.

2.2.3.1 Domestic and grid demand peak-shaving with BESS

Recently, there has been a number of projects investigating the use of BESS for grid support. Figure 5 refers to research by [52], which illustrates the concept how the combination of PV and BESS can help peak demand shaving in households, to provide grid support. Integrating renewable PV energy generation with BESS [53] makes the battery work as a buffer to store the surplus energy (as shown in red shaded area from Figure 5) from a residential PV system to then be used when required by the load (as shown by the blue shaded area). This results in a smoother grid energy demand curve. The targeted demand from the grid is to be almost constant (as shown in grey shaded area), and this could be achieved, in a given supply region, if PV+BESS was installed in each household in that area.

Through the modelling in Narasimha Kumar's research [54], the authors demonstrated the control of distributed storage in the domestic arena. The approach can be divided into two levels: grid level and home level. At the grid level, the grid controller is responsible for the total amount of energy required by the home from the grid, and grid aggregator measures the energy required for each house, feeding the sum to the grid controller. Breaking this down to a single home level, controllers in the homes manage the load with PV generation, battery storage and load consumption control to achieve the overall demand. An intelligent controller hardware module was introduced in [55] to control household appliances on a smart grid system, including a distributed storage facility similar to the work done in [54]. Both types of home smart controllers are installed outside the appliances, and aim to calculate the energy needed for household appliances at different time intervals, relaying the information back to the energy management system (EMS), where the processor controls the amount of energy needed from the grid. The smart controller in [55] is described as integrating the energy storage with home appliance control, and was demonstrated in real world scenarios. The results were validated, and with the introduction of controlled domestic energy storage, the grid peak demand in the area was be reduced significantly, the excess load being shifted to fill the valley demand, which increased the grid stability while reducing the grid operating costs.

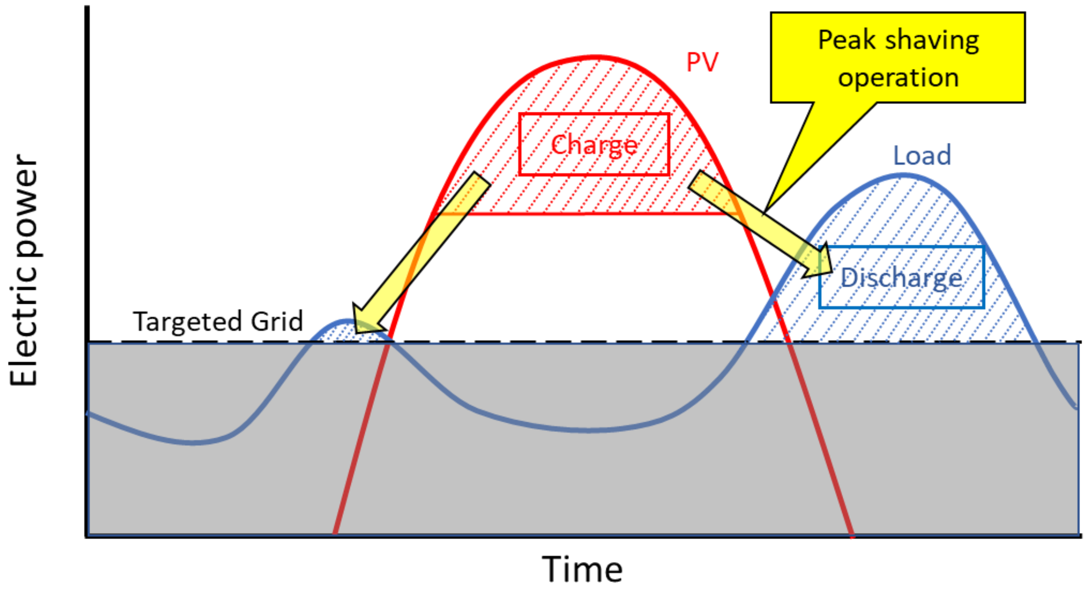


Figure 5. Concept of energy profile in domestic household with PV and ESS as energy buffer to support grid

2.2.3.2 Matching renewable energy supply and demand with BESS

As electricity supply and demand varies all the time, due to the intermittency of PV power generation typically caused by shading on panels or bad/variable weather conditions, BESS's in a region are required to manage the power flow more flexibly as a buffer, and to minimise this intermittency. In any given period at a typical location, when the renewable energy generation exceeds the local demand, batteries can absorb that excess energy, either to use at a later time or export to support other local areas connected to the grid at some future time. BESS enables better utilization of renewable energy to cover local demand, and hence aims to reduce overall conventional generation.

2.2.3.3 Grid reliability with BESS

Grid reliability is defined as the ability to match the unexpected fluctuations in supply and demand [56]. A reliable grid should supply sufficient energy at all times, while lowering the loss-of-load probability. The issue of reliability is highlighted when domestic renewable energy sources are incorporated into the supply portfolio, as the uncontrollability of the generation, coupled with the short-term intermittency can lead to instabilities and local loss of reliability. BESS has the ability to smooth the grid supply portfolio, lowering the effects of intermittency of renewable energy and the impact on grid reliability / instability [34]. Therefore, this prevents the appearance of overvoltages for small-scale PV systems, and smooths the supply profile for large-scale PV generation. The grid operators will get benefit from this to ensure the system stability.

2.2.3.4 Maintaining grid frequency with BESS

In conventional power plants, electricity is generated by converting the kinetic energy of a spinning turbine. For the most common steam-driven generator, the rotor inside the generator is turned by a high-pressure steam turbine, energising the copper coils on the rotor with electricity creates a rotating magnetic field, and the rotation of this field inside the stator, containing windings of large, heavy duty copper bars [57], induces the generated voltage.

Because of the north and south poles of the magnetic field, the direction of magnetic field passing through the copper bars alternates every revolution of the rotor, which results in a sinusoidal induced voltage. 3 sets of copper bars in the stator produces the familiar three phase voltage supply.

Electric frequency is the number of cycles per second in an alternating current (AC) sine wave. In the UK the frequency is typically 50 Hz, produced by a 3000 rpm two-pole generator [58]. However, load can affect the grid frequency. When a large demand is required, it places a large load on the generator, slowing down the machine and resulting in falling frequency. Similarly, the generator speeds up if a large load is removed from the grid resulting in rising frequency. It is important to maintain the grid frequency at 50Hz as frequency variations will damage equipment sensitive to frequency as a timing signal, and is serious on a national scale. The primary response to keep a consistent electrical frequency is to adjust the speed of generator / turbine system. However, a BESS can act with a rapid response to quickly compensate for load changes on the grid system, mitigating changes in frequency, supplying or absorbing energy to counteract changes in load.

2.2.3.5 Challenges of BESS

Considering current battery technologies, constraints brought about by cycle life and depth-of-discharge (DOD) make BESS systems less favourable to rapid cycling. Cell degradation in larger batteries over years of use require replacement after periods of time, which count as maintenance cost, thus although the efficiency of a BESS is high (above 85%) and the price of battery has dropped 87% from £830 per kilowatt-hour in 2010 to about £117 per kilowatt-hour in 2019 [59], it is still very expensive and is only just becoming suitable for large scale application considering the capital investment (£3-5 million for 20 MWh unit) and possible ongoing maintenance costs.

2.2.4 Vehicle to Grid technology

Vehicle to Grid technology (V2G) is developing as a way to treat electric vehicles as a distributed energy storage system, which will reduce the cost for local storage infrastructure and increase the flexibility of operation [60]. This section will describe the previous research on V2G technology and how this can support the grid.

2.2.4.1 Types of electric vehicles (EVs) and how they work

There are three main types of electric vehicles, categorised with increasing electric drive capacity: hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs) [61].

HEVs have a normal internal combustion engine (ICE) installed and the smallest battery bank of the three types. They don't need external charging outlets to remotely recharge the battery, there are two ways to charge the battery, the first is using the electricity generated from petrol engine to recharge the battery during normal driving. The other charging method is called regenerative braking. It converts the kinetic energy from the vehicle movement into electricity while the electric motor acts as a generator to help slow down the vehicle when driver presses the brake pedal. This leads to braking energy from the vehicle being recovered instead of being wasted as heat through the standard mechanical friction brakes. There are also two types of hybrid systems, one is with parallel power train whereby electric power is delivered to the wheels in parallel with the output power of the internal combustion engine (ICE) [62]. The other, a series hybrid, has a series power train whereby the output power of the ICE is fully converted to electrical energy which is either used to power the motors or charge the battery. This decouples the ICE from the wheels and allows the vehicle to cover short distances with zero emission. The benefit of HEVs is they can have high MPGs which leads to lower fuel costs.

Similar to HEVs in operation, PHEVs have relatively larger battery capacity than HEVs. The vehicle is now powered with two resources, as it can recharge the battery not only from the ICE and regenerative braking, but also from an external charging outlet connected with the utility grid. PHEVs can drive more miles on pure electric drive thanks to a bigger battery than a HEV, and they can switch between pure electric drive, pure ICE drive and a combination of both. The ICE engine will recharge the battery as it gets low if required in a similar fashion to the HEV.

BEVs are fully powered by electricity, there are electric motors and a battery pack inside the vehicles' power system. They do not have ICE installed as an alternative power resource. BEVs are also termed plug-in electric vehicles (PEVs) as they require external charging equipment to recharge the battery, and they have the largest battery capacity among these three main types of EVs.

2.2.4.2 What is V2G

Vehicle to Grid (V2G) is a concept developed to better construct energy storage systems (ESS), and make use of vehicle batteries whilst they are stationary. By integrating V2G with smart grid technology, it is possible to use the battery packs inside EVs as distributed energy storage [63]. As shown in Figure 6 [64], V2G technology is aimed at helping renewable energy system integration with smart grids, due to the ability to store excess energy generated in low demand periods, while discharging the energy back into the grid to support periods of high demand, therefore, reducing electricity costs for customers, and peak demand issues on the grid.

Figure 7 shows by connecting the EV to electric vehicle supply equipment (EVSE), it can provide bi-directional flows of energy. G2V means the EVs are charging their batteries by taking energy from the electric power grid, whilst energy can be provided back to the grid as V2G, as the EV battery discharges.

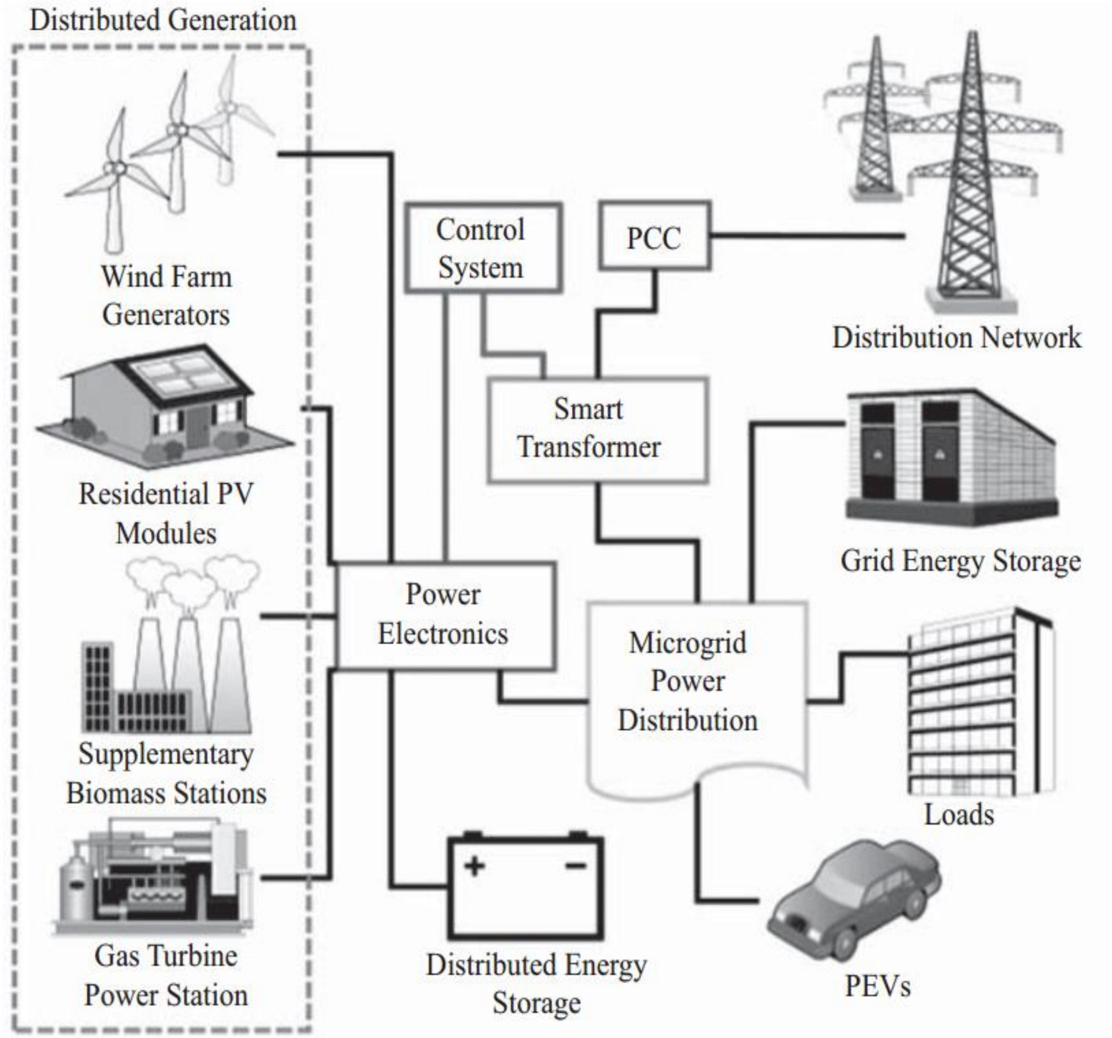


Figure 6. Basic concept of smart grid with V2G technology and renewable energy system [64].

Apart from V2G, vehicle to building (V2B) and vehicle to home (V2H) are two other applications through plug-in electric vehicles (PEVs). V2H is a concept that uses PEV's battery to store energy from domestic renewable resources and provide this stored energy to home loads [65]. It has the potential to increase system efficiency, reduce electricity bills for households and provide reliable emergency backup power [66].

V2B is an intermediate step between V2G and V2H, this concept benefits both PEVs and buildings owners [67]. Generally, when a set of PEVs are parked in public parking slots at office buildings, shopping centres, universities etc., V2B manages the PEV fleet during the time when they are plugged to lower the electricity cost for buildings by discharging energy to the building loads at high demand time, and recharging the PEVs at low cost periods. In return, the owners of PEV will also receive a share of the building's cost savings [68]. In addition, the relative high capacity of storage can support critical loads of the buildings to avoid service interruptions and data loss in the situation of power outages.

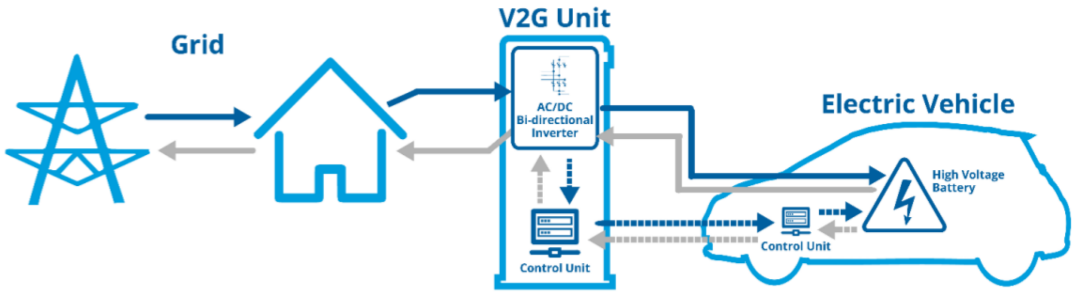


Figure 7. V2G and G2V systems schematic diagram [69].

2.2.4.3 How V2G can support grid

V2G can support the grid in four main areas, which are valley filling, peak shaving, frequency regulation and spinning reserve.

Valley filling and peak shaving with V2G are just like that with BESS described in previous section. They utilise the EV battery to charge at night when the demand is low or at off-peak load, then supply the power back to the grid when the demand of electricity is high. This helps balancing the load. However, using V2G there is the extra constraint of the availability of the vehicle battery to provide power to the vehicle when the EV is required.

Similar to BESS, EVs can provide regulation as they can be used both as load and generating source. In this way frequency can be maintained by charging the battery of vehicle when there is too much generation in the system. When there is too much load in the system, they can behave as generating sources by discharging the battery power [70]. Besides this frequency regulation service, EVs can provide some other services when connecting to the grid such as spinning reserve, peak management and back-up service etc. Back-up service is provided when one or more vehicles are connected together to behave as a micro grid in case of power outage in a neighbourhood. Peak management concept can be realised as when there are number of EVs in V2G mode, an emerging and optimised storage system of electricity can be established.

2.2.4.4 Advantages of V2G

The strengths of V2G are summarised as below:

- V2G is able to supply the power to resident houses as V2H as well as office buildings as V2B during the peak of demands without the limitation of power supply to grid.
- V2G provides voltage and frequency regulations in micro grids by using the storage capacity of EVs to cover the intermittency of renewable energy sources.
- Valley filling and peak shaving are two terminologies of using EVs to help balancing the load. By this way, operation cost can be reduced for utility companies as the efficiency of power grid is improved [71].
- V2G can provide backup energy for grid in the emergency cases such as power outages, or sudden change in demands.
- As power system is designed to be able to cope with the highest demand at any time, which means the generation capacity is supposed to be larger than the consumption. However, it is hard to predict the duration and occurrence of demand peaks in a day, which leaves energy "unused" during low demand periods [72] (see figure 5). Thus V2G enables the utilisation of energy overproduction at low demand period to charge the EVs. This would allow the utility company to earn more operating profit. [73].
- The price of electricity is high at peak hours, V2G allows to store cheap energy for using during high demand periods, which saves money for users.

2.2.4.5 Barriers to V2G

Although V2G can bring a lot of benefits to both the utility grid operator and users, challenges still exist with the limitation of current research and technology. Higher cost of EVs when compared to ICE vehicles, due to the battery installed, is slowing the uptake of EV technology. Additionally, the absence of V2G units that are compatible with common European EV connectors makes V2G hard to implement, as the UK energy distribution network was only designed for single direction communication. New standards and protocols therefore need to be implemented to lead to widespread adoption of V2G technology.

Battery degradation is another serious problem that may affect V2G implementation. The degradation of batteries broadly depends on the amount of energy charged and discharged in a cycle, cyclic frequency and discharge depth. Therefore, in general, continuously charging and discharging the EV battery leads to shorter battery life span. Furthermore, the recycling of old or completely utilised batteries may cause many environmental issues [74].

The reliability of V2G is dependent on the vehicle owner behaviour. Driving habits of the EVs owner have significant impact on V2G operation. Lack of vehicles connected into the system may cause serious issues if the energy demand is high, and when not enough EVs are connected to the power grid. The connection location and time are also very important from the efficiency perspective if vehicles are being used to provide grid reinforcement mitigation. Considering the difference between local demand and energy availability, if a high demand occurs at one side of the town while a group of EVs are connected at the other side, unexpected energy shortage may occur as well as transmission losses when transmitting the energy from the vehicles around the grid [75].

System constraints are also considerable as the use of EV's battery for V2G operation require both charging and discharging. It is important to make sure the EV has enough energy for the owner to use, thus defining an estimate time of use is fundamental to avoid flat battery after providing grid support.

2.3 Relative works

Mahmud [76] introduced a smart power conversion technology between smart grid and EVs based on a dynamic model. A mathematical model of a bi-directional converter was developed in this study to enable the highly efficient power conversion within a smart grid, and a distributed partial feedback linearising controller enables the communication between different EVs to manage active and reactive power in order to ensure a highly stable and efficient power system. A power control and monitoring system for EVs to couple with smart grid was designed in [77], with smart monitoring system in both charging and discharging mode, the results showed that the implementation of V2G can significantly enhance the grid stability and dynamic performance.

Other than smart energy management systems, V2G is also introduced to integrate with emergency inverter backups (IBKs) to manage end users demand in study [78], in this project, IBKs were reviewed as they are operated for both emergency energy backup and to reduce operating cost by its charging and discharging mode.

IBKs are designed to operate at peak time to prevent energy outages, the operator will shift the load to IBK inverters when domestic load exceeds the energy generation capacity. Then a smart controller was developed to link the EVs with IBKs. Following the V2G technology described before, the charging and discharging of EVs will reduce the system demand to force the load on the grid under the maximum capacity of supply. The results were validated under real time tests.

2.4 Conclusions

This chapter has presented various approaches to smart grids. Home automation and load remote management are designed to use household appliance more efficient, in order to reduce the energy consumption, hence lowering the cost on bill without significant impact on daily use. Using BESS in a domestic household to work with a renewable energy source has many advantages as described, and such a system is a path to obtain energy self-sufficiency. BESS can be used as a buffer to store excess renewable generation, or as an absorber to charge at low tariff period then discharge to support later use. This enables the household to use energy at relative lower cost and helps shaving the high demand of the grid. A control system needs to be developed to manage complex energy flow under different scenario with constraints of each component within the system applied. The V2G concept is also reported in this chapter, the basic principle and current state-of-the-art promoting the idea of integrating EVs into a domestic energy management system. Due to the large capacity of EV battery, it can theoretically bring considerable enhancement to the overall system performance. The next chapters will investigate domestic energy management systems based on existing literatures.

Chapter III.

Developing energy storage for Domestic Household with PV to Support the Grid

Based on the state of the art introduce in Chapter 2, in this chapter, load profile modelling is introduced as the basis of the research, besides, as described in Section 2.1.1, PV systems with up to 4kW capacity are most commonly installed in the UK household because of the limited house roof size. Therefore, a practical photovoltaic (PV) profile for a typical UK household with 4kW PV system is presented to couple with the load as the 4kW system can generate the maximum amount of energy.

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.

3.1 Introduction

Recently, grid connected domestic solar PV with BESS has been studied and the benefits evaluated in multiple papers [79] - [83]. Renewable energy generation and energy storage systems are introduced as two keys to the smart grid [79], 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 as has been previously discussed in Chapter 2. In other studies, an optimisation-based approach was used to evaluate the daily profits for a domestic PV system with a coupled battery storage system [80] [81]. The benefits gained from the PV-battery hybrid system under different electricity tariffs was analysed and presented for typical summer and winter days [82]. Reference [83] also extended the research in paper [82] by presenting the optimal battery sizes for use in PV-battery hybrid systems 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 battery control algorithm under real world tariffs, and the 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 minimum of a household payback period. Batteries of different sizes were then employed on the system with the developed control algorithm, and payback periods were calculated using average real-world costs quoted from battery companies. The results were compared with the results from the literature [81][82][83] for comparison.

The main objectives of this chapter are as follows:

- The domestic load profile was modelled on an hourly basis for a year using the Goldsim simulation tool based on a real-world dataset from the government energy survey.

- A 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 performance model together with the domestic load profile.
- Battery control logics and constraints were developed for energy storage system to increase the system revenue.
- Cost of the system and various tariffs were included in the model to investigate the system behavior under multiple setups. The payback periods were evaluated to determine the marginal and most suitable battery sizes

3.2 System modelling

3.2.1 Domestic load profiled modelling

Goldsim is a simulation tool which allows Monte Carlo analysis to be applied to models in order to evaluate uncertainties. The software is highly graphical and extensible, and by dragging and editing graphical objects, the models can be visually created and algorithms easily dispatched through linking equations with data blocks in an appropriate manner to automatically indicate their influences. It is easier to manipulate large amount of data and calculations than programming in other software.

Goldsim has a wide range of built-in elements for modelling, users can enter inputs to the model using input elements. There are three input elements that are commonly used in modelling as described below [84]:

- Data element enables users entering a specific scalar value or an array of related values. This is the basic element used for defining constants and system specifications in the system modelling, and the following functions such as equations will be performed on the input values.

- Time series element allows the user to specify a time series of a value. It defines the basic computational time step for a model.

- Stochastic element defines the uncertainty for a particular input.

Function elements provide a variety of algorithms for defined input to give out a required output. Sum function can easily manipulate the accumulating and subtracting operations between two or more inputs by selecting corresponding inputs in the function properties. AND, OR and NOT function can be added onto the inputs to form a logic diagram while expression functions can provide more complicated algorithms to defined inputs such as calculus.

Container elements produce a new path to enable the ability to build hierarchical models, they allow the programmes to run in parallel. Containers are used manage the algorithms constructed by input data and functions to form a subsystem, then a group of subsystems can be grouped up into a general system. Model users can change the variables of the system on the dashboard interface created specifically for the model. With buttons, gauges, sliders and display panels, model designers can easily make a tidy and user-friendly dashboard for their models.

In this research, real-world data is used in the Goldsim simulations, the data used can be found on the UK government website [85], 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 follows:

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

This real-world dataset is in the format of an Excel file, the accessible format can be requested on the UK government website. The dataset generally divides household energy consumption into a sum of seven main categories of appliances, and through monitoring of appliances in each category for months, the average hourly load profile for each of them is produced for both weekends and weekdays.

Cold appliances include a set of electric products that can provide lower temperature for domestic uses. Four main types of cold appliances were considered in the government survey, they are fridge-freezer, refrigerator, chest-freezer and upright freezer. Wet appliances include washing machine, dish washer and tumble dryer. Computer and printer are included in ICT appliances while TVs are categorised in another section. Kitchen and lighting appliances also play important roles in the formation of household electricity consumption curve. Energy consumed by heating appliances are mainly caused by space heating and water heating which are highly affected by outside temperature and seasons. The average hourly energy consumption (without seasonality correction) for each appliance within these seven categories are therefore integrated into the input elements of Goldsim, Figure 8 shows an example of Goldsim data elements that include average hourly energy consumption for each type of cold appliance.

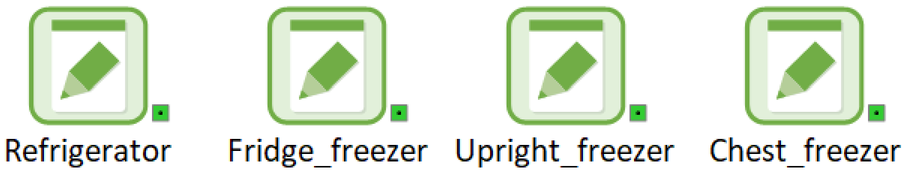


Figure 8. Goldsim data elements for cold appliances.

A bottom-up approach is used in this simulation method, Figure 9 shows the diagram of the design flow of the load profile generation model. According to the flow chart, the basic idea is to first identify the type of household to be modelled, after letting users select the household type, they also need to select which day is going to be simulated due to differences between a typical weekday energy consumption, and the weekend consumption. Week of the year is then requested due to seasonal use for all household appliances. Next, the type and number of household electric appliances owned is defined by the user to couple with the real-world hourly load profile, in order to calculate the total energy consumed by each category of appliance. Finally, the load curves for each category of appliance are summed up to produce the total household hourly load curve throughout the day.

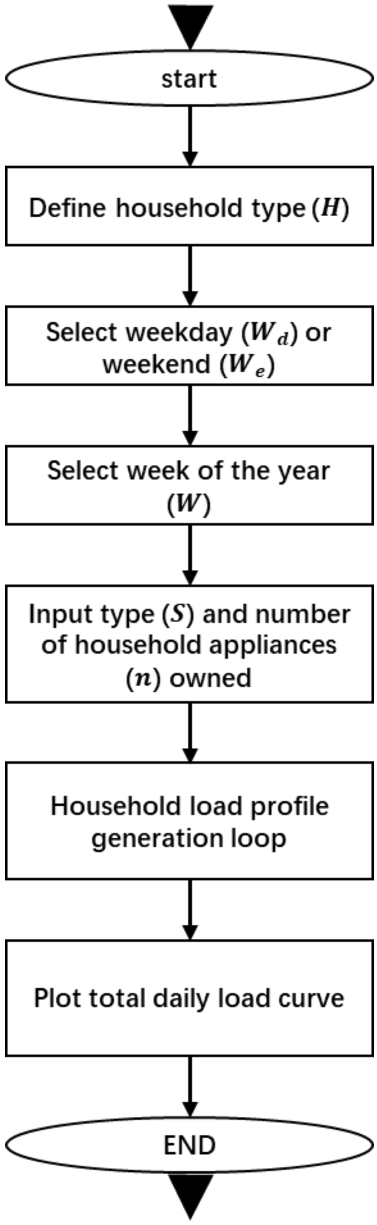


Figure 9. Bottom-up design flow for domestic load profile modelling

To implement the model and precisely simulate the hourly energy demand, a dashboard was created in Goldsim in Figure 10 to link with the embedded load profile generation model following the design flow described in Figure 9. It asks users 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 the outputs selection.

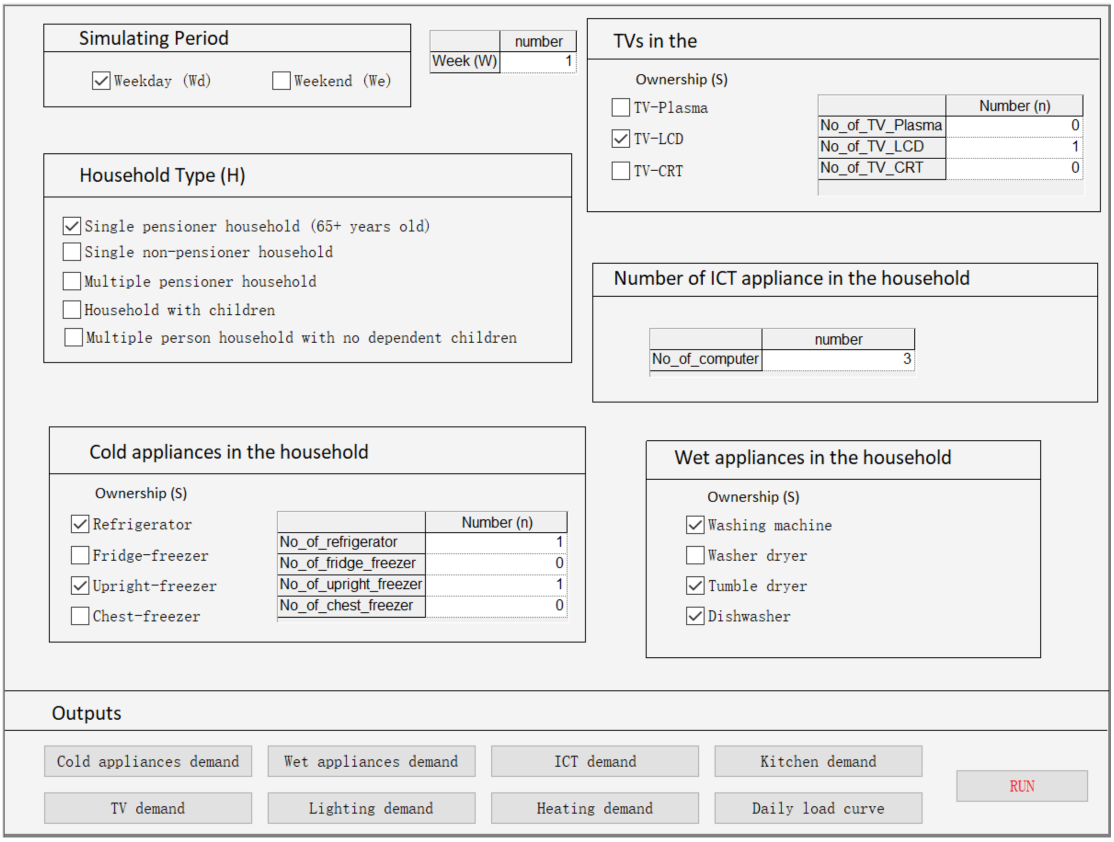


Figure 10. Screenshot of dashboard created in Goldsim for gathering basic households' appliances setup information from users

Each choice section in the dashboard links to a data element in the model, by ticking the boxes, the relevant data element will show a logic "1". Each number input section in the dashboard also links to the corresponding data element, but it will show the exact same number entered in the dashboard. Therefore, load profiles for TVs and ICT appliances can be derived according to Equation (3) and (4):

$$E_{TVs} = (S_{TV\_plasma} \times n_{TV\_plasma} \times E_{TV\_plasma} + S_{TV\_lcd} \times n_{TV\_lcd} \times E_{TV\_lcd} + S_{TV\_crt} \times n_{TV\_crt} \times E_{TV\_crt}) \quad (3)$$

$$E_{ICT} = n_{computer} \times E_{computer} \tag{4}$$

In Equation (3), E represents the load profile for appliance, S represents the ownership of the appliance, n represents the number of appliances owned.

According to the equations, load profiles for TVs and computers are not influenced by seasonality (Y), household type (H) or which day of the week (W_d, W_e) it is. While for cold appliances, the load profile is:

$$\begin{aligned} E_{cold\_appliance} = Y_{cold\_appliance}(W) \times (& S_{refrigerator} \times n_{refrigerator} \times E_{refrigerator} \\ & + S_{fridge\_freezer} \times n_{fridge\_freezer} \times E_{fridge\_freezer} \\ & + S_{upright\_freezer} \times n_{upright\_freezer} \times E_{upright\_freezer} \\ & + S_{chest\_freezer} \times n_{chest\_freezer} \times E_{chest\_freezer}) \end{aligned} \tag{5}$$

According to Equation (5), seasonality is a function of week of the year (W), week 1 is defined as the first week starting from January of each calendar year. Load profile for cold appliance is mainly affected by seasonality, type and number of appliances owned by the household. People put more items in the cold appliance to keep them fresh in summer rather than in winter, which results in relatively higher energy consumption in summer.

Besides the seasonality, day of the week has impact on energy usage for kitchen appliances. People normally wake up later on weekends comparing with weekdays, therefore, load profiles for kitchen appliances have different patterns:

$$\begin{aligned} E_{kitchen\_appliance} = Y_{kitchen\_appliance}(W) \times [& W_d \times (E_{oven}(W_d) + E_{microwave}(W_d) \\ & + E_{kettle}(W_d)) + W_e \times (E_{oven}(W_e) + E_{microwave}(W_e) + E_{kettle}(W_e))] \end{aligned} \tag{6}$$

In Equation (6), the load profile for each type of kitchen appliance is a function of day of the week, different usage patterns appear between weekdays and weekends. If weekday is chosen in the dashboard, W_d will have a logic “1”, as a result, weekday load profile for each kitchen appliance will be generated by the embedded load profile generation model.

Heating appliances include water heating appliances and space heating appliances, they are affected by seasonality as well as day of the week, as people use more energy for heating in winter, and especially on winter weekends when they don't work. Thus, load profile for heating is:

$$E_{heating\_appliance} = Y_{heating\_appliance}(W) \times [\, W_d \times (\, E_{water\_heating}(W_d) + E_{space\_heating}(W_d)) + W_e \times (\, E_{water\_heating}(W_e) + E_{space\_heating}(W_e))] \quad (7)$$

Household type (H) has impact on the energy consumption of wet appliances and lighting appliances lighting appliances. For instance, single pensioner households normally stay at home throughout the entire week as they don't work, so they use longer time of lighting comparing with single non-pensioner households, multiple person households have more people live together, so they may use washing machines more often than single person households. Therefore, load profiles for wet appliances and lighting appliances are:

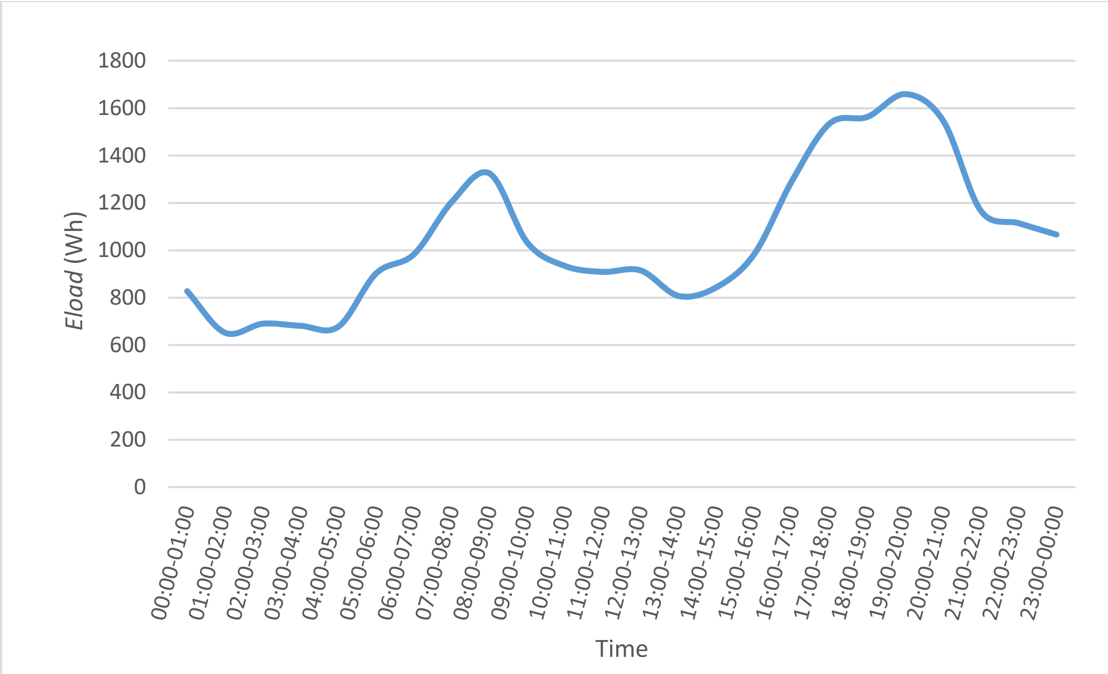
$$E_{wet\_appliance} = Y_{wet\_appliance}(W) \times H \times [\, E_{washing\_machine}(H) \times S_{washing\_machine} + E_{tumble\_dryer}(H) \times S_{tumble\_dryer} + E_{dishwasher}(H) \times S_{dishwasher} + E_{washer\_dryer}(H) \times S_{washer\_dryer}\,] \quad (8)$$

$$E_{lighting\_appliance} = Y_{lighting\_appliance}(\,W) \times H \times [\,W_d \times E_{lighting}(W_d, H)$$
$$+ W_e \times E_{lighting}(W_e, H)\,] \quad (9)$$

Then the household load profile is derived by adding every appliance owned by the household,

$$E_{load} = E_{TV} + E_{computer} + E_{cold\_appliance} + E_{kitchen\_appliance} + E_{heating\_appliance}$$
$$+ E_{wet\_appliance} + E_{lighting\_appliance} \quad (10)$$

Figure 11 shows the generated load profile of a single non-pensioner household from load profile generation modelling. According to domestic appliances, cooking & cooling equipment report published by Department of Energy and Climate Change [86], there are 97% households own a washing machine, over half of households (in fact 62%) own a tumble dryer and 41% of households own a dishwasher. In this study, washing machine, clothes dryer and dishwasher are selected in the wet appliances section. Since the report indicates that almost every household has a TV, and around 3 ICT appliances own by single non-pensioner household, thus corresponding input were added in the model. Moreover, there are 99% of households own a refrigerator and most of them also have a freezer, typically an upright freezer, Hence the electricity consumed by 1 refrigerator and 1 upright freezer were added into the profile. Ovens and hobs are essential kitchen appliance for all households alongside with kettle and microwave, meanwhile lighting and heavy loads such as water and space heating were also considered.



1800
1600
1400
1200
1000
800
600
400
200
0
Eload (Wh)
00:00-01:00
01:00-02:00
02:00-03:00
03:00-04:00
04:00-05:00
05:00-06:00
06:00-07:00
07:00-08:00
08:00-09:00
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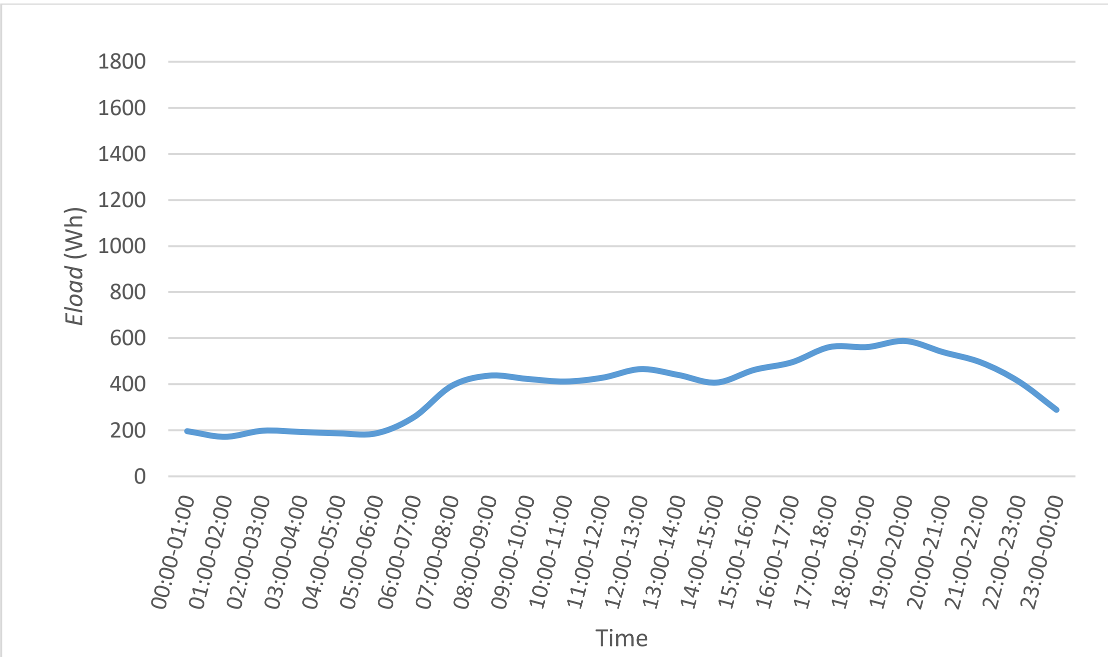
Time

(a)



1800
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Eload (Wh)
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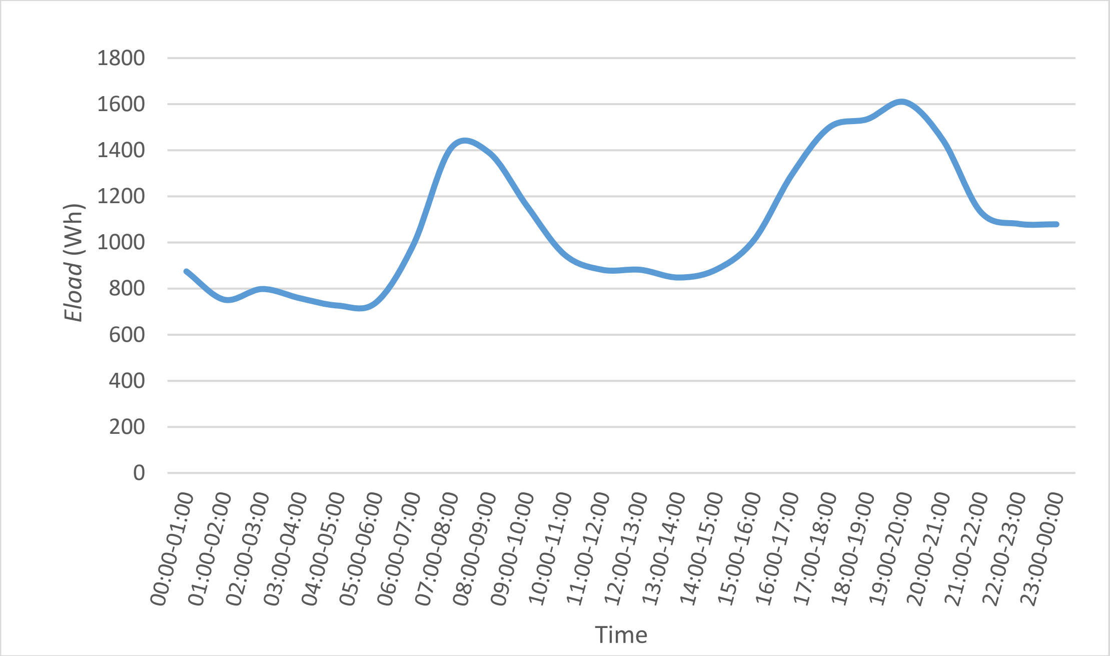
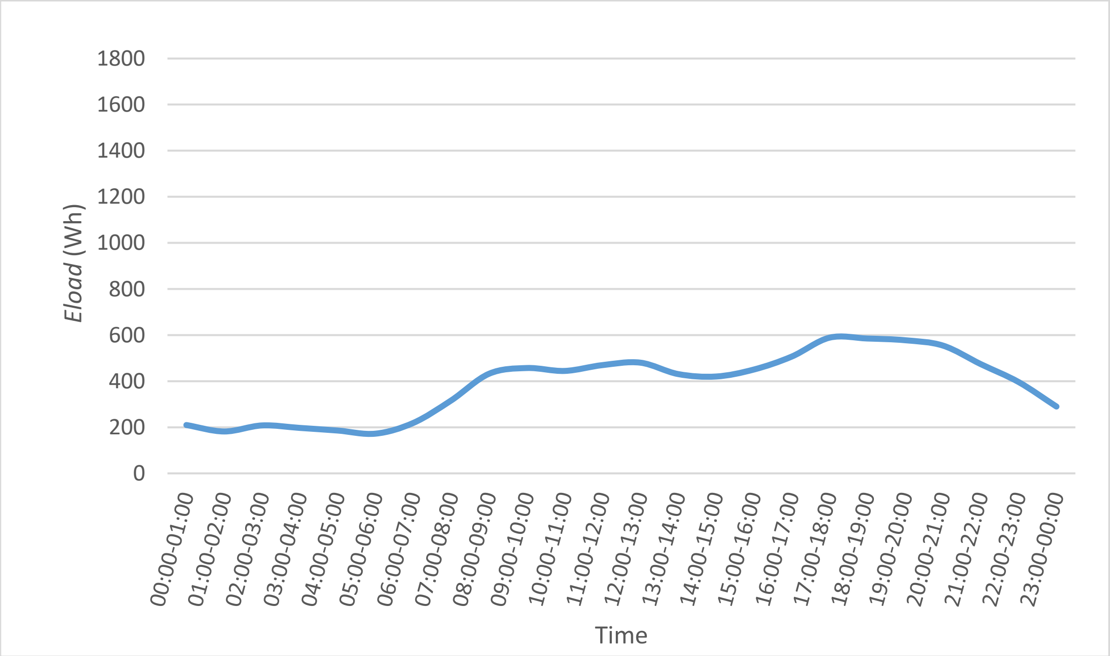
(b)



(c)

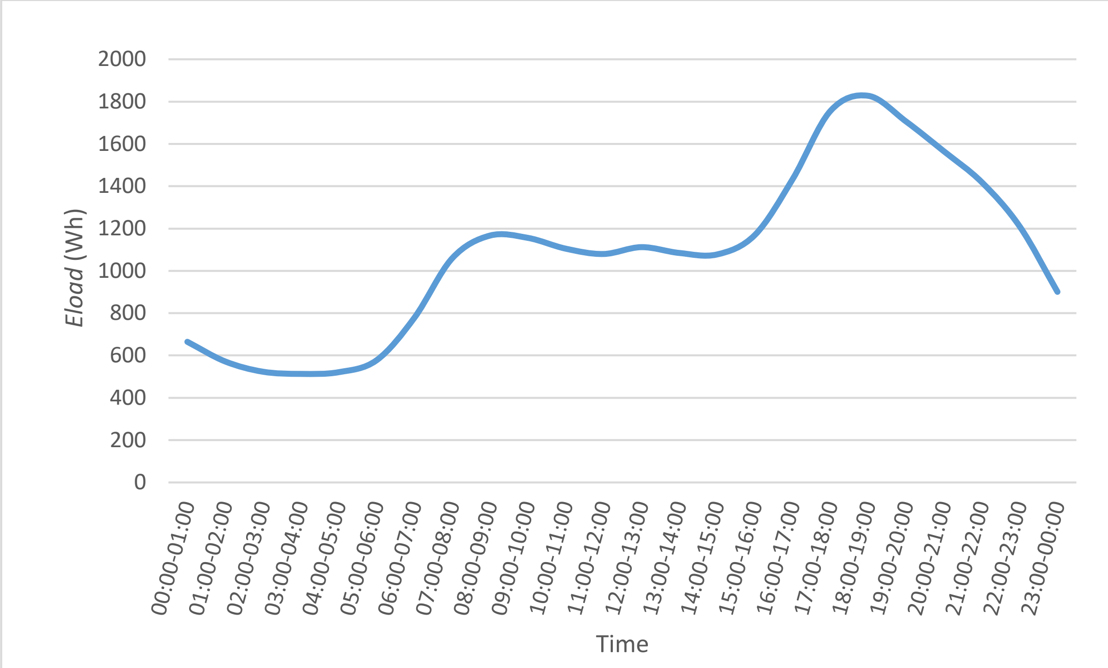


(d)

Figure 11. Average hourly load profile for a single non-pensioner household, on (a) weekday in winter (week 1); (b) weekday in summer (week 26); (c) weekend in winter (week 1); (d) weekend in summer (week 26)

Seasonal effects have also been considered for all appliances. Figure 11 (a) shows the typical weekday energy demand in winter, compared to Figure 11 (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 a higher demand for heating. Total energy consumed in winter weekday is 25.3 kWh while 9.1 kWh is used daily in the summer. The two diagrams at bottom Figure 11 (c) and (d) show the typical weekend energy demand in both winter and summer, they show the similar usage pattern as that of a weekday, but the total energy consumption increased as the household does not contain anyone who commutes to work leaving the house empty during the weekend. The total daily electricity consumed in winter weekend is about 25.7 kWh and 9.2 kWh of electricity is consumed in summer. The simulated domestic load profiles were validated with real world measured data to evaluate their reliability

Figure 12 is a set of measured energy consumption curves for a typical household on an hourly basis for both weekend and weekday in different seasons. Such load profiles can be found on the website of ELEXON [87]. The load profiles are the average across random households. From the diagrams, they show the same trend as the simulated results, in which the energy consumption in winter is much higher than that in summer, meanwhile, energy consumed on weekend in both seasons are observed higher than that on weekday. According to this observation, the monitored household type is most likely a working family, people who have a job need to go to work during daytime on weekdays while they are likely to spend more time stay with family at home on weekend. 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.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0
Eload (Wh)
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03:00-04:00
04:00-05:00
05:00-06:00
06:00-07:00
07:00-08:00
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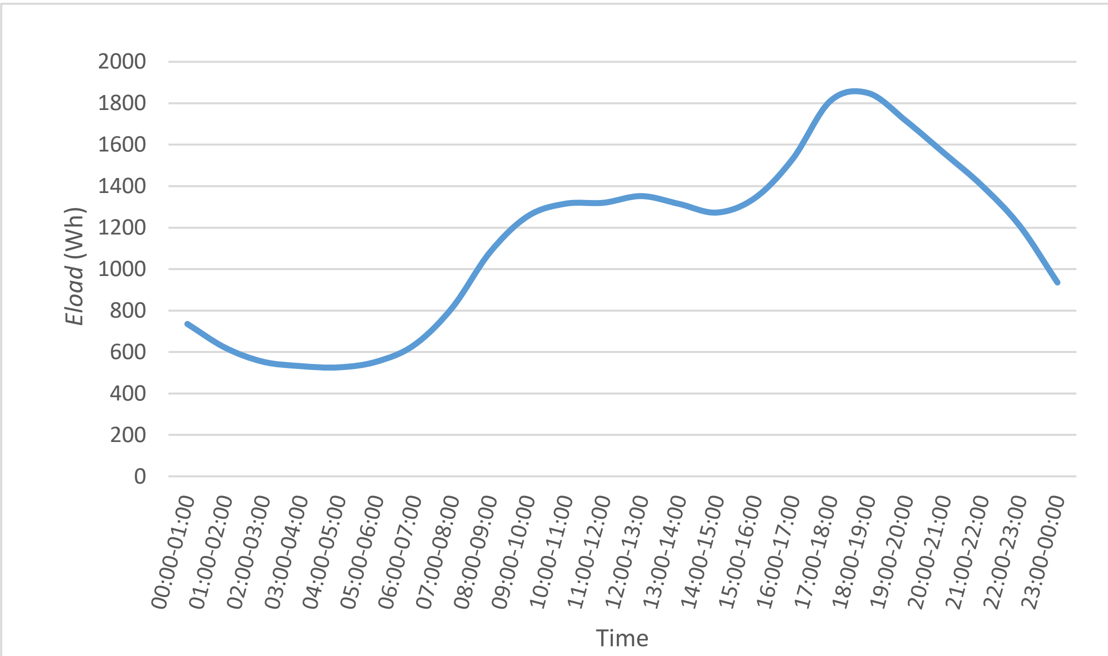
21:00-22:00
22:00-23:00
23:00-00:00
Time

(a)


2000
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0
Eload (Wh)
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03:00-04:00
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05:00-06:00
06:00-07:00
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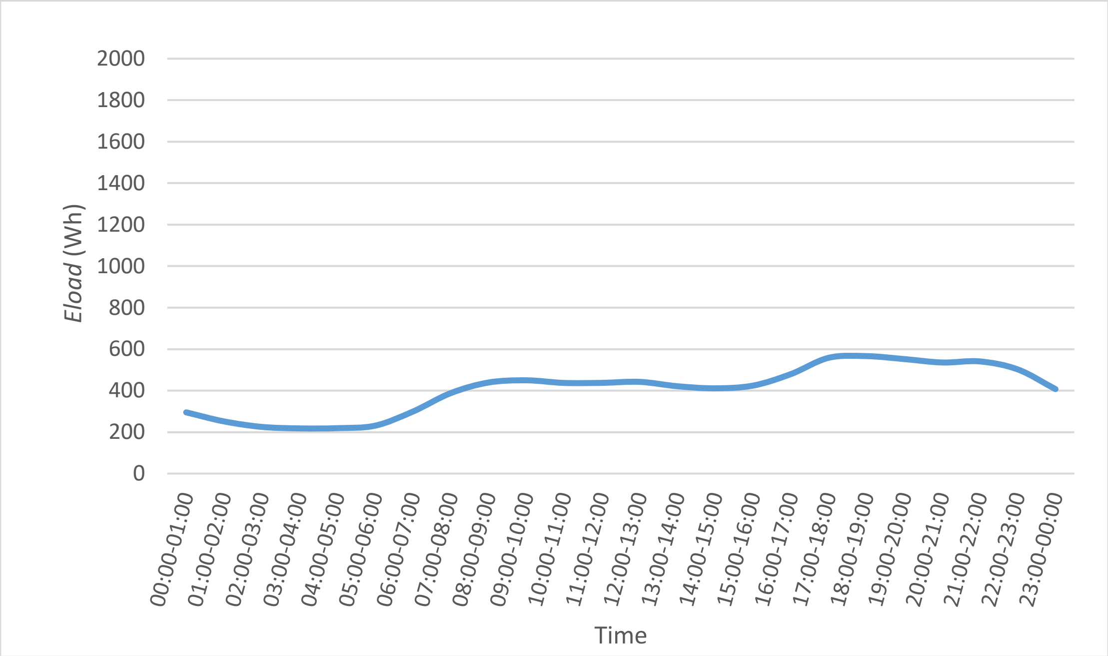
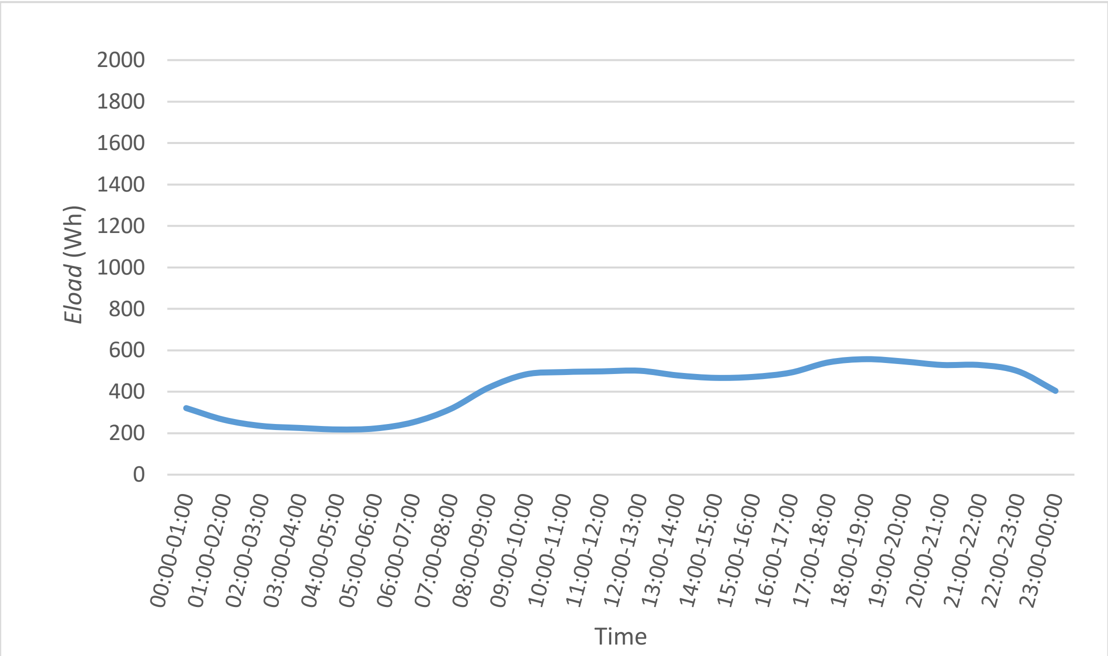
Time

(b)



(c)



(d)

Figure 12. Measured hourly load profile on (a) weekday in winter; (b) weekday in summer; (c) weekend in winter; (d) weekend in summer

Comparing the simulation results with the measured data, the trends of the load profile curves are very similar, both simulated and measured energy usage in winter is dramatically higher than that in summer for weekday and weekend. The difference between the total energy consumption (e.g., 25.3 kWh vs 25.9 kWh in winter weekday) is a result of several factors, such as number of family members, number of household appliances, type of heating installed, etc. As the model generate unique energy usage profile for different families according to their input, such variation is acceptable.

3.2.2 Hourly PV profile simulation

The previous section described the generation of the hourly load profiles for a house. However, in order to integrate the load with a domestic renewable energy system, an hourly PV generation profile needs to be obtained to compare with the load curve, and hence find the most suitable battery size.

To precisely integrate the renewable energy generation with domestic electricity consumption, it requires a dataset which tracks the PV generation every hour with weather effects such as solar irradiation and cloud coverage considered. To this end, a tool called System Advisor Model (SAM) is used for PV profile generation. This is a free software created by the National Renewable Energy Laboratory (NREL) in U.S [88], 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 a selected size of PV system, at a targeted location.

Figure 13 shows the user interface for solar resources in SAM, users can select the closest meteorological station from the built-in library. In this study, weather and solar resources used are from the Finningley weather station, which is reasonably close to Sheffield. A 4kW PV system is considered for the model development, as data is available from a practical 4kW PV installation for model verification.

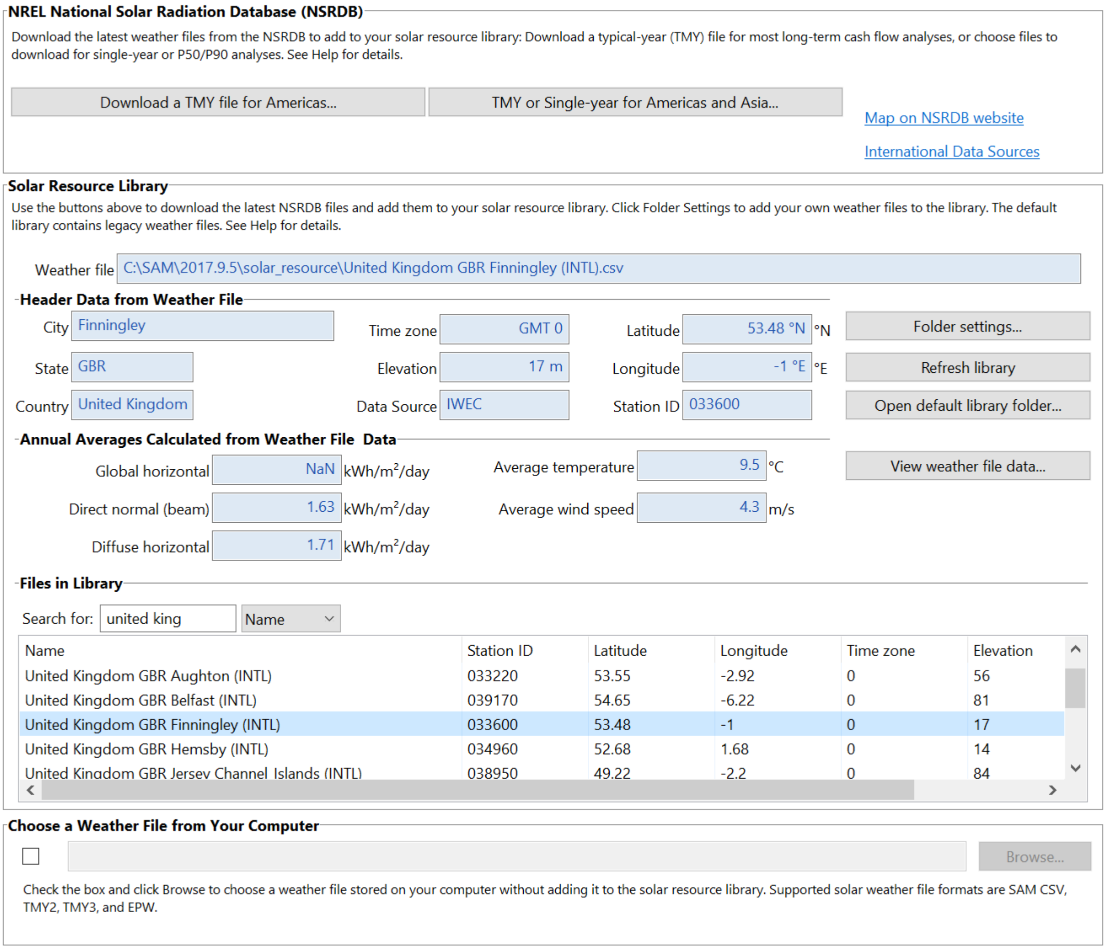


Figure 13. Solar and weather configuration in SAM.

Figure 14 shows the user interface in SAM for solar panel module configuration, in this interface, corresponding PV module can be selected from the built-in library. Yingli Solar panel with a nominal efficiency of 14.4% of the total incident sunlight power is selected in this study for model validation.

Hence, the configuration of PV system model as shown in Figure 15 is set to have a nameplate size of 4kWdc and an inverter with a typical DC/AC ratio of 1.2. The nameplate DC power of the system shows the PV array is rated to have the capacity to produce 4kW of power at standard testing conditions (STC) [89], which solar panels are tested at 25℃ of solar cell temperature and under 1000 watts per square meter of solar irradiance. The inverter is used to convert the electricity produced by the PV array from DC to AC for household appliances to use. In real-world situation, it is common practice and often economically advantageous to size the inverter to be less than the PV array, as the PV array rarely produces power to its STC capacity, thus a typical DC/AC ratio of inverter 1.2 is set in SAM. If this ratio is set too high, clipping losses will increase as the PV array produces more power than the inverter can handle. The efficiency of the inverter is 96% as it is the most commercially available [90].

Figure 14. Solar panel module configuration in SAM.

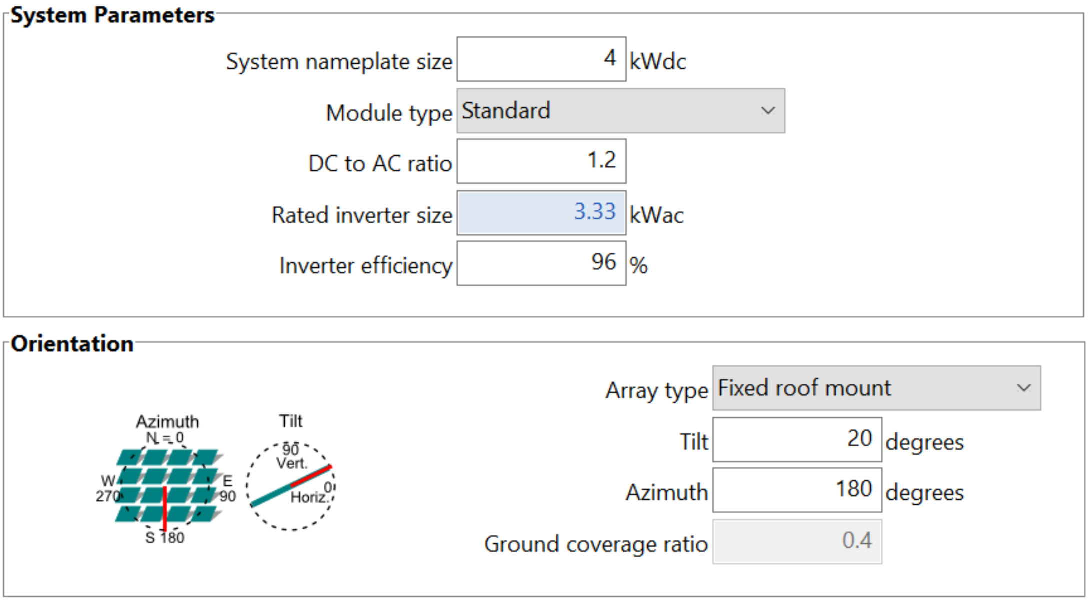
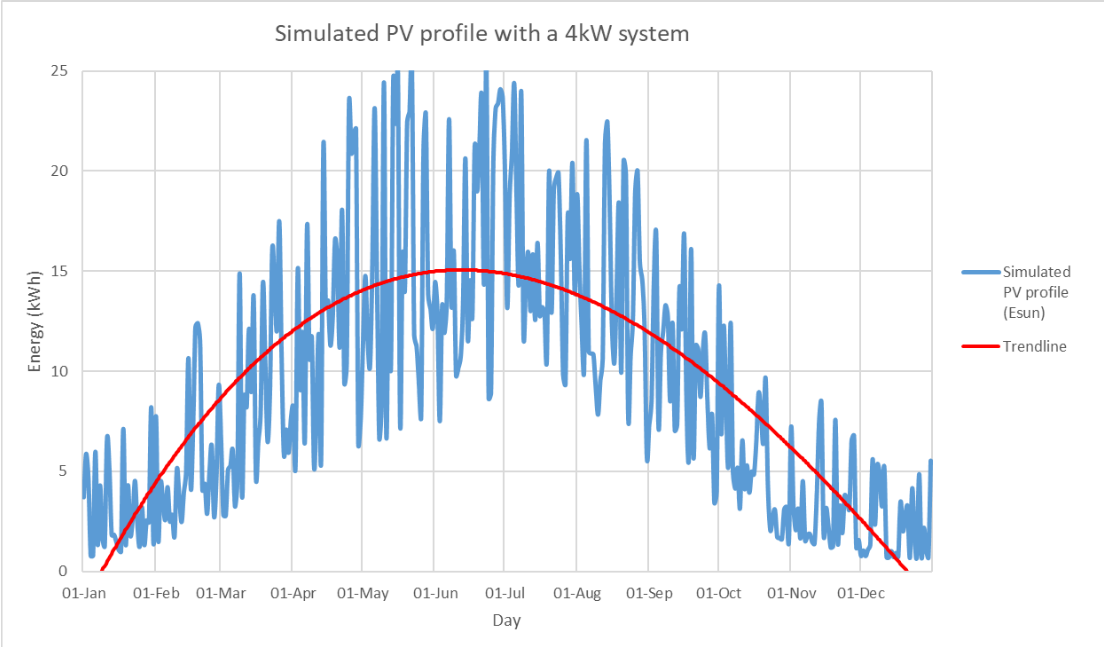


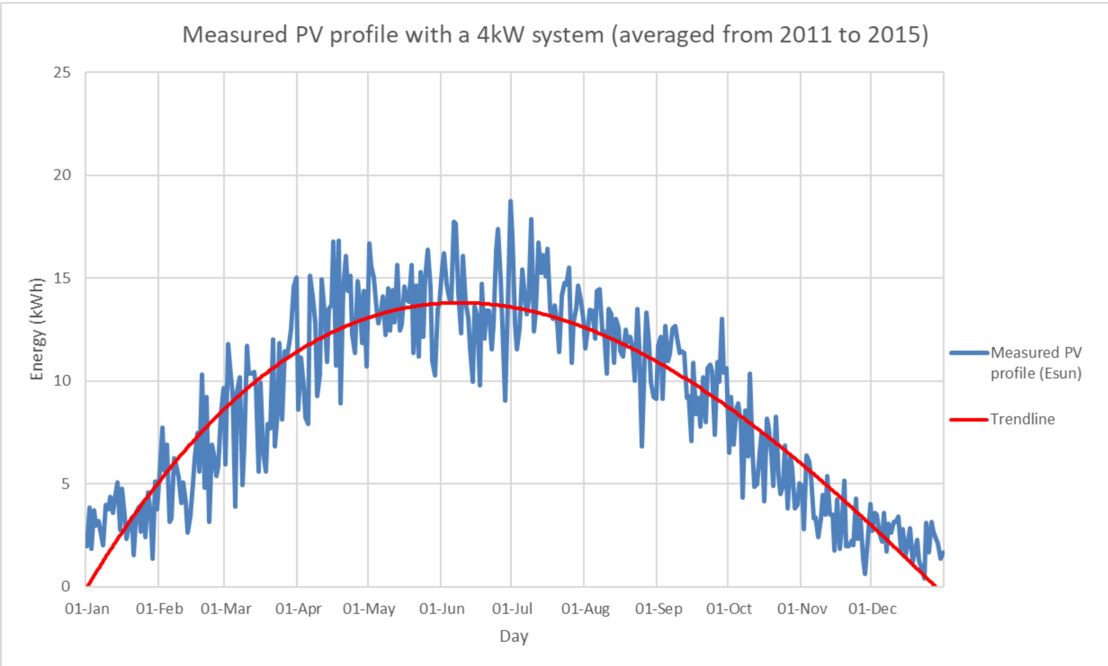
Figure 15. PV system model configuration in SAM.

After constructing the corresponding PV system model, SAM is running to simulate the PV profile E_{sun}, this data is in hourly basis, but can be cumulated to produce in a daily format. Figure 16(a) shows the simulated daily PV profile, the result is produced by running the PV system model described above. It is then used to compare with the measured daily PV generation shown in Figure 16(b) to validate the PV model. The practically measured data is recorded from my supervisor's house for a period of 2011 to 2015, and the data is in daily basis. In order to prevent error figures produced by the data logger and minimise the weather uncertainty, averaged data is used for model validation.

Taking a look at the simulated PV profile, the trend of solar power daily generation increases to the peak as the date increases from early January to mid-June, then the trend decreases for the rest of the year. Due to the longer daytime in the middle of the year, the average daily generation reaches the maximum per day in summer. The simulated PV profile has similar trend comparing with measured profile and with the help of plotting trendline, both peaks appear at mid-June and the value of the averaged peak daily PV generation is saturated at 15kWh for simulated data while slightly lower in practice.



(a)



(b)

Figure 16. (a) Simulated and (b) Measured daily PV profile with 4kW system

This slight difference in figure is mainly because the model uses the weather information from Finningley station, which is located in Doncaster, although it is very close to Sheffield, the geographical difference may result in different cloud cover, different landscapes also have impact on PV generation. Therefore, to mitigate the errors caused by weather and specifically prove the model is reliable in hourly basis, Figure 17 shows six sunny summer days simulated from 26th June to 1st July by using PV system model in SAM. Blue line represents the measured PV profile extracted from a data log in 2018. From the figure, it is obvious that the simulated curve almost matches with the practical curve, with the peak PV production over 2.5 kWh per hour in the mid-day of a typical summer day. The total amount of electricity generated in these six days in practice is 131.0 kWh while the model generates 134.7 kWh of electricity. The error is derived of 2.8%. Meanwhile the total amount of electricity produced by model during the period between 27th March to 31st December is 2940.0 kWh which has 4% average error than the measured 2826.1 kWh. Hence, the generated dataset is validated and can be utilized in the following research.

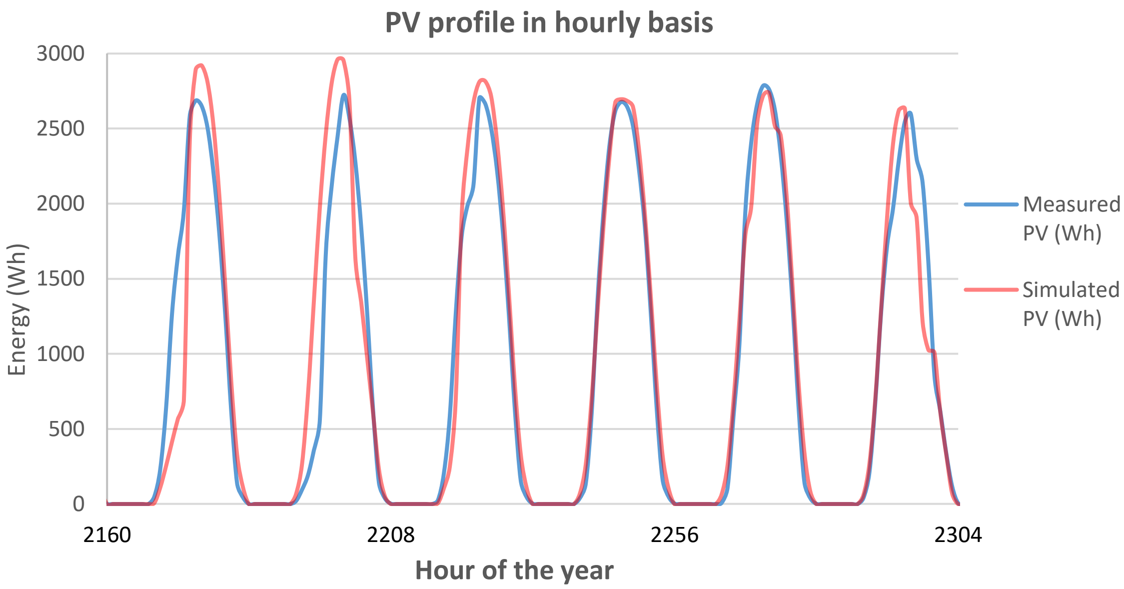


Figure 17. Simulated hourly PV profile vs measured profile for a period of 6 days in typical sunny summer days.

Table 1 lists the typical costs of different sized PV systems currently on the market in 2018 [91], the prices include installation and the supporting hardware, these prices are used for the following study and payback calculation.

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

Table 1. Costs of PV system for range of sizes

3.3 Domestic Energy Storage System and Control Algorithm

The basic concept of a grid connected PV-battery hybrid system is shown in Figure 18. An AC bus is set as the interface between the load and the different energy sources. The grid provides AC input E_{grid} to the AC bus, while solar panel produces DC power E_{sun} alongside the BESS discharge $E_{discharge}$ and EV discharge $E_{EVdischarge}$, DC-AC inverters are needed for all three energy sources to transform the DC power into an AC supply E_{load} for the domestic load. A building energy management system (BEMS) is a device following the BESS control logic, to control the charging and discharging process for the BESS in combination with the solar PV system, to maximise the annual system revenue and reduce the payback period for the installation. The energy E_{charge} used to charge the BESS is either from part of E_{grid} or absorbing from excess production of PV system. Energy flows from the AC bus to the EV charger is defined as $E_{EVcharge}$, and energy export to the grid is defined as E_{export}.

In this section, BESS control logic and BEMS control strategy are introduced and developed to manage BESS operation, the opportunity of energy self-sufficiency by storing the PV overproduction in the BESS for night and peak time usage has been evaluated to reduce high electricity bills when variable tariffs are implemented.

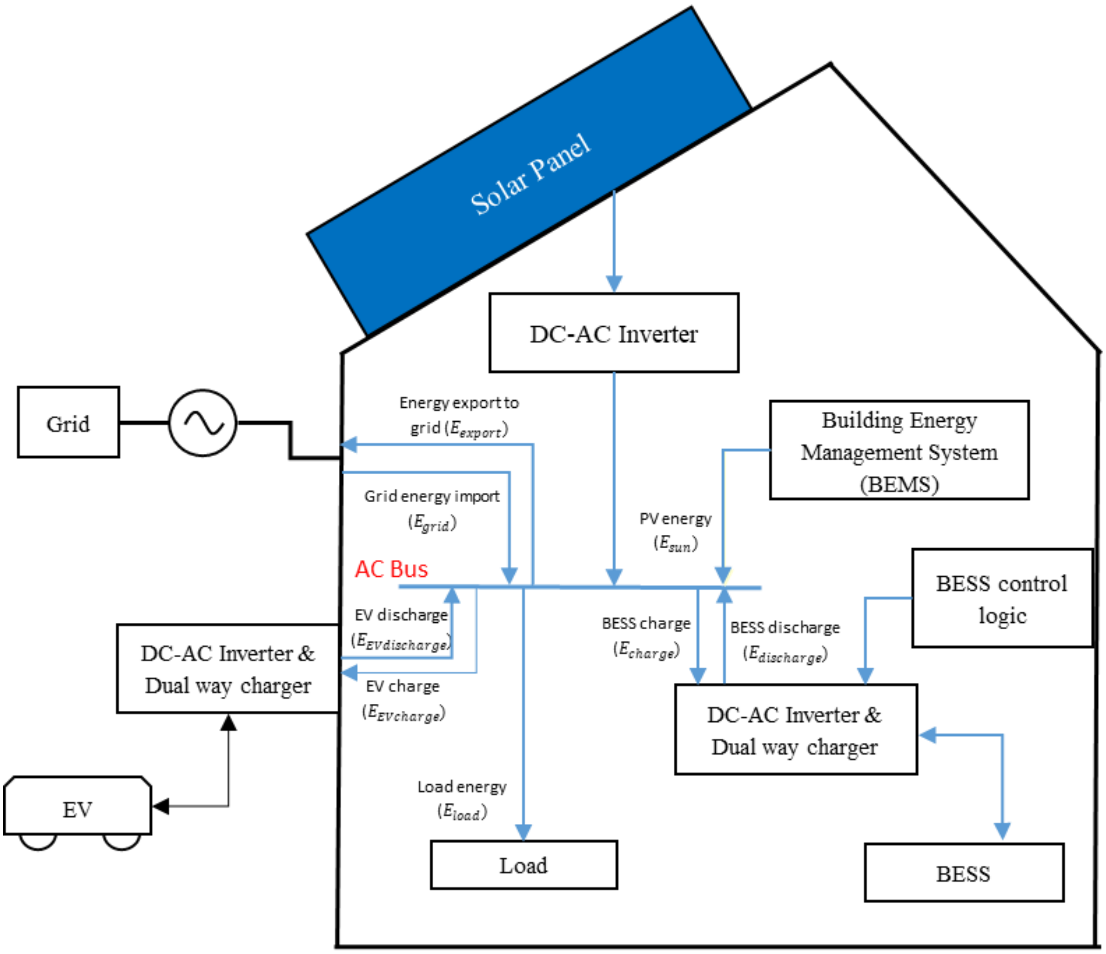


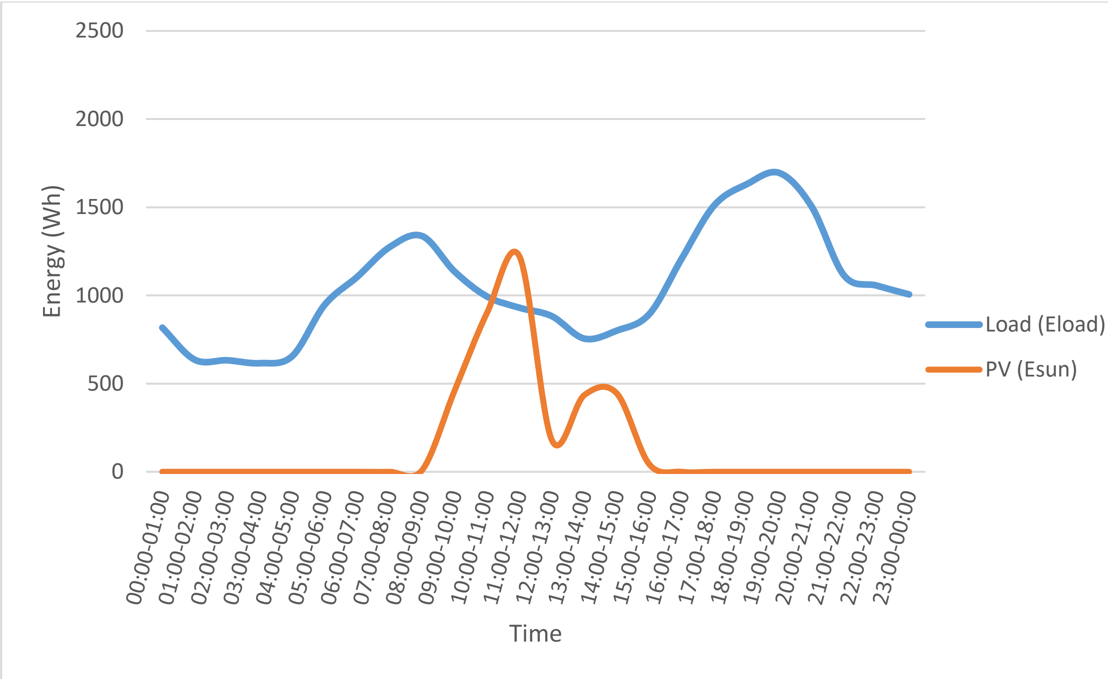
Figure 18. Basic concept of grid connected-battery hybrid system

3.3.1 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 the household first, then compare this 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, any excess energy generated by the PV, over and above the house load, 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 utilise PV energy to supply part of the load, then deliver the remaining energy through discharging the battery to try to meet the total load. If the load is too high and cannot be met by this approach, the controller will import electricity from the grid to fully cover the household consumption as a last resort. Studies have shown that the UK economy 7 and 10 tariffs are benefiting those households with storage heating by setting two-tier tariffs [92]. In this research, the default Economy 7 hours ran 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 [93]. Thus, in this study, the performance model also seeks to make better use of the cheap tariff electricity during the night to store energy in the battery if required, to be deployed in the daytime peak hours, when the electricity price is higher.

3.3.2 Battery sizing

After modelling the domestic load profiles and PV profiles, it is necessary to combine them together to see the overall energy usage pattern. Figure 19 shows the energy consumption in a single pensioner household, against the modelled output of a 4 kW PV installation as an example, for a typical day in the four seasons. This system with only PV installed is set as the benchmark performance for later comparison. By the definition of four seasons in the northern hemisphere [94], week 10 is where spring begins until week 22, then week 23-week 35 is defined as summer in week calendar of the year, week 36-week 48 is the fall and week 49-week 9 of the next year is the winter. The blue curve shows the hourly simulated PV profile (E_{sun}), and the orange curve represents the domestic load profile (E_{load}). The PV energy generation appears as the lowest in winter, this is due to shortest daytime. The average daily generation from the simulated dataset in winter is around 3kWh as shown in Figure 19(a), while during summer period, as shown in Figure 19(c), the average daily renewable energy generation is over 13kWh, and can cover the daily domestic electricity consumption. Figure 19(b) and (d) show the load profiles in spring and autumn respectively.


2500
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Energy (Wh)
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02:00-03:00
03:00-04:00
04:00-05:00
05:00-06:00
06:00-07:00
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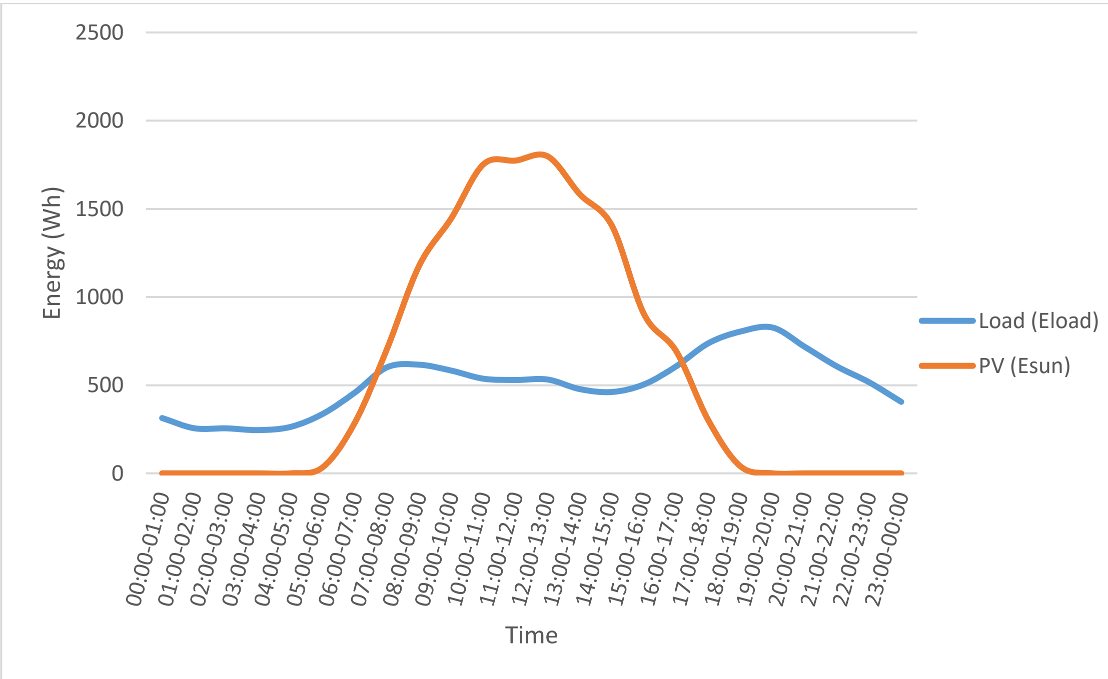
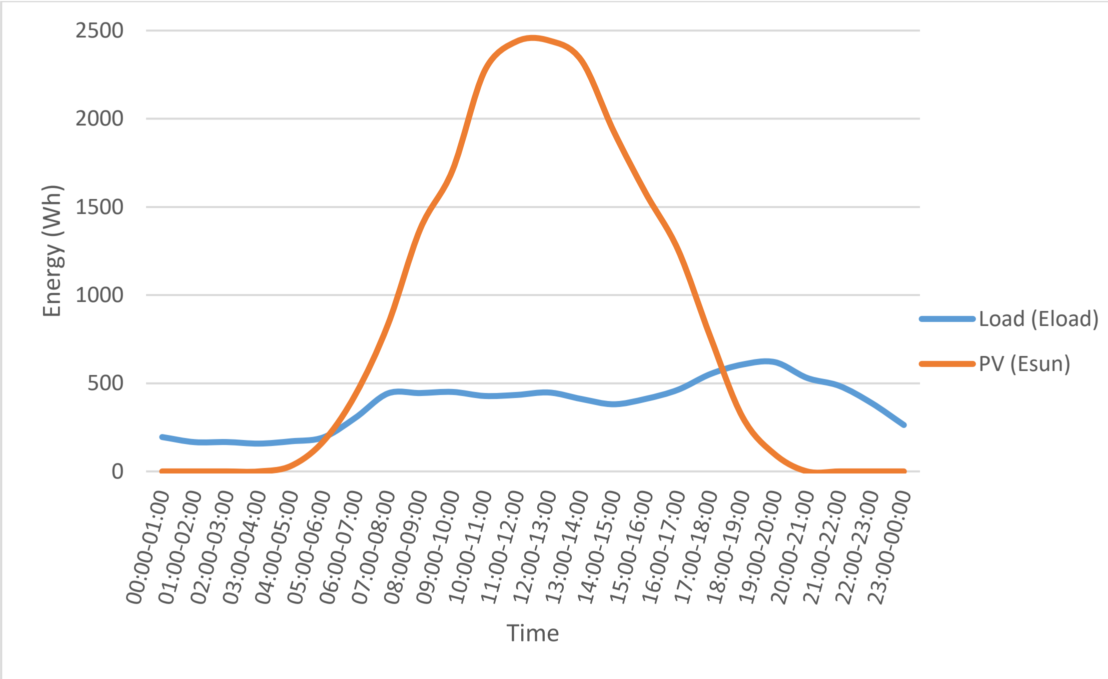
18:00-19:00
19:00-20:00
20:00-21:00
21:00-22:00
22:00-23:00
23:00-00:00
Time
Load (Eload)
PV (Esun)

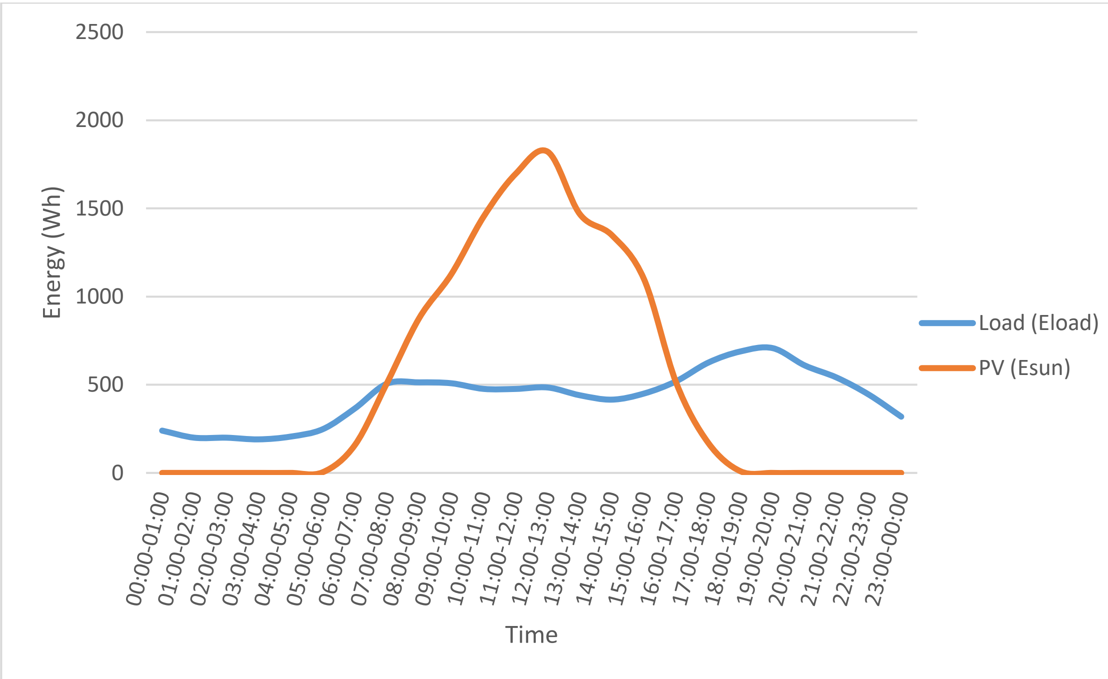
(a)


2500
2000
1500
1000
500
0
Energy (Wh)
00:00-01:00
01:00-02:00
02:00-03:00
03:00-04:00
04:00-05:00
05:00-06:00
06:00-07:00
07:00-08:00
08:00-09:00
09:00-10:00
10:00-11:00
11:00-12:00
12:00-13:00
13:00-14:00
14:00-15:00
15:00-16:00
16:00-17:00
17:00-18:00
18:00-19:00
19:00-20:00
20:00-21:00
21:00-22:00
22:00-23:00
23:00-00:00
Time
Load (Eload)
PV (Esun)

(b)



(c)



(d)

Figure 19. Domestic hourly load profile and PV profile of a typical day in (a) winter; (b) spring; (c) summer and (d) autumn

The main aim of the use of battery bank is to help reducing customers' expenditure on electricity and support grid when it has high demand during peak times. Thus, it is very important to find the correct size of battery that can store the PV overproduction especially in sunny summer day. From the simulated load and PV profiles for 5 types of households, the maximum PV overproduction per day appears at week 25 as shown in Table 2, it is calculated by subtracting daily load demand from the daily PV generation, which 25.4kWh of PV energy is generated results in around 16kWh of energy left unused for each type of household. In this case, batteries with less than 16kWh capacity are unable to absorb the total amount of the excess energy whilst sizes larger than 17kWh have limited utilisation. Meanwhile the maximum average daily PV energy generation within a week appears for a 4kW system at week 26, from which the amount is 20.5kWh as blue curve represented in Figure 20.

Household type	Maximum PV overproduction(kWh)
Single pensioner household	16.398
Single non-pensioner household	16.148
Multiple pensioner household	16.683
Household with children	16.090
Multiple person household with no dependent children	15.729

Table 2. Maximum excess energy generated in summer for each type of household

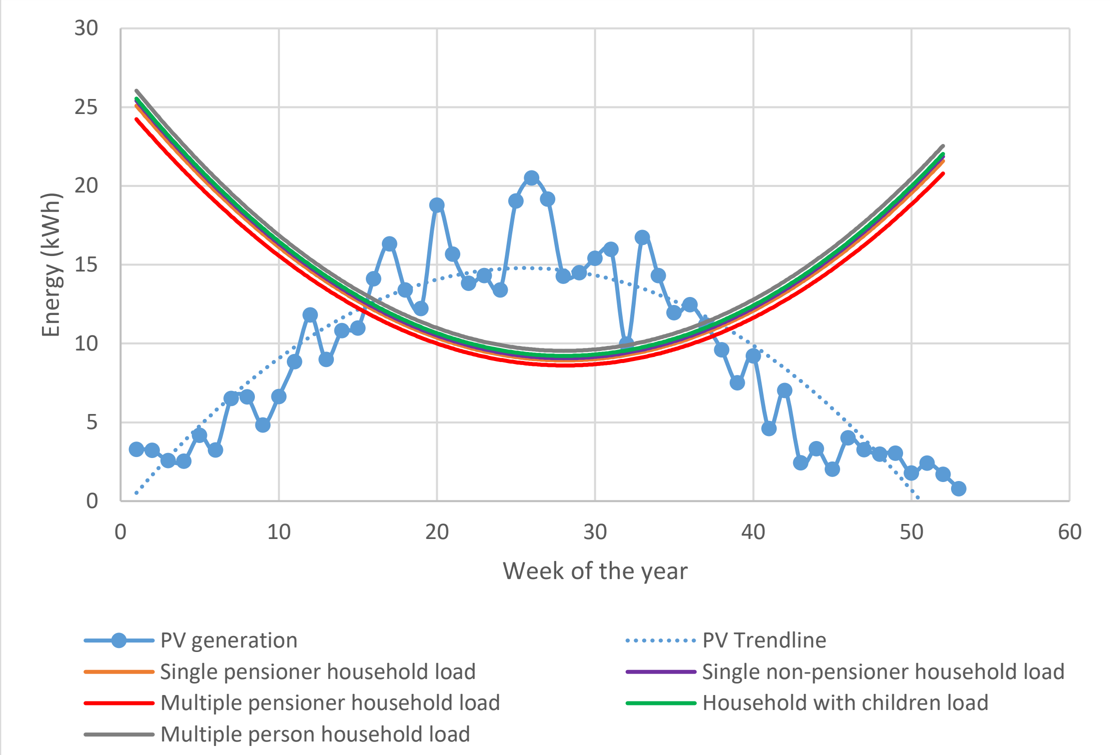


Figure 20. Simulated average weekly PV profile for a 4kW PV system over a year with trendline plotted and simulated weekly load profile by different types of households throughout a year

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 3. The communication functions are required as the batteries must feed their status such as SOC back to BEMS, in order to generated certain control logic for charging and discharging operation. The battery specification from the supplier [95] mentioned the lifetime is 6000 cycles for 90% depth of discharge which means the capacity will lose 20% after 6000 charge/discharge cycles with each cycle distribute 90% of the full capacity. If the battery is set to make a full cycle operation every day, it will last 15 years at 365 cycles per year, as against the manufacture guarantee, hence, the battery degradation cost can be calculated using the following equation [96]:

$$P_{degradation} = \frac{(P_{battery} + P_{install})}{(N_{cycle} \times E_{battery} \times DoD)} \tag{11}$$

Where $P_{degradation}$ is the degradation cost, $P_{battery}$ is the battery replacement cost,

$P_{install}$ is the installation labor cost, the installation cost of battery is required for an electrician to replace the battery is about £80 according to the average quotation from local area [97] [98] [99]. N_{cycle} is the life cycles of the battery, 6000 cycles is defined in this study. $E_{battery}$ is the battery capacity in kWh and DoD is the depth of discharge. Table 3 shows the list of degradation cost for each size of battery in £/kWh calculated from Equation (11). It appears that the battery degradation cost is very low compare with the capital investment. 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 for the high-power appliances. Since the system is designed for energy independence and not power independence, which requires a much larger inverter for the battery pack at a significantly higher cost, the integration of battery with PV and load is economic.

Battery capacity (kWh)	Price	Degradation cost (£/kWh)
1	£290.16	0.0685
2	£580.32	0.0611
3	£870.49	0.0587
4	£1160.65	0.0574
5	£1392.63	0.0545
6	£1671.30	0.0541
7	£1949.98	0.0537
8	£2228.66	0.0534
9	£2507.34	0.0532
10	£2785.25	0.0531
11	£2968.23	0.0513
12	£3238.49	0.0512
13	£3507.98	0.0511
14	£3778.24	0.0510
15	£4047.73	0.0510
16	£4317.98	0.0509
17	£4439.71	0.0492
18	£4700.78	0.0492
19	£4961.85	0.0491
20	£5222.92	0.0491

Table 3. Battery prices and degradation costs for the range of capacities

3.3.3 System operating sequence

In this section, a simulation is performed based on previous works, an advanced building energy management system which manages the PV and BESS operation to the domestic load is developed and simulated. The advanced BEMS is configured to run in the following sequence.

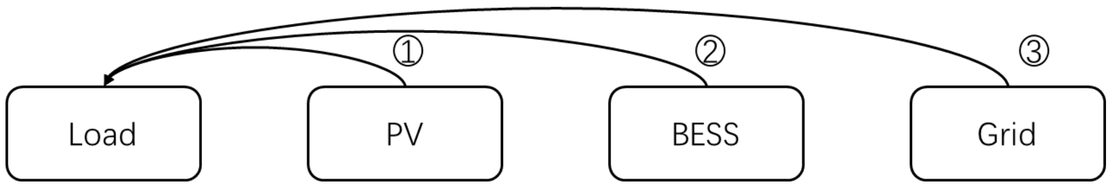


Figure 21. Advanced BEMS dispatching mode

Figure 21 illustrates the proposed energy dispatching mode for the advanced BEMS from domestic load point of view, the number in the circle on the side of each black line shows the corresponding priority in a numerical sequence. As described earlier, 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. Ideally, the load requirements should be met in this way. However, if the battery is not allowed to dispatch or it has already reached the minimum state of charge (SOC), energy is imported from the grid. The state of charge (SOC) is a percentage measurement of the amount of energy in a battery at a certain time relative to its capacity. It can be calculated by:

$$SOC = \frac{E_{remain}}{E_{battery}} \times 100\% \quad (12)$$

Where E_{remain} is the remaining capacity of the battery and $E_{battery}$ is the total capacity. A typical Li-ion discharge voltage curve is shown below in Figure 22, from the diagram, it shows a rapid fall of voltage at the end of the discharge cycle while it remains flat throughout much of the cell's discharge range. As the battery chosen in this study has rated cycle life of 6000 cycles at 90% DoD, and a minimum SOC is set at 10%, the discharging voltage is assumed constant in later sections.

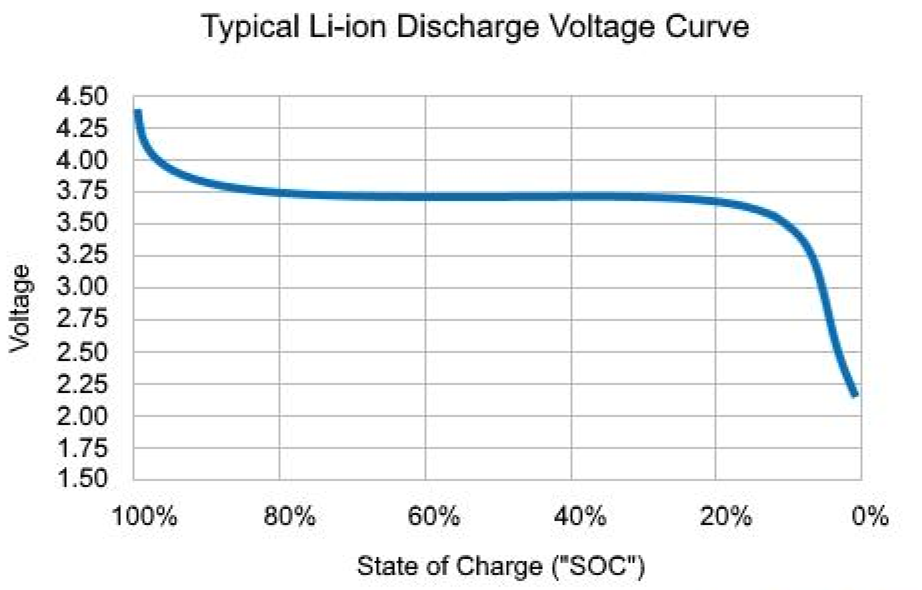


Figure 22. Li-ion discharge characteristic curve [100].

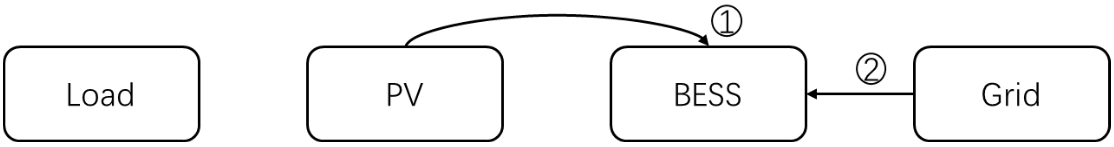


Figure 23. Advanced BEMS charging mode

While in energy charging mode as shown in Figure 23, which typically happens when PV production exceeds the load usage, the excess energy will be dumped into the battery until it is fully charged. Alternatively, if the BESS is controlled to charge to a certain level of SOC while PV overproduction is not enough, energy import from the grid is required.

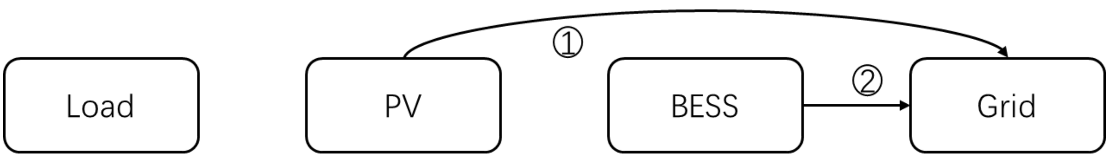


Figure 24. Advanced BEMS export mode

In the case when load is fully covered and BESS is fully charged or not available, BEMS goes into export mode as shown in Figure 24, which any remaining PV overproduction is controlled to export directly to the grid. Export payments for domestic PV production are small as the systems are not metered for export. Typically, calculations for PV generation assume that one half of what is generated is exported at a payment of 5.24 pence per unit (kWh) [25]. At the meantime, BESS can be controlled to feed energy back to grid in certain circumstances, to provide grid support services at peak demand periods.

The aim of this system is to reduce the customers' spending on electricity bills in winter or on a bad weather day, in which the BESS will charge to the targeted amount within Economy 7 cheap rate hours to provide energy throughout the rest of the day in order to reduce the amount of energy imported from the grid at higher rate. The system will store PV overproduction in summer or sunny days to provide night time usage which increases domestic electricity self-sufficiency. In addition, the system is capable to sell energy back to grid during high demand periods to help balancing supply and demand, also make profits for uses.

3.3.4 Battery control logic

Following the description of advanced BEMS above, battery control logic is generated before feeding into the system. The targeted state of charge of the BESS (SOC_{tar}) by the end of cheap tariff hours under different cases are examined. The design flow chart of battery control logic is introduced in Figure 25.

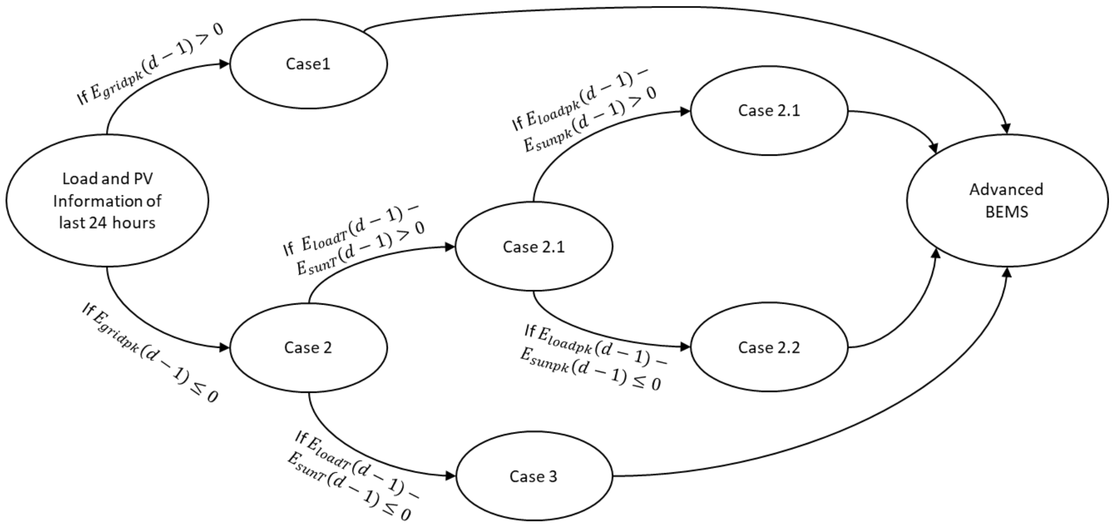


Figure 25. Diagram of battery control logic and the determinations.

The system first needs to analyse the energy usage in the previous day to provide a control logic for the BESS to manage its charging and discharging operation of battery throughout the current day. The load and PV information from the previous day are gained initially, then based on this, the total amount of energy required to import from the grid between 07:00 and 24:00 is calculated to power the household load for the previous day:

$$E_{gridpk}(d-1) = E_{loadpk}(d-1) - E_{sunpk}(d-1) - E_{battery} \tag{13}$$

Here, $d-1$ indicates the previous day, hours between 07:00 and 24:00 is defined as Economy 7 peak hours, E_{loadpk} is total energy required by load in Economy 7 peak hours, E_{sunpk} is defined as total energy generated by PV system in Economy 7 peak hours and $E_{battery}$ represents maximum usable capacity of battery. In this study, 90% depth of discharge is recommended as described earlier to prolong the battery life, thus the usable capacity of the battery is 90% of its nameplate capacity. The unit of each element is watt-hour (Wh). Battery control logics are summarised in the following cases.

3.3.4.1 Case 1: When $E_{gridpk}(d-1)$>0, BESS needs to be fully charged within Economy 7 off-peak hours, it is set to not to support valley demand but fully support peak demand within Economy 7 peak hours until it reaches the minimum SOC

In circumstances where there is low ambient temperature, or unfavourable weather, PV system cannot provide sufficient energy while domestic load is at its peak demand, which results in $E_{gridpk}(d-1)$ to be positive. Therefore, both PV production $E_{sunpk}(d-1)$ and a fully charged battery $E_{battery}$ cannot match the load in Economy 7 peak hours $E_{loadpk}(d-1)$. Subsequently, the battery use is specifically disabled between 10:00 and 15:00 where the valley demand appears (as shown in Figure 11), to preserve energy in order to have better performance on peak demand support.

Thus, the battery is targeted to be fully charged within Economy 7 off peak hours,

$$SOC_{tar} = 100\% \quad (14)$$

the amount of energy required to charge E_{char} at each time step from 00:00 – 07:00 can be calculated by:

$$E_{char}(h) = (SOC_{tar} \times E_{battery} - E_{SOC(END)}) \div 7 \quad (15)$$

Where each time step is defined as an hour h, SOC_{tar} is the targeted state of charge, the multiply of SOC_{tar} and $E_{battery}$ represents the total energy targeted to be stored in the BESS by the end of Economy 7 off-peak hours. $E_{SOC(END)}$ is defined as energy left in the battery at the end of the previous day. Since the battery is set to have a maximum depth of discharge of 90% of its full capacity, thus a maximum of 15% of SOC is set to charge to smooth the demand from grid within each hour.

In this case BESS discharges during Economy 7 peak hours exclude the valley demand time, energy discharge from the battery is calculated by :

$$E_{discharpk}(h) = E_{load}(h) - E_{sun}(h) \tag{16}$$

Where h represents the current time step of an hour, $E_{load}(h)$ therefore represents the energy consumed by the household load at the current time step, $E_{sun}(h)$ is the energy provided by renewable PV system at current time step.

3.3.4.2 Case 2: When $E_{gridpk}(d-1) \leq 0$, BESS needs to obtain targeted SOC within Economy 7 off-peak hours

On the other hand, if $E_{gridpk}(d-1)$ is negative or zero, it represents load demand of the Economy 7 peak hours can be covered by the energy from the renewable generation together with the energy storage facility. Thus, different situations need to be considered separately as below.

3.3.4.3 Case 2.1: When $E_{loadT}(d-1) - E_{sunT}(d-1) > 0$, BESS needs to obtain targeted SOC within Economy 7 off-peak hours

When $E_{loadT}(d-1) - E_{sunT}(d-1) > 0$, where E_{loadT} is the total energy required by the load throughout the day, E_{sunT} is the total energy generated by the PV system throughout the day, this case represents the total energy consumed by the household load throughout the whole day yesterday is higher than the total energy generated by the PV system, therefore the targeted SOC of the BESS is set by further determinations as discussed in Case 2.1.1 and Case 2.1.2.

3.3.4.4 Case 2.1.1: When $E_{loadpk}(d-1) - E_{sunpk}(d-1) > 0$, BESS charges to the targeted SOC within Economy 7 off-peak hours of the current day, then fully cover the load within Economy 7 peak hours until it reaches the minimum SOC

When $E_{loadpk}(d-1) - E_{sunpk}(d-1) > 0$, in this case, PV energy is insufficient to cover the load consumption within Economy 7 peak hours, therefore the battery needs to matching the load between 07:00-24:00. The targeted SOC (SOC_{tar}) required to be stored in the battery by the end of Economy 7 off-peak hours is calculated by the equation:

$$SOC_{tar} = 10\% + SOC_{min} + \left(\frac{E_{loadpk} - E_{sunpk}}{E_{battery}} \right) \quad (17)$$

where SOC_{min} is the battery minimum SOC set by the user to prevent deep-cycle events, for example, and a further 10% of the battery SOC 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. The energy required to charge the BESS at each hour in the Economy 7 off-peak period can then be derived from Equation (15). Moreover, energy discharged from the BESS to support the load at Economy 7 peak hours can be derived from Equation (16).

3.3.4.5 Case 2.1.2: When $E_{loadpk}(d-1) - E_{sunpk}(d-1) \leq 0$, BESS discharges to the targeted SOC within Economy 7 off-peak hours of the current day, then fully cover the load within Economy 7 peak hours until it reaches the minimum SOC

If $E_{loadT}(d-1) - E_{sunT}(d-1) > 0$ but $E_{loadpk}(d-1) - E_{sunpk}(d-1) \leq 0$, the PV energy cannot cover the load consumption throughout the whole day (24-hour period) but can cover the load consumption within Economy 7 peak hours. So the battery will discharge to its targeted SOC within Economy 7 off-peak hours, and then fully cover the load during the rest of the day. In this case, the targeted SOC is controlled to have:

$$SOC_{tar} = 10\% + SOC_{min} \quad (18)$$

Energy required to discharge to the load at each hour within Economy 7 off-peak hours can be calculated by:

$$E_{discharop}(h) = \left(E_{SOC(END)} - SOC_{tar} \times E_{battery}\right) \div 7 \qquad (19)$$

While energy required to discharge to the load at each hour within Economy 7 peak hours can be found in Equation (16).

3.3.4.6 Case 2.2: When $\boldsymbol{E_{loadT}(d-1) - E_{sunT}(d-1) \leq 0}$, BESS is controlled to discharge throughout the whole day of the current day, energy self-sufficiency obtained

Moreover, as state machine shows, if $E_{loadT}(d-1) - E_{sunT}(d-1) \leq 0$, it means the PV system can provide sufficient energy to the load throughout the whole day with no electricity needed to import from the grid. Hence the battery is used as a buffer to store PV overproduction within Economy 7 peak hours of the previous day $(d-1)$ to discharge throughout the whole day of the current day (d). In this circumstance, the targeted SOC of battery is the minimum SOC that can be reached, as previously set at 10%, also energy discharged to the load from the BESS can be found in Equation (16).

$$SOC_{tar} = SOC_{min} \qquad (20)$$

3.3.5 BEMS control strategy

Once the BESS control logics are identified, they are then fed to the advanced BEMS, which generates control signals to manage the charging/discharging operations of the BESS throughout the day, BEMS control strategy is shown in Figure 26. The system runs on an hourly basis throughout a day. At each hour, battery control logic introduced in the previous section is applied to give relative control signal under different cases. Then BEMS control strategy is used to determine the energy flow between the grid, household load, PV and BESS following the application of battery control algorithm.

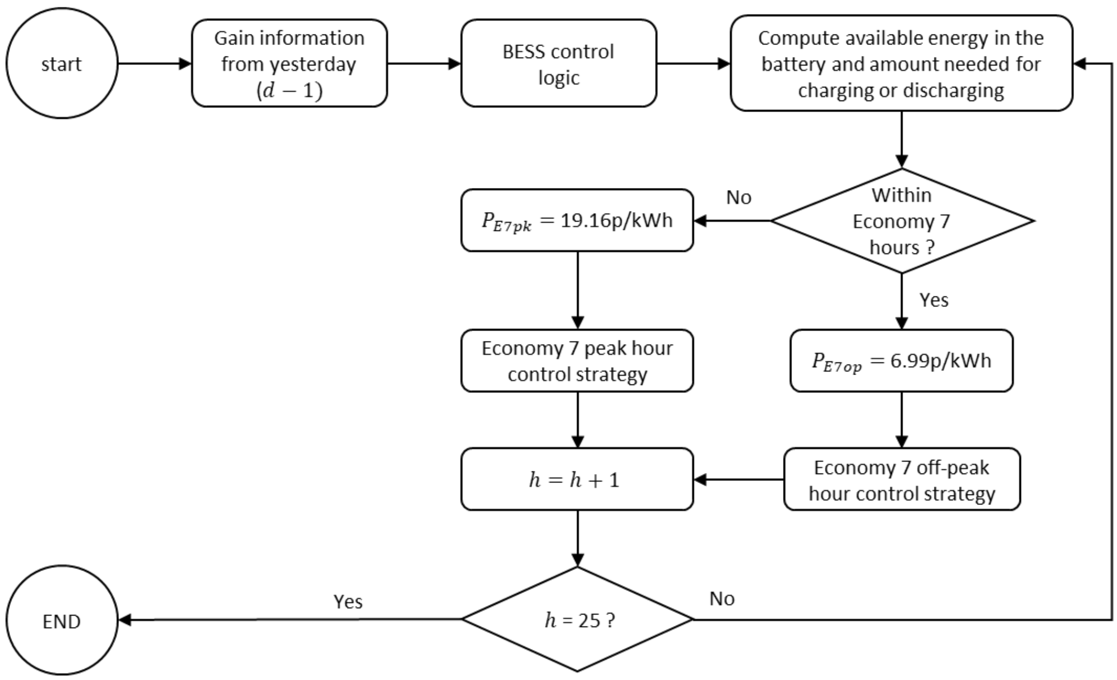


Figure 26. BEMS control strategy design flow

The system first gains historical recorded information of the last 24 hours at the beginning of the first time step which is the first hour of the current day (d), Then the system processes the historical data and generates BESS control logic for the current day. BEMS then needs to evaluate how much energy remained in the battery bank at the last time step $(h-1)$, and how much energy is needed to be charged to or discharged from the BESS via the AC-DC converter in dual way charger at the current time step (h). Then a checking function is used to define whether the current hour is within the Economy 7 off peak hours. If current time step is within the Economy 7 off peak hours, it is defined as an off-peak hour on which the lower electricity rate P_{E7op} is applied. The system will then jump into the Economy 7 off-peak hour control strategy as shown in Figure 27.

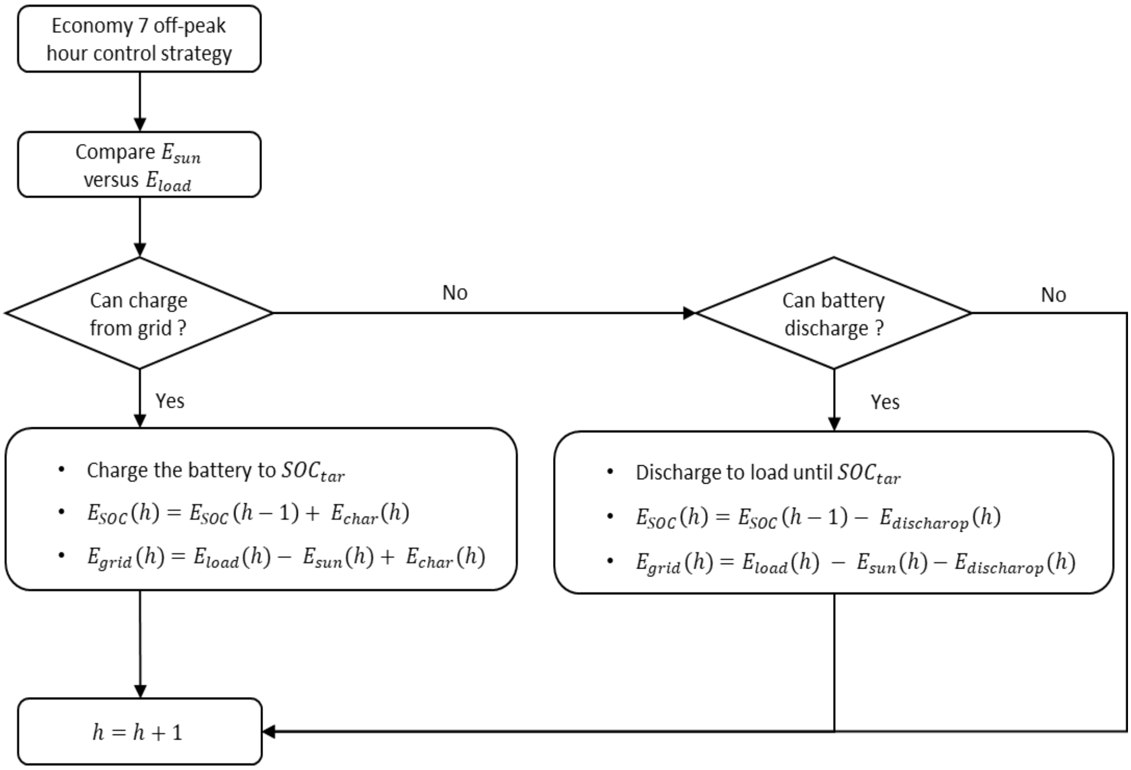


Figure 27. BEMS Economy 7 off-peak hour control strategy

As shown in Figure 27, after comparing the PV energy generated with the load demand at the current time step, the system will manage the BESS to charge from the grid or discharge to the load following the BESS control logic. Both operations are aimed at making the energy stored in the BESS equal to a targeted value, if BESS is controlled to charge during Economy 7 off-peak hours, energy stored in the BESS at each time step is:

$$E_{SOC}(h) = E_{SOC}(h-1) + E_{char}(h) \quad (21)$$

Where E_{SOC} is the energy stored in the BESS, h indicates current hour and $h-1$ indicates previous hour correspondingly.

The total energy required from grid (E_{grid}) at current time is therefore:

$$E_{grid}(h) = E_{load}(h) - E_{sun}(h) + E_{char}(h) \quad (22)$$

Where E_{load} is defined as the energy consumption at domestic household at current time step, E_{sun} is the energy generated by renewable PV system at current time step.

On the other hand, if the BESS is allowed to discharge during the Economy 7 off-peak period, it will try to support the load until the targeted SOC is reached. Thus, energy stored in the BESS changes to:

$$E_{SOC}(h) = E_{SOC}(h-1) - E_{discharop}(h) \tag{23}$$

The energy required from the grid changes to

$$E_{grid}(h) = E_{load}(h) - E_{sun}(h) - E_{discharop}(h) \tag{24}$$

An increment of the time is performed at the last step of the control strategy, and then feed back to the period check. The battery should have reached its target SOC at the end of Economy 7 off peak period.

Any periods after 07:00 am and up to 23:59 are defined as peak electricity tariff hours. The system will perform Economy 7 peak hour control strategy on the BESS charge controller. According to the control strategy shown in Figure 28, the first procedure is to compare PV energy available against the load requirements. Then control signals will be generated for corresponding circumstances as described in the previous section.

If the generated PV energy is sufficient to supply the load, at the meantime battery is fully charged at current hour, in this circumstance, energy stored in the battery equals to the rated maximum capacity of the battery, all of PV overproduction will be fed back to the grid. Therefore

$$E_{SOC}(h) = E_{Battery}$$

$$E_{grid}(h) = 0$$

$$E_{export}(h) = E_{sun}(h) - E_{load}(h) \tag{25}$$

Otherwise, when battery is not fully charged, it is controlled to absorb as much as PV overproduction as possible:

$$E_{SOC}(h) = E_{SOC}(h-1) + (E_{sun}(h) - E_{load}(h))$$

$$E_{grid} = 0 \tag{26}$$

If the PV energy generated in a given hour period, is insufficient to fully cover the load, due to perhaps a cloudy or rainy day, or in the winter season, and the BESS is allowed to dispatch energy at this time step, the load will be met with energy discharged from the BESS. In this situation, the battery will discharge to match any load that PV energy cannot cover, hence there is no need to import the electricity from the grid,

$$E_{SOC}(h) = E_{SOC}(h-1) - E_{discharpk}(h)$$

$$E_{grid} = 0 \tag{27}$$

If the battery is not allowed to discharge by the control signal (e.g., minimum SOC is reached), then the extra energy needed by the load over what is available from the PV is imported from the grid:

$$E_{grid}(h) = E_{load}(h) - E_{sun}(h) \tag{28}$$

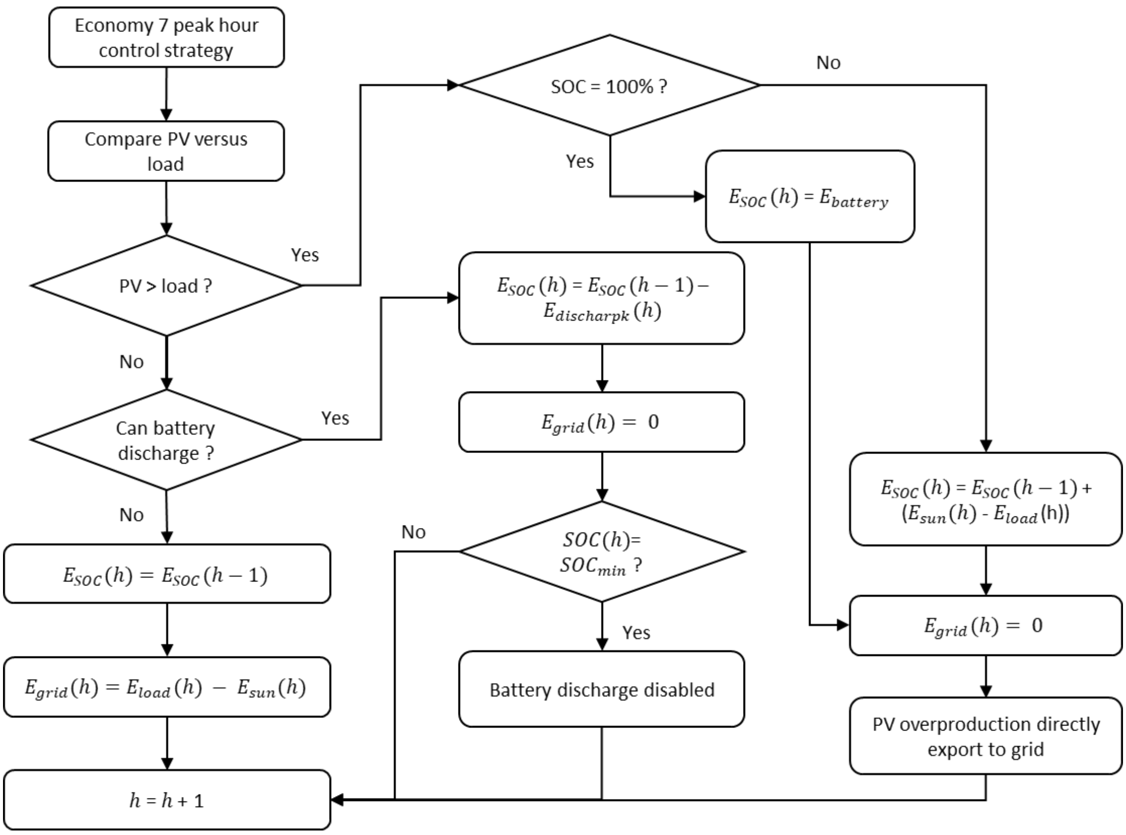


Figure 28. BEMS Economy 7 peak hour control strategy

3.3.6 Battery discharging constraints

Few constraints are made for the system as listed below.

The BESS is only allowed to charge from the grid in Economy 7 off peak 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. As variable pricing is introduced, Economy 7 peak hour tariff is more than doubled than that of off-peak hour. At certain time of the day, usually between 17:00 until 21:00 when people get back home from work, the load on the grid increases to a peak, the use of BESS also helps to lower that load on the grid to reduce the high operation cost for utility companies.

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 until 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, as the battery supplier guarantees their product have 6000+ cycle life at 90% depth of discharge [95].

If the 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.

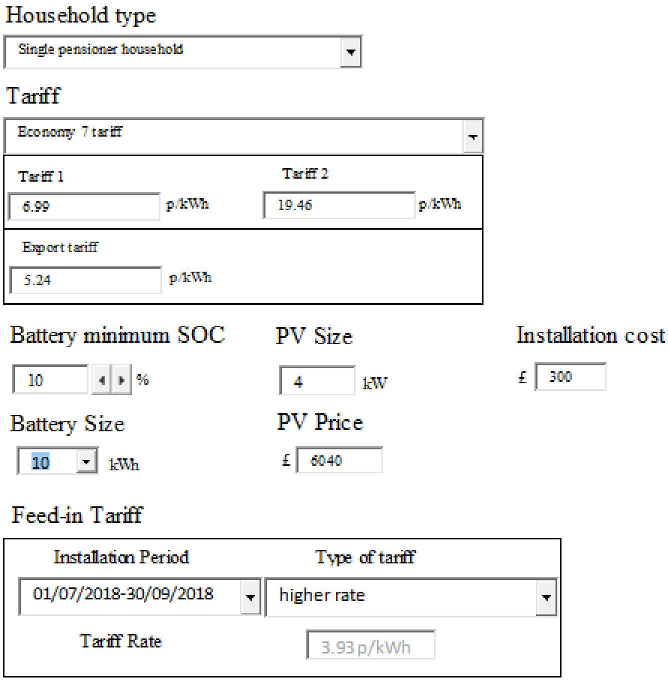
3.4 Results and discussion

3.4.1 Advanced BEMS control strategy

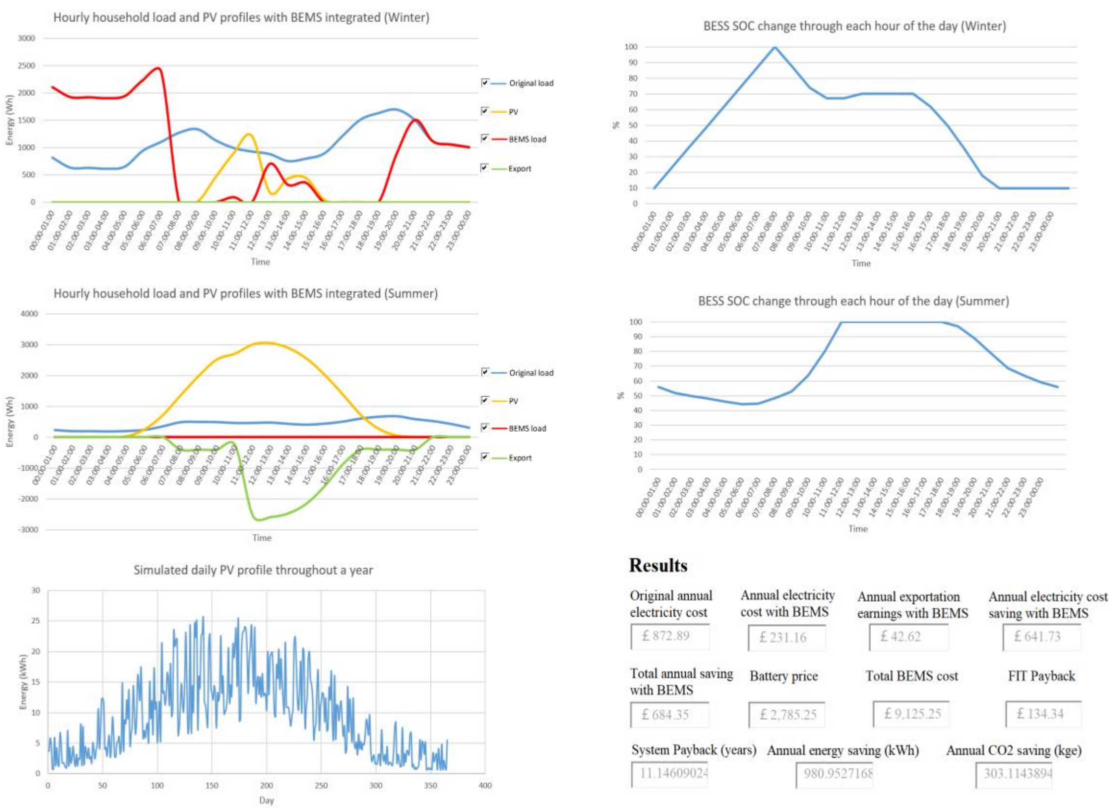
The assumptions listed in Table 4 are used in the Goldsim load profile modelling and SAM PV profile modelling, the datasets generated from both models are exported to Excel for analysis. A dashboard was created in Excel, as shown in Figure 29, by coding in Visual Basic for Application (VBA). The dashboard is used to input variables and present results, it constructs a complete tool to simulate the performance of the BESS integration. The tool first asks users to input parameters listed in Figure 29 (a), such as household type, electricity tariff contract, size of PV and BESS and their purchase price, installation labour cost as well as FIT eligible period and the corresponding FIT tariff rate. Then the tool looks up for the relative load and PV profiles and applies the BEMS control strategy to them, the tool can automatically calculate the outputs and feed back to the dashboard for data visualisation.

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 Solar panel efficiency: 14.4% 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 using the cheap electricity rate to support expensive hours. The day rate P_{E7pk} is 19.46 p/kWh, night rate P_{E7op} is 6.99 p/kWh. The export tariff P_{expo} 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 [27].	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 3.

Table 4. Assumptions made for domestic load profile and PV



(a)



(b)

Figure 29. Dashboard created in Excel for (a) data input and (b) result presentation.

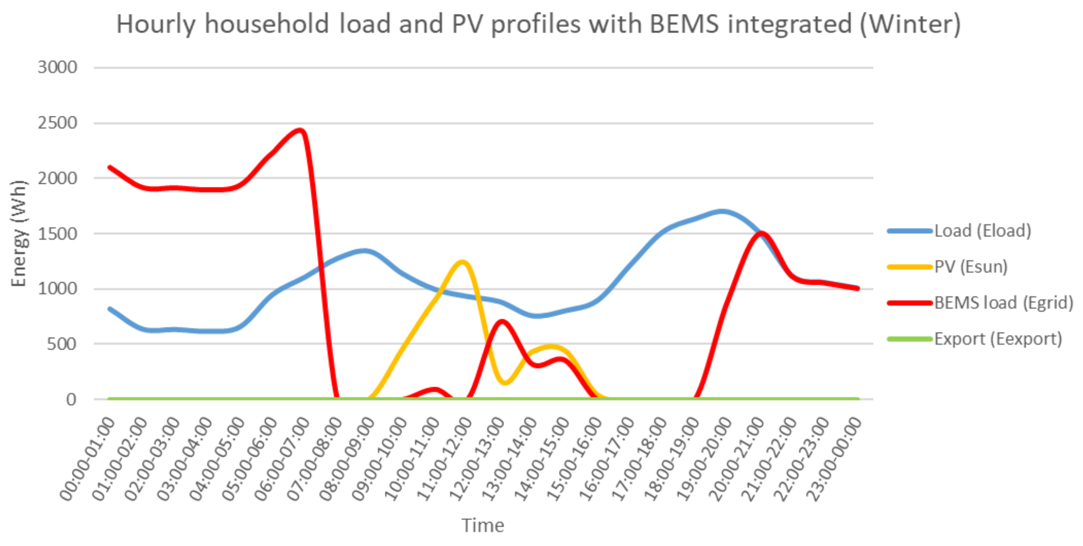


Figure 30. Diagrams of system behaviour in a typical winter day in single pensioner household

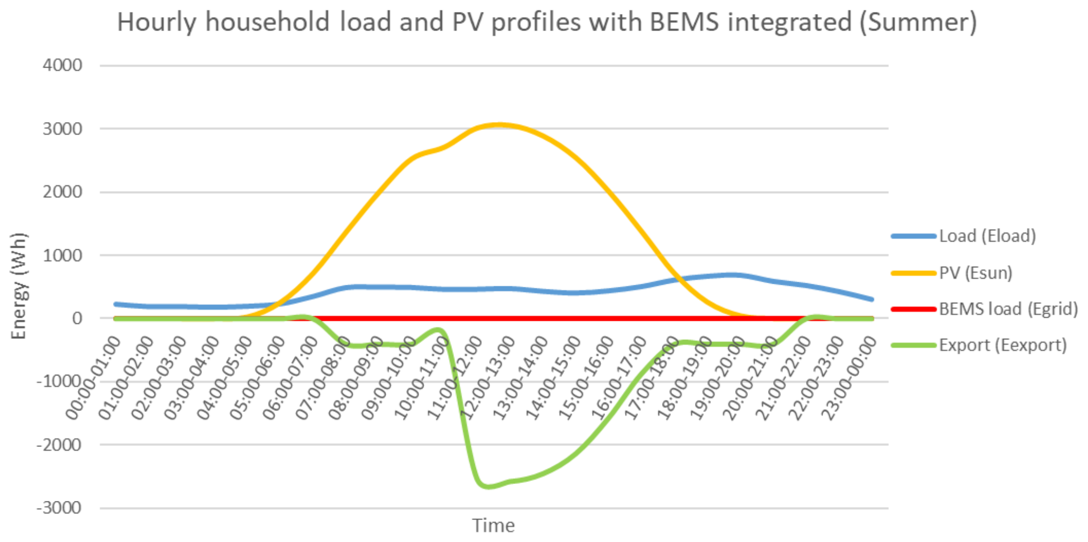


Figure 31. Diagrams of system behaviour in a typical summer day in single pensioner household

Take an example of single pensioner household for BEMS performance presentation, the system configuration is shown in Figure 29 (a), 4kW PV and 10kWh BESS are used. By zooming in the result section on the dashboard, advanced BEMS performance for calendar week 1 (Figure 30) and week 26 (Figure 31) were plotted, which represent for typical winter and summer respectively. From the figures, where the blue bars represent original domestic load profile, yellow bars represent hourly PV energy production, red represents the load profile with BESS 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. The performance diagram for winter shows when E_{gridpk} is positive, where the load within Economy 7 peak hours cannot be matched by both PV generation and a fully charged battery, hence, battery is not disabled between 10:00-15:00. In this situation, the BEMS will try to cut the electricity cost for customers by charging the battery at cheaper rate and provide energy to load during peak hours, so the peak hour usage is mostly shifted to Economy 7 off peak hours. Energy drawn from the grid between 21:00-24:00 is because the BESS has reached its minimum SOC, and the house requires energy import. The change of battery SOC throughout the day is also shown in Figure 29, 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 until the minimum SOC is reached. The result matches the BESS control logic and BEMS control strategy proposed in the previous sections.

The system performance diagram for summer shows when E_{gridpk} is negative, the load can be fully provided by renewable energy, the remaining energy in the battery from the previous day will support the demand between 00:00-07:00, then the PV overproduction will charge the battery when load is fully met during Economy 7 peak hours. The export of energy between 07:00-10:00 is due to the configuration of the previous information, so part of the excess energy stored in the previous 24 hours will export to the grid to balance early peak demand. Between 13:00-17:00, when the BESS is already fully charged, then the excess PV generation will be sold back to the grid, the amount is recorded by the export meter when smart metering is rolled out. After that, the late peak load 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 throughout a year and with the chosen electricity tariff, household with PV and BESS installed comparing with only PV will save 981kWh of electricity annually. The government department for Business, Energy & Industrial Strategy (BEIS) publishes the most up-to-date greenhouse gas report in 2021 [101], which states the greenhouse gas emission for generating 1kWh electricity is 0.231kgCO_2e[3], therefore, a reduction of 226 kgCO_2e of greenhouse gas emission is achieved by using BESS together with PV. 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:

$$payback = \frac{P_{systot}}{P_{profit\_tot}} \tag{29}$$

Where

$$P_{systot} = P_{battery} + P_{PV} + P_{install}$$

$$P_{profit\_tot} = P_{savtot} + P_{export} + P_{FIT} \tag{30}$$

P_{systot} is the total system price including the price of battery system ($P_{battery}$), PV system (P_{PV}) and installation ($P_{install}$). P_{profit_tot} is the total profit gained by using the system. P_{savtot} represents the total saving on electricity bills, P_{export} 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 available for the system, P_{FIT} represents the total return on feed-in tariff. The return on FIT in this study for 4kW PV system based on current FIT scheme is fixed, which is £134.34 per year.

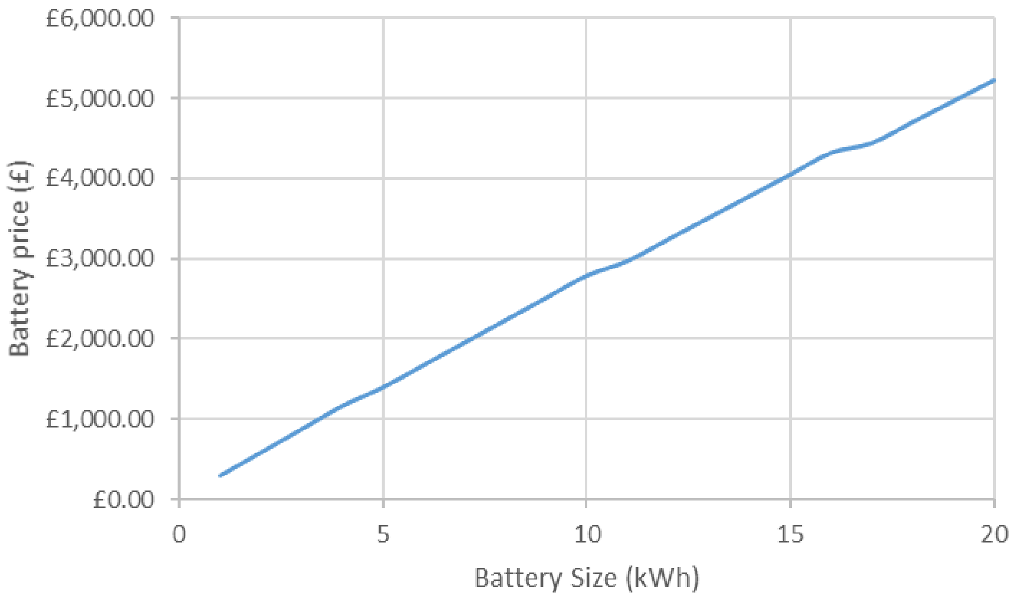
The payback period of the system is 11.15 years as calculated, from the evaluation of the results, the system performance is proved reliable and the payback period seems

[3] kgCO_2e refers to kilogram carbon dioxide equivalent, which includes CO_2 and other greenhouse gases such as CH_4 and N_2O.

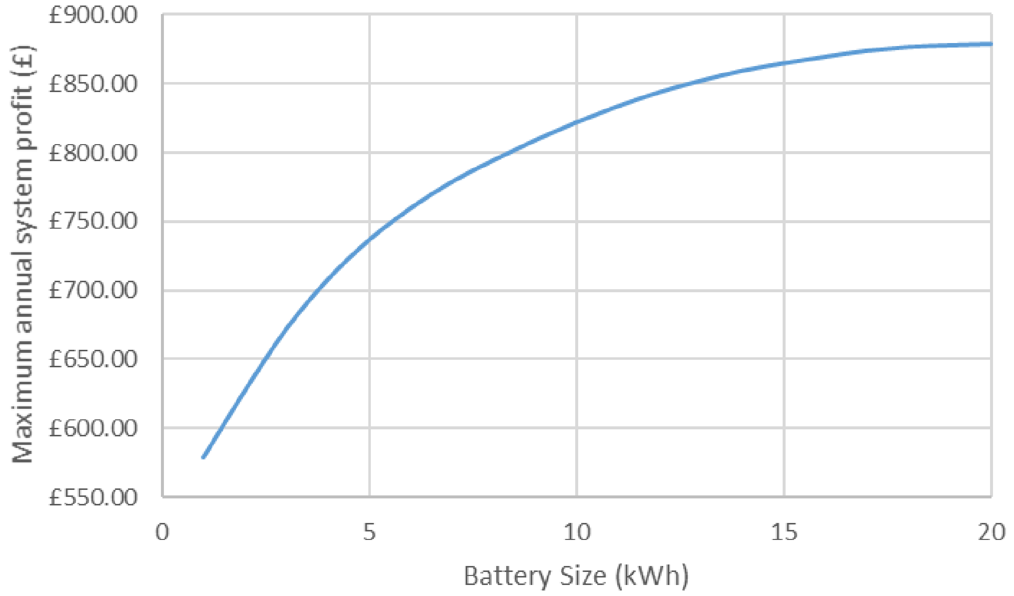
reasonable for domestic users. The battery energy storage system was also applied to different types of households for further validation.

3.4.2 Sensitivity analysis

The performance of the energy storage is evaluated in the form of the payback period for the system installation, brought about both through the FIT tariff, and the savings on the electricity bill. As mentioned before, the system payback can be calculated from Equation (29), 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 system installation costs.



(a)



(b)

Figure 32. (a) Prices of battery for corresponding sizes and (b) maximum system annual profit for different sizes of battery

Figure 32 shows how battery cost varies with the increasing battery size and how maximum annual profit varies with the increasing battery size respectively. With the same 4kW PV system installed, In Figure 32(a), the horizontal axis represents the range of battery capacity in kWh, and the vertical axis represents the battery price in pounds (£). From the figure, the curve shows a positive linear increase against battery size, the price increasing from £290.16 for 1kWh capacity battery to £5222.92 for 20kWh battery.

However, the maximum annual profit shows a logarithmic growth against battery size. In Figure 32(b), when a system is fitted to single pensioner household and analysed as an example, the horizontal axis represents the range of battery capacity in kWh and the vertical axis shows the annual system profit includes savings in pounds (£). It shows the profit increases quickly in the beginning where the battery size increases from 1kWh to 5kWh and the revenue increases by 27%. Then the gains decrease as battery size increases further, the profit increases by 19% from £736.69 for 5kWh battery to £879.02 for 20kWh. The profit will eventually saturate at £879.02, at which, the increasing battery size will no longer provide any more profits but only increases the system cost.

The reason for this curve shape is mainly due to a fully charged 20kWh battery bank (during economy 7 off peak hours) can cover the maximum energy demand from the grid for the household during the rest of the day. As the cost saving on electricity bills p_{savtot} saturates, and the fixed amount of FIT returns, according to the Equation (30), no further improvement will be obtained for a battery size beyond 20kWh.

Thus, the larger capacity of battery may not bring proportionally higher profits, but it 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 BESS, to evaluate the marginal and most suitable battery sizes for each size of PV system installed in different types of households.

The sensitivity analysis is carried out using the algorithm shown in Figure 33. With the setup and assumptions listed in Table 4 and the costs of the range of batteries listed in Table 3, the algorithm calculates the payback periods for each size combination of PV and BESS according to Equation (29), then records them in a spreadsheet named "table A". Then if the calculated payback period ($payback$) is shorter than the benchmark payback period ($payback_{org}$) which is for household with PV only, the algorithm will generate a logic 1 and record in a spreadsheet named "table B", otherwise, it will output a 0. The "table B" is used to find out and highlight the marginal sizes of BESS for each size of PV system, which is acceptable to apply to the household. The algorithm also finds out the minimum payback period for each PV-BESS setup.

Table 6 shows the calculated system payback periods under different sizes of PV and battery setup for single pensioner household. The shortest system payback for household with only PV but no BESS is also listed at the top row as a benchmark performance. 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 most suitable 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 domestic energy system has 7.7%, 10.1%, 11.0%, 7.7% improvement on payback time for 1 to 4 kW PV 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 = P_systot / P_profit_tot ;
        tableA(i, j) =  payback ;

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

  end for
  payback_min = min(tableA) ;

end for
```

Figure 33. System payback evaluation algorithm

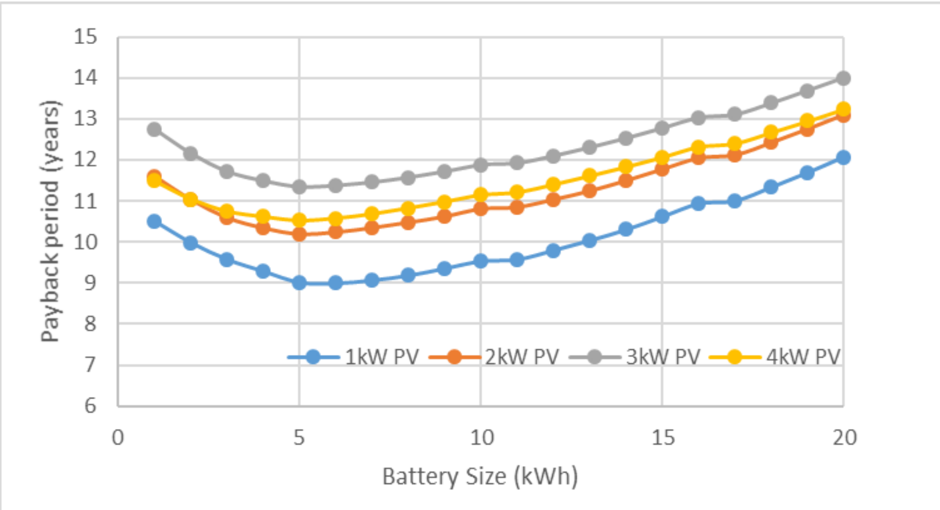


Figure 34. Payback periods of various battery sizes for different sizes of PV system installed in single pensioner household

PV size / Battery size	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.

Table 5. Payback periods for single pensioner household with various sizes of PV and battery system

For comparison, the same simulation was applied to different types of households with a similar appliance profile to investigate the change in payback periods for different households. Analyzing the following results (Table 8-11 and Figure 36-39), they display a similar trend but with different values. The shortest payback period for each scenario is illustrated in Table 6.

PV size / Household type	1kW	2kW	3kW	4kW
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)

Table 6. Minimum system payback period and corresponding battery size for different household types with different sizes of PV system coupled.

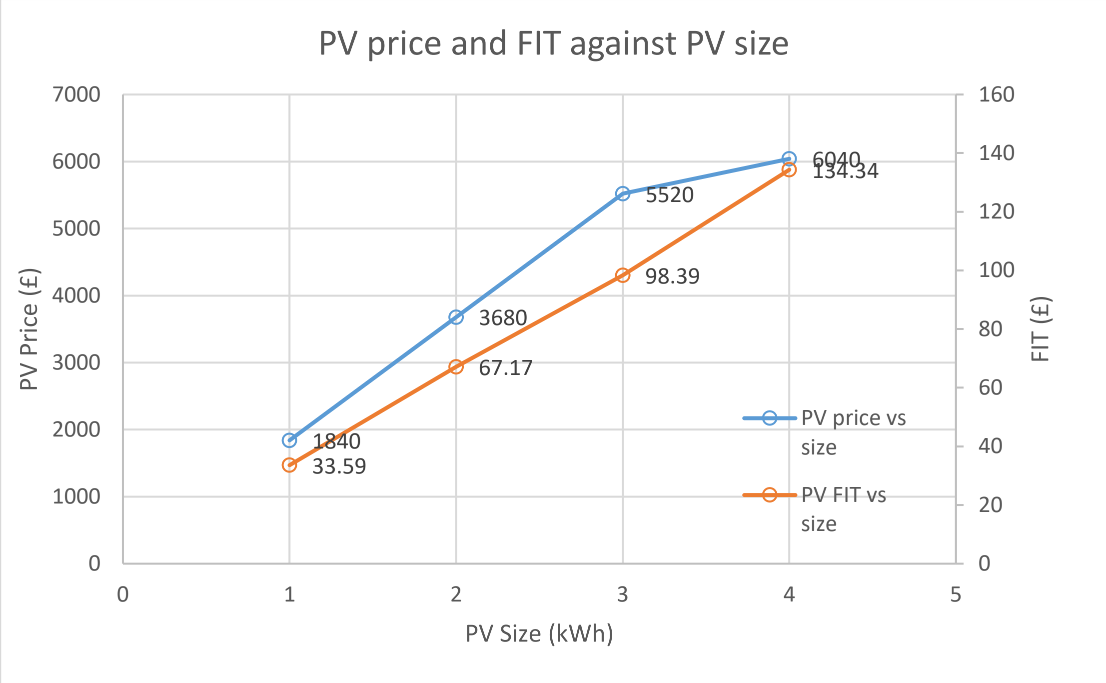


Figure 35. PV system price and annual feed in tariff earningsversus PV size

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 shown between integrating with 5kWh and 6kWh battery systems. Table 6 shows regardless of the type of household, the shortest payback time increases with the rising PV size from 1kW to 3kW, then decreases for 4kW system. This is mainly caused by the unmatched PV system price and FIT. As shown in Fig.39, feed-in tariff is in direct proportion to the size of PV array, while the PV price initially has a linear increase but with a slightly larger gradient, as a result, increasing payback period is found on the integration of 1 to 3 kW system. But the curve of PV price turns flattened when the size increases to 4kW, the gradient is smaller compare with that of FIT. Thus, it explains the rollback on payback years from 3kW system to 4kW system.

The cost of lithium-ion battery packs is reducing 25% from 2009 level to 2014 [102] according to the literature, hence the results will improve due to lower battery price with passing time, the system payback time will reduce and the best fit system size will increase. Thus, the customers will tend to buy larger size of battery systems in the future for better energy self-sufficiency.

According to Table 7, it lists the annual energy and emission savings for each type of households with 5kWh BESS installed alongside 4kW PV system, each household with domestic energy system installed can reduce approximately in average 821kWh of electricity use and 190kgCO_2e greenhouse gas emission every year. There are an estimated 27.8 millions households in the UK [103], if every household has this example system installed, 2.8×10^7MWh of electricity will be saved nationwide every year, also approximately 6.4×10^6tCO_2e of emission[4] will be removed. It is worth the government to explore this huge potential by subsidizing not only PV system installation, but also energy storage facilities. Since 5kWh BESS shows relative shorter payback time, a suggested government support up to £140 annually for 10 years can help encouraging more installations of domestic energy system, and a huge reduction on carbon footprint in domestic area is realistic in the future.

Household type	Annual energy saving (kWh)	Annual emission saving (kgCO_2e)
Single pensioner household	818.91	189.17
Single non-pensioner household	815.79	188.45
Multiple pensioner household	827.76	191.21
Household with children	833.86	192.62
Multiple person household with no dependent children	809.81	187.07

Table 7. Annual energy and emission saving for each type of households after installing 5kWh BESS and 4kW PV

[4] tCO_2e refers to tonnes of carbon dioxide equivalent.

PV size / Battery size	1kW	2kW	3kW	4kW
No battery	9.72 yrs.	11.31 yrs.	12.70 yrs.	11.35 yrs.
1kWh	10.52 yrs.	11.60 yrs.	12.74 yrs.	11.46 yrs.
2kWh	10.00 yrs.	11.04 yrs.	12.15 yrs.	11.04 yrs.
3kWh	9.59 yrs.	10.61 yrs.	11.72 yrs.	10.73 yrs.
4kWh	9.29 yrs.	10.34 yrs.	11.47 yrs.	10.60 yrs.
5kWh	9.01 yrs.	10.18 yrs.	11.32 yrs.	10.50 yrs.
6kWh	8.98 yrs.	10.22 yrs.	11.35 yrs.	10.55 yrs.
7kWh	9.05 yrs.	10.32 yrs.	11.42 yrs.	10.64 yrs.
8kWh	9.15 yrs.	10.45 yrs.	11.53 yrs.	10.78 yrs.
9kWh	9.32 yrs.	10.58 yrs.	11.67 yrs.	10.94 yrs.
10kWh	9.49 yrs.	10.76 yrs.	11.83 yrs.	11.10 yrs.
11kWh	9.54 yrs.	10.80 yrs.	11.87 yrs.	11.16 yrs.
12kWh	9.77 yrs.	10.99 yrs.	12.04 yrs.	11.35 yrs.
13kWh	9.99 yrs.	11.19 yrs.	12.24 yrs.	11.56 yrs.
14kWh	10.25 yrs.	11.43 yrs.	12.46 yrs.	11.77 yrs.
15kWh	10.54 yrs.	11.69 yrs.	12.71 yrs.	12.01 yrs.
16kWh	10.85 yrs.	11.97 yrs.	12.96 yrs.	12.25 yrs.
17kWh	10.93 yrs.	12.05 yrs.	13.03 yrs.	12.33 yrs.
18kWh	11.24 yrs.	12.34 yrs.	13.30 yrs.	12.59 yrs.
19kWh	11.59 yrs.	12.65 yrs.	13.60 yrs.	12.87 yrs.
20kWh	11.96 yrs.	12.99 yrs.	13.90 yrs.	13.15 yrs.

Table 8. Payback periods for single non-pensioner household with various sizes of PV and battery system

PV size / Battery size	1kW	2kW	3kW	4kW
No battery	9.82 yrs.	11.54 yrs.	12.97 yrs.	11.60 yrs.
1kWh	10.63 yrs.	11.80 yrs.	12.97 yrs.	11.68 yrs.
2kWh	10.07 yrs.	11.20 yrs.	12.35 yrs.	11.23 yrs.
3kWh	9.64 yrs.	10.75 yrs.	11.90 yrs.	10.91 yrs.
4kWh	9.34 yrs.	10.50 yrs.	11.67 yrs.	10.77 yrs.
5kWh	9.09 yrs.	10.35 yrs.	11.53 yrs.	10.69 yrs.
6kWh	9.10 yrs.	10.42 yrs.	11.55 yrs.	10.75 yrs.
7kWh	9.19 yrs.	10.53 yrs.	11.64 yrs.	10.87 yrs.
8kWh	9.34 yrs.	10.66 yrs.	11.77 yrs.	11.01 yrs.
9kWh	9.51 yrs.	10.83 yrs.	11.92 yrs.	11.17 yrs.
10kWh	9.72 yrs.	11.02 yrs.	12.09 yrs.	11.35 yrs.
11kWh	9.77 yrs.	11.08 yrs.	12.14 yrs.	11.43 yrs.
12kWh	10.01 yrs.	11.28 yrs.	12.34 yrs.	11.64 yrs.
13kWh	10.27 yrs.	11.52 yrs.	12.56 yrs.	11.86 yrs.
14kWh	10.58 yrs.	11.79 yrs.	12.81 yrs.	12.10 yrs.
15kWh	10.90 yrs.	12.07 yrs.	13.07 yrs.	12.35 yrs.
16kWh	11.24 yrs.	12.37 yrs.	13.34 yrs.	12.61 yrs.
17kWh	11.33 yrs.	12.46 yrs.	13.44 yrs.	12.72 yrs.
18kWh	11.69 yrs.	12.80 yrs.	13.75 yrs.	13.00 yrs.
19kWh	12.08 yrs.	13.15 yrs.	14.08 yrs.	13.30 yrs.
20kWh	12.51 yrs.	13.52 yrs.	14.41 yrs.	13.60 yrs.

Table 9. Payback periods for multiple pensioner household with various sizes of PV and battery system

PV size / Battery size	1kW	2kW	3kW	4kW
No battery	9.77 yrs.	11.40 yrs.	12.80 yrs.	11.44 yrs.
1kWh	10.54 yrs.	11.68 yrs.	12.85 yrs.	11.54 yrs.
2kWh	10.02 yrs.	11.11 yrs.	12.23 yrs.	11.11 yrs.
3kWh	9.62 yrs.	10.67 yrs.	11.78 yrs.	10.79 yrs.
4kWh	9.30 yrs.	10.35 yrs.	11.47 yrs.	10.59 yrs.
5kWh	8.98 yrs.	10.14 yrs.	11.28 yrs.	10.46 yrs.
6kWh	8.93 yrs.	10.15 yrs.	11.28 yrs.	10.49 yrs.
7kWh	8.98 yrs.	10.24 yrs.	11.34 yrs.	10.57 yrs.
8kWh	9.09 yrs.	10.36 yrs.	11.44 yrs.	10.70 yrs.
9kWh	9.24 yrs.	10.50 yrs.	11.57 yrs.	10.85 yrs.
10kWh	9.40 yrs.	10.66 yrs.	11.73 yrs.	11.01 yrs.
11kWh	9.44 yrs.	10.70 yrs.	11.76 yrs.	11.07 yrs.
12kWh	9.66 yrs.	10.88 yrs.	11.93 yrs.	11.25 yrs.
13kWh	9.88 yrs.	11.08 yrs.	12.12 yrs.	11.45 yrs.
14kWh	10.13 yrs.	11.32 yrs.	12.34 yrs.	11.66 yrs.
15kWh	10.42 yrs.	11.57 yrs.	12.57 yrs.	11.89 yrs.
16kWh	10.72 yrs.	11.84 yrs.	12.81 yrs.	12.13 yrs.
17kWh	10.79 yrs.	11.91 yrs.	12.89 yrs.	12.21 yrs.
18kWh	11.11 yrs.	12.19 yrs.	13.15 yrs.	12.46 yrs.
19kWh	11.44 yrs.	12.50 yrs.	13.44 yrs.	12.74 yrs.
20kWh	11.80 yrs.	12.83 yrs.	13.74 yrs.	13.02 yrs.

Table 10. Payback periods for household with children with various sizes of PV and battery system

PV size / Battery size	1kW	2kW	3kW	4kW
No battery	9.66 yrs.	11.16 yrs.	12.53 yrs.	11.20 yrs.
1kWh	10.44 yrs.	11.46 yrs.	12.61 yrs.	11.34 yrs.
2kWh	9.94 yrs.	10.94 yrs.	12.03 yrs.	10.92 yrs.
3kWh	9.56 yrs.	10.53 yrs.	11.60 yrs.	10.62 yrs.
4kWh	9.25 yrs.	10.23 yrs.	11.32 yrs.	10.45 yrs.
5kWh	8.94 yrs.	10.03 yrs.	11.14 yrs.	10.34 yrs.
6kWh	8.88 yrs.	10.04 yrs.	11.14 yrs.	10.37 yrs.
7kWh	8.91 yrs.	10.12 yrs.	11.21 yrs.	10.45 yrs.
8kWh	8.99 yrs.	10.24 yrs.	11.30 yrs.	10.57 yrs.
9kWh	9.13 yrs.	10.37 yrs.	11.43 yrs.	10.72 yrs.
10kWh	9.30 yrs.	10.52 yrs.	11.58 yrs.	10.88 yrs.
11kWh	9.31 yrs.	10.56 yrs.	11.61 yrs.	10.94 yrs.
12kWh	9.52 yrs.	10.75 yrs.	11.78 yrs.	11.11 yrs.
13kWh	9.74 yrs.	10.93 yrs.	11.95 yrs.	11.29 yrs.
14kWh	9.97 yrs.	11.15 yrs.	12.16 yrs.	11.50 yrs.
15kWh	10.25 yrs.	11.39 yrs.	12.38 yrs.	11.72 yrs.
16kWh	10.55 yrs.	11.66 yrs.	12.62 yrs.	11.95 yrs.
17kWh	10.60 yrs.	11.71 yrs.	12.69 yrs.	12.03 yrs.
18kWh	10.89 yrs.	11.98 yrs.	12.93 yrs.	12.26 yrs.
19kWh	11.22 yrs.	12.27 yrs.	13.20 yrs.	12.53 yrs.
20kWh	11.56 yrs.	12.59 yrs.	13.49 yrs.	12.79 yrs.

Table 11. Payback periods for multiple person household with no dependent children with various sizes of PV and battery system

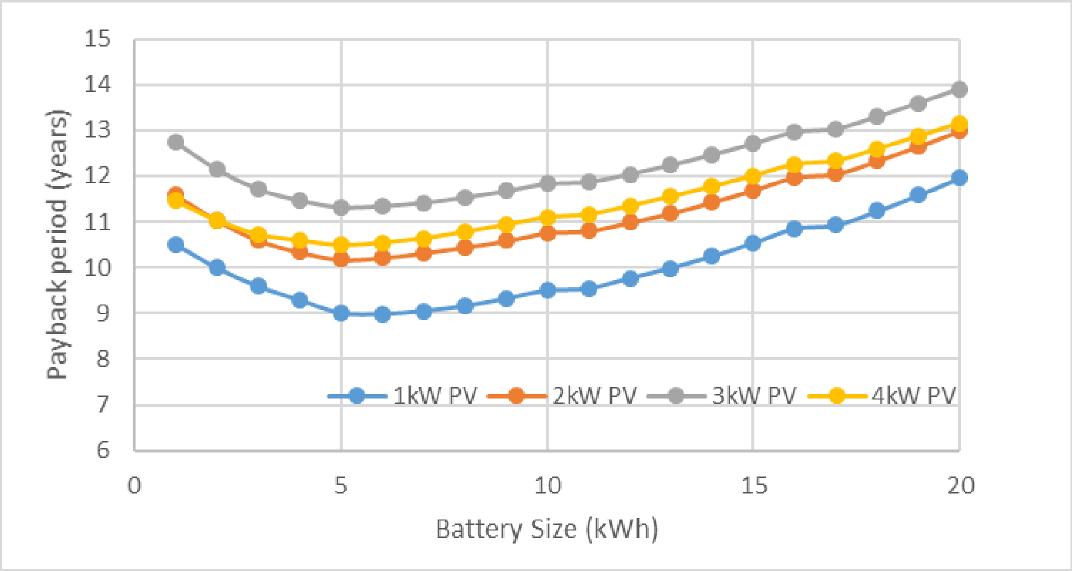


Figure 36. Payback periods of various battery sizes for different sizes of PV system installed in single non-pensioner household

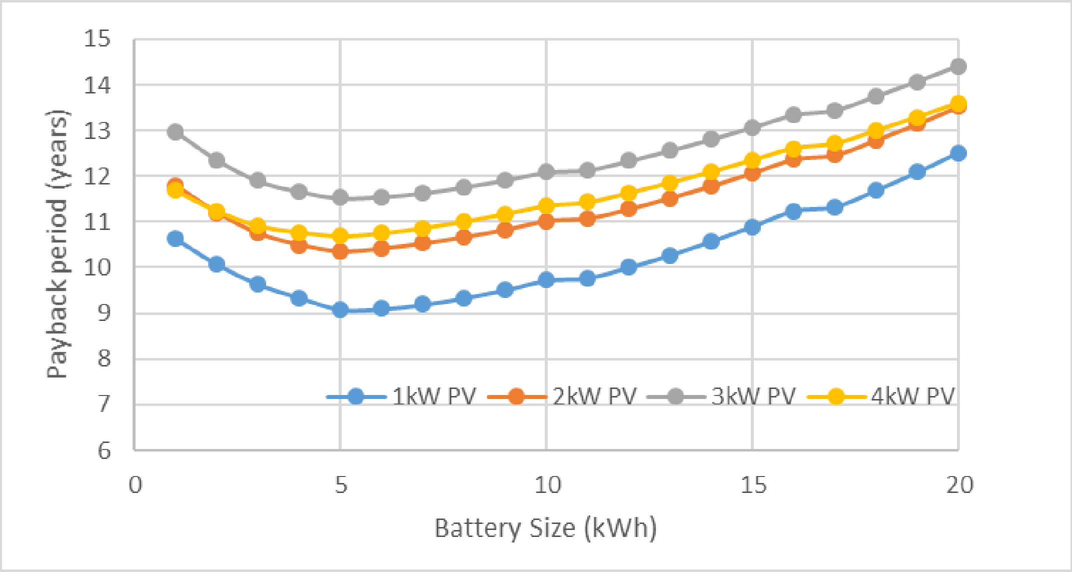


Figure 37. Payback periods of various battery sizes for different sizes of PV system installed in multiple pensioner household

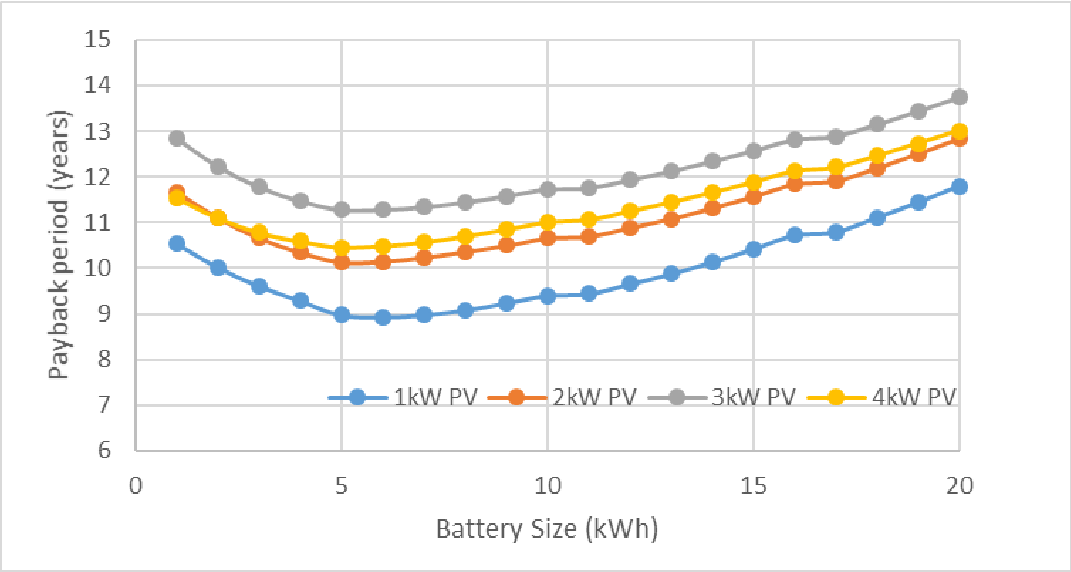


Figure 38. Payback periods of various battery sizes for different sizes of PV system installed in household with children

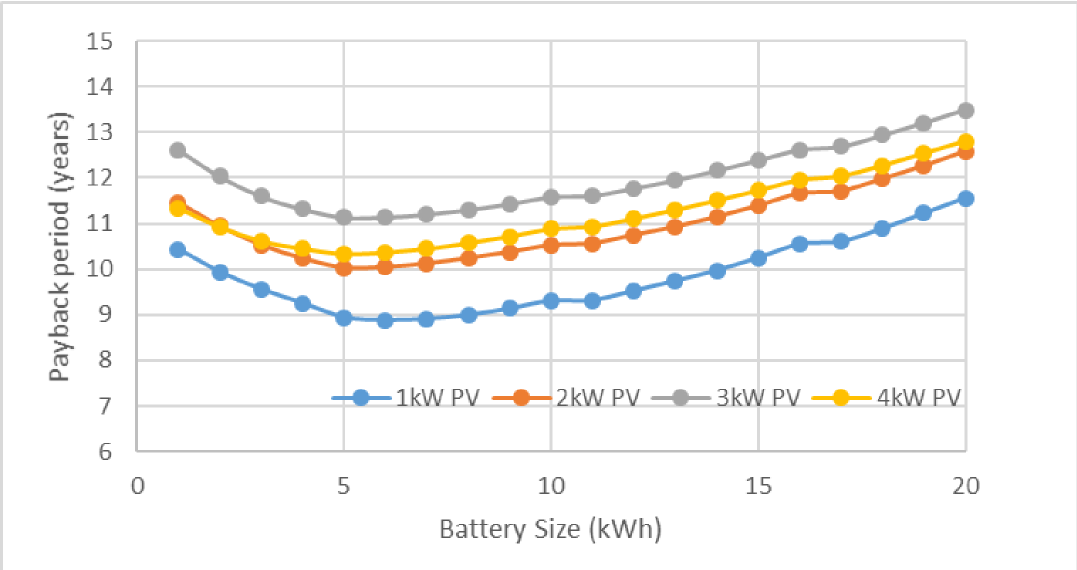


Figure 39. Payback periods of various battery sizes for different sizes of PV system installed in multiple person household with no dependent children

3.5 Conclusion

This chapter first introduces domestic load profile modelling to simulate hourly energy consumption throughout a day in typical residential household. The Goldsim simulation model constructed 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 generate typical hourly electricity consumption for different scenarios. Thus the Goldsim simulation was used to produce domestic load profile for this study. Then, a PV profile was generated by using SAM to couple with the load profile, in order to size the battery. The PV profiles generated by SAM were validated against the practical measured data from a 4kW practical system.

A BEMS control strategy with BESS control logic was developed for the energy storage system, best match battery sizes for different sizes of PV system in different types of households were evaluated with tariff incentives. The developed smart energy storage system and its control algorithm manage the domestic energy usage and improve grid stability. With the benefit of this, the system can lower the users' expenditure on electricity bills, and also make money from energy export. Energy self-sufficiency can be achieved only in summer by applying this system, and can effectively support the peak demand of the grid. System behaviour in practice will be monitored for further validation and development.

The most suitable 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 to lie between the installation of a 5kWh and a 6kWh battery system. Due to logarithmic growth on system revenue, the system has higher payback periods due to limited utilisation of larger battery systems, and conversely, there is insufficient capacity to make useful profits from smaller battery systems.

Chapter IV.

Study into Payback Periods for Domestic Energy Systems Including PV, Battery Storage and V2G

Following the previous chapter, the domestic energy system model including photovoltaic (PV) panels, battery energy storage system (BESS) and electric vehicle (EV) is further developed to examine likely EV usage patterns and the effects on the payback periods for a consumer. It includes various input selection choices, such as household type, PV size, BESS size and EV model etc. to better approximate real-world households. By applying a series of control algorithms to the system, in combination with possible electricity tariffs, the minimum energy use scenario for the household can be calculated, along with the payback period for each variation of PV and BESS sizes within a proposed system. Simple battery aging models for both EV and BESS batteries are included to evaluate the battery degradation cost due to deep-cycle operation. The Return on Investment (ROI) for a household with a V2G enabled EV, installed alongside a BESS and PV will be calculate to examine the system economic performance.

4.1 Introduction

Recently, there has been a number of initiatives taken by the UK government to incentivise the use of EVs. The government Road to Zero strategy published was published in 2018 [104], and prior to that, it introduced the government investment grant of around £1.5 billion from April 2015, which included £400 million on charge point infrastructure and up to £500 reduction on the cost of home charging equipment for electric vehicle owners, to encourage EV penetration. This was targeted towards replacing almost every petrol and diesel cars on the road with low and zero emission EVs by 2050 [105]. Hence in the last few years, the number of licensed electric vehicles on road, including hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEV) and range-extended electric vehicles (REEV), has increased from 352,200 in 2016 to the level of 758,100 in 2019, according to vehicle licensing statistics published by the Department for Transport and Driver and Vehicle Licensing Agency in 2019 [106]. However, the market share of electric vehicles is still small compared with over 30 million conventional fossil-fuelled vehicles in the UK market. The slow rate of EV penetration is mainly due to the higher capital cost of EVs. To overcome this drawback, Vehicle-to-Grid (V2G) and Vehicle-to-Home (V2H) schemes are being suggested to allow the electricity in EV battery packs to be fed back into the grid and home respectively [107]. By selling energy to the grid, the owner could make profit, and self-using energy for peak domestic loads could result in energy self-sufficiency or lower peak tariff costs, which reduces the energy bill costs for the owner. Both advantages can offset the capital cost over the vehicle life-time.

The main objectives of this chapter are as follow:

- The domestic energy consumption model developed in the previous chapter, including photovoltaic (PV) panels and a battery energy storage system (BESS), is now expanded to include an electric vehicle (EV). It includes various input selection choices, such as household type, PV size, BESS size and EV brand etc. to better approximate real-world households.
- By applying a series of control algorithms to the model, in combination with possible electricity tariffs, the best energy use scenario for the household can be

calculated, along with the payback period for each variation in PV and BESS sizes within a proposed system.

- A battery aging model for both EV and BESS batteries is included to calculate the degradation cost and evaluate overall system economic performance.
- EV charging and discharging constraints are defined, and battery control algorithms for both EV and BESS are updated.
- The costs of the system, and yearly revenue created by the system are analysed. System performance is represented in the form of return on investment (ROI).

4.2 System configuration

4.2.1 Drive pattern

V2G and V2H strategies are intended to maximise the utilisation of domestic renewable energy. The owner can charge the EV battery using renewable energy source (RES) overproduction, and discharge to supply peak household demand. This can potentially make benefit from energy self-sufficiency and energy exportation. PV is mainly the RES technology applied to domestic sector in the UK, and is considered throughout this study.

Different from a stationary energy storage system (S-ESS), here a driver's behaviour pattern and trips range have a significant impact on the use of an EV as a mobile energy storage unit. Table 12 shows typical driving patterns by UK EV drivers.

In the table, there shows three states of the EV, being classified as driving, parked at home, and parked away from home [108]. The classification is necessary to define whether the EV is able to absorb the surplus energy produced by household PV and use this later to supply the household appliances. Within each hourly time step, the state of the EV is marked in different coloured bars. Red colour bar represents the EV is moving, and it is consuming energy from the battery. Yellow is when EV is parked outside, or away from home, and is unavailable for charging and discharging. Grey shows the vehicle is parked at home and the bi-directional charger is connected to allow any of the following four functions: charge the EV using PV overproduction, charge the EV from the grid, sell energy to grid, or feed energy to the domestic load.

	Trip pattern	**Time** **0 12 24**	**Trip distribution in a week**
Weekday	Systematic		38%
	Unsystematic		22%
	Others		22%
Weekend	Systematic		2%
	Unsystematic		10%
	Others		6%

Table 12. Drive patterns of vehicle [109]

Generally, there are three main categories of trip pattern identified, these being systematic mobility, unsystematic mobility and others. Systematic mobility is normally defined as the trips from home to a workplace in the morning and the return journey in the afternoon. A typical departure time is 8:00 and most of drivers return home from work at 17:00. According to a mobility survey on driving and parking patterns of European car drivers [109], due to the majority of people working on weekdays, approximately 38% of all trips made in the UK within a week is accounted for by systematic mobility, from Monday to Friday. While only 2% falls in this category on a weekend. The majority of trips (10%) during the weekend are unsystematic mobility, where drivers use cars for shopping, leisure, visiting friends or personal reasons which are not related to work. This trip pattern also accounts for 22% of all the trips in the UK during working days. The departure time from home for unsystematic mobility is normally later than that for systematic mobility falling between around 11:00 and 12:00 for weekday and weekend use respectively. Most people tend to stay out for 2 hours and then return home in this driving pattern. Other non-work-based travel are not specifically categorised in the survey, accounting for 28% in total of all the trips. The departure and return time vary for different households, a typical time plan is shown in the table.

If the EV is used for systematic mobility where it is parked outside during the most of daytime, then there's an unmatched condition occurring in which most of the PV overproduction cannot be stored in the EV battery. Considering the trip distribution in a week, this chapter focus on investigating the performance of V2G and V2H operation within a domestic household that has a PV system and a stationary BESS installed, and where systematic mobility is expected for weekdays and unsystematic mobility is considered on weekends (the most likely scenario).

4.2.2 EV energy consumption

Unlike with the conventional internal combustion engine vehicle, miles per gallon isn't the metric used to represent the energy consumption of electric vehicles. Instead, the new 'mpg' for EVs is 'miles per kilowatt-hours' (miles/kWh) [110]. The rated figure normally can be found on the vehicle fuel consumption label, as shown in Figure 40 [111], or in the owner's manual. The rated consumption usually represents the optimal energy usage figure under a given test cycle, and it is difficult to calculate an exact total consumption of each trip as numerous factors are taken into account such as: speed, vehicle load, ambient temperature, road condition, driving habit, etc. Similar to petrol or diesel engine vehicles, the consumption of electric cars is different across range of brands and models. The UK electric vehicle database (UKEVDB) [112] gathers detailed information of most EVs on the market, it concludes rated performance of the vehicles and real performance data under different weather scenarios and road conditions provided by users, there are six conditions: city – cold weather, highway – cold weather, combined – cold weather, city – mild weather, highway – mild weather and combined – mild weather. Cold weather is defined as when the high temperature of the day is below 10℃ [113], there's a large possibility the driver will turn on the heating which increases the energy consumption. While mild weather is defined as when the high temperature is above 10℃ but below 25℃, in this case, air conditioning is not in use. According to the UK weather reports collected for areas near Sheffield during a decade since 2005 [114], cold weather normally occurs from November until early March the following year, based on the average monthly temperature. While the average monthly temperatures of the remaining months of the year are all within the range classified as mild weather within the UK. Thus, the typical period of cold weather in weekly basis is set from week 45 to week 9 the following year, based on the temperature information recorded for 2019-2020 calendar year in this study.

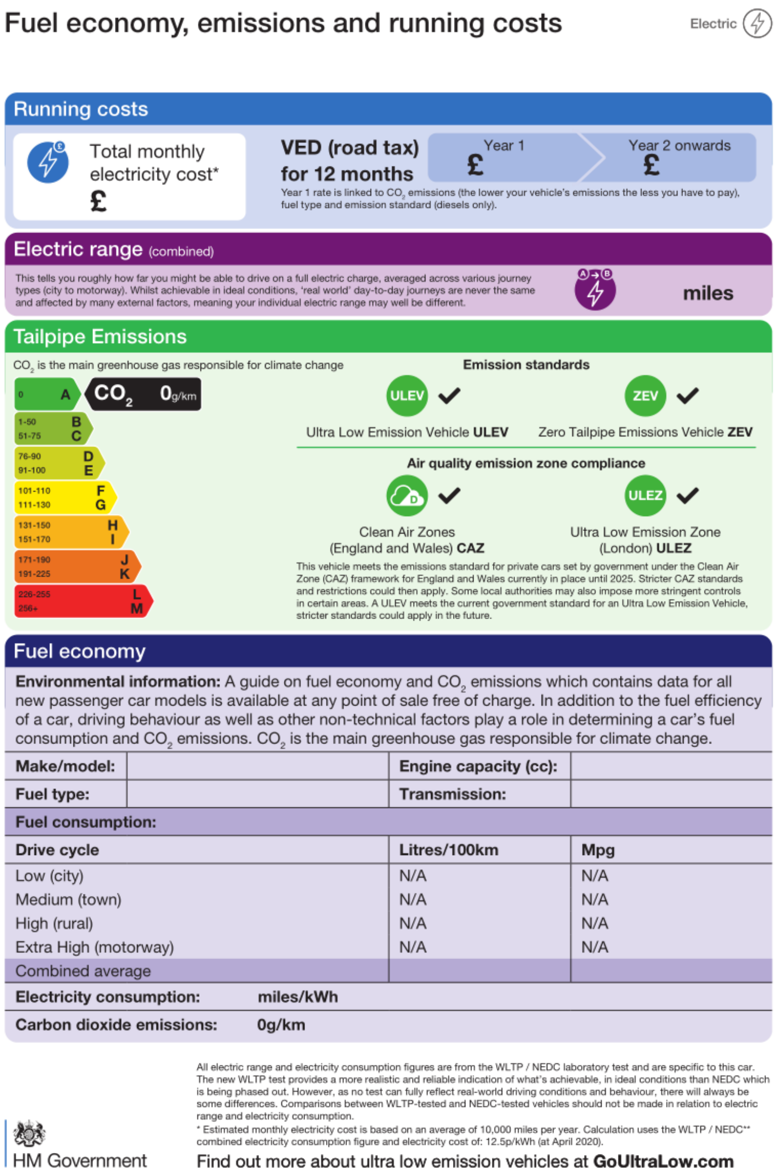


Figure 40. Example of vehicle fuel consumption label.

As discussed previously, systematic mobility is set for routine use on weekdays, therefore the vast majority of trips are between workplace and home, and are assumed to be within the city. Thus, energy consumption for the EV under city road conditions is considered. Conversely, cars used for unsystematic mobility on weekends are likely to experience longer trips, thus the energy consumption for an EV under combined road conditions is used. In these conditions, part of the trip is assumed to be on the highway, the remainder is in the city. Hence the energy consumption of a trip may calculate by:

$$E_{trip} = \frac{D}{U_{EV}} \tag{31}$$

Where E_{trip} is the trip energy consumption in kilowatt-hour (kWh), and is equal to the distance travelled (D) in miles divided by EV energy consumption figure, U_{EV}, in the unit of miles/kWh.

Make:	Mitsubishi		
Model:	Outlander PHEV		
Battery capacity:	13.8 kWh		
Battery Useable:	11.0 kWh		
Rated* electric range:	28 miles		
Rated* energy consumption:	3.68 miles/kWh		
UKEVDB real range:	23 miles		
UKEVDB real consumption:	City - cold weather: 440 Wh/mile	Highway - cold weather: 685 Wh/mile	Combined - cold weather: 550 Wh/mile
	City - mild weather: 365 Wh/mile	Highway - mild weather: 550 Wh/mile	Combined - mild weather: 440 Wh/mile

Table 13. EV information from UKEVDB

In order to validate these assumptions on typically calculated trip consumption, trips made between my supervisor's home to the university car park were monitored. The vehicle used for validation is a Mitsubishi Outlander PHEV. Vehicle information from UKEVDB is concluded in Table 13 [115]. The rated figure represents the official WLTP rating published by the manufacturer, where WLTP stands for The Worldwide

Harmonized Light Vehicle Test Procedure, it is a test to establish official figures of vehicle fuel consumption and CO_2 emission before new cars go into the market. The Outlander PHEV has three modes: fuel-driven mode, hybrid mode and pure electric mode. The route information was recorded using an application called Ultra GPS logger on a GPS enabled Android phone, the phone is placed in the EV during each measurement. The exported data file shows the location in longitude and latitude on a real time basis, the altitude is also measured to indicate whether the EV is climbing uphill or going downhill [116].To compare the EV real consumption for each mile of trip with the UKEVDB figure, the vehicle is set to drive in pure electric mode. The routes are illustrated in Google maps, shown as Figure 41. Trip A, of 8.1 miles from workplace to home, was made on week 9 2018 in Sheffield. The trip started at 16:30 and arrived at 17:01. The duration of the trip is 30 minutes 52 seconds. The measured energy consumption of this trip is 3.34 kWh, and from Equation (31),

$$U_{EV} = \frac{8.1}{3.34} = 2.43\, miles/kWh \tag{32}$$

Transform the calculated U_{EV} into the unit of watt-hour per mile, it gives a figure of 412 Wh/mile. Moreover, Figure 42 shows a different trip from the home to the workspace, the total distance driven is 7.7 miles through a different route. Trip B originated from home at 07:00 and arrived at university car park at 07:31, the duration is 30 minutes 58 seconds. However, the energy consumption is higher for shorter distance, it consumed 3.54 kWh. The EV consumption is derived from Equation (32):

$$U_{EV} = \frac{7.7}{3.54} = 2.18\, miles/kWh \tag{33}$$

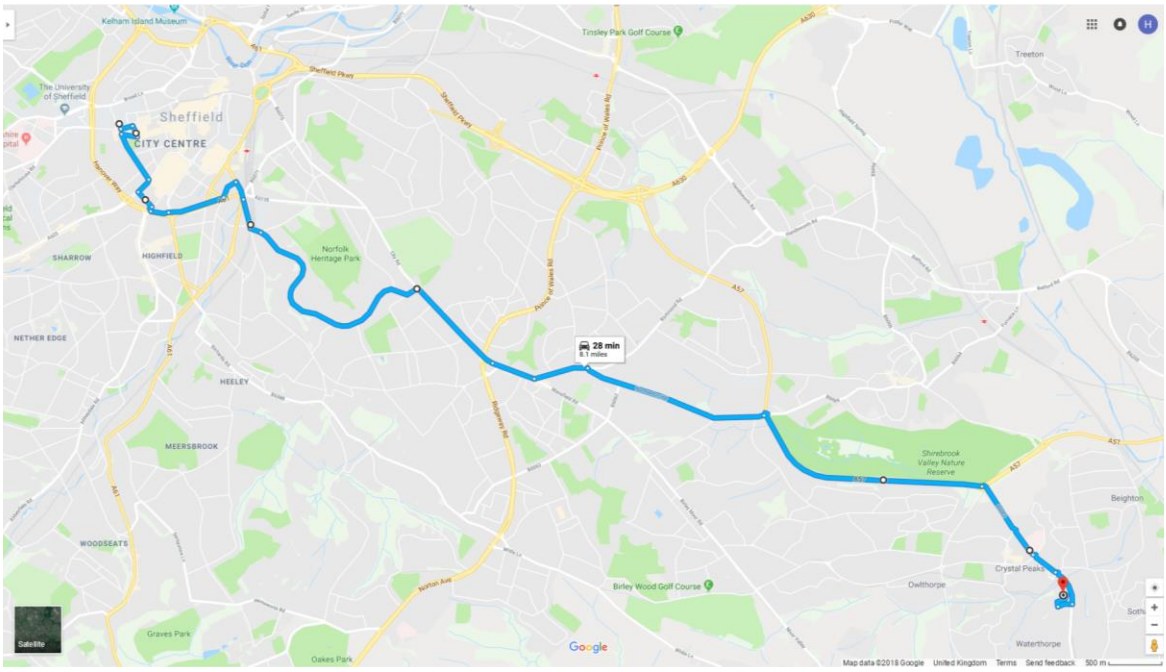


Figure 41. Trip A route from work to home.

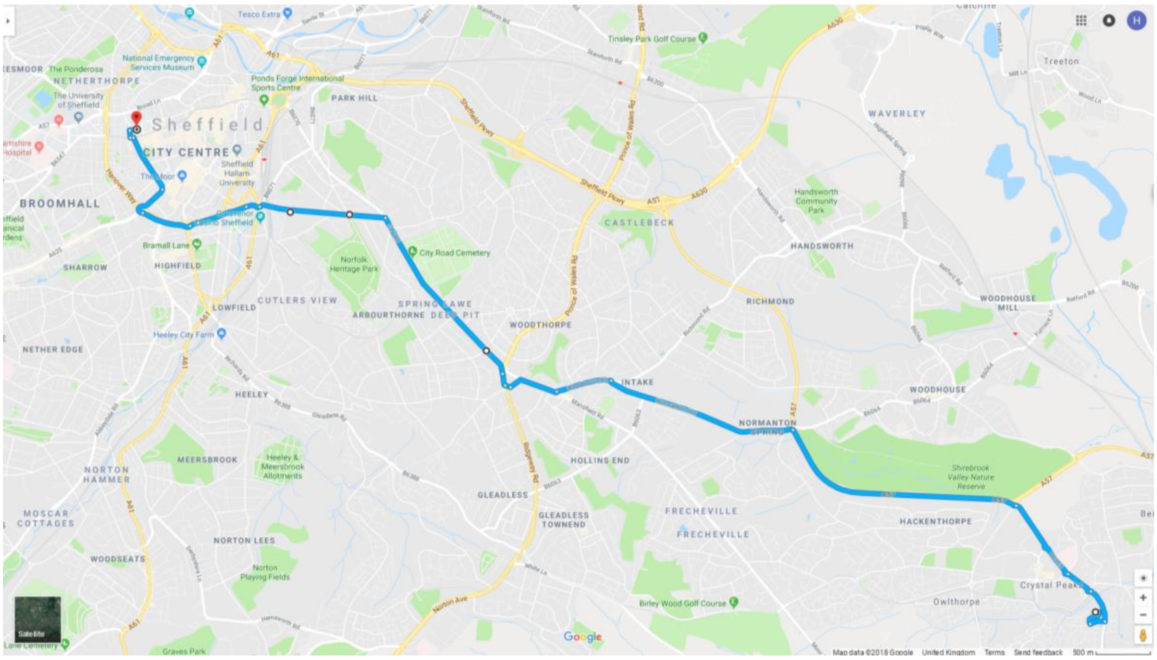
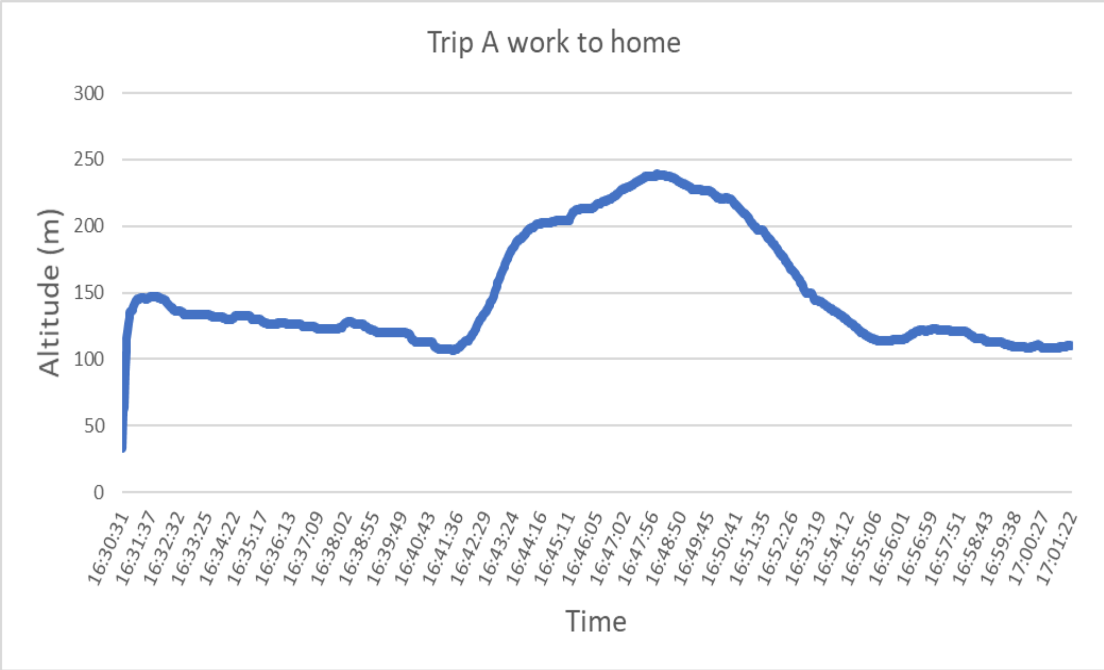
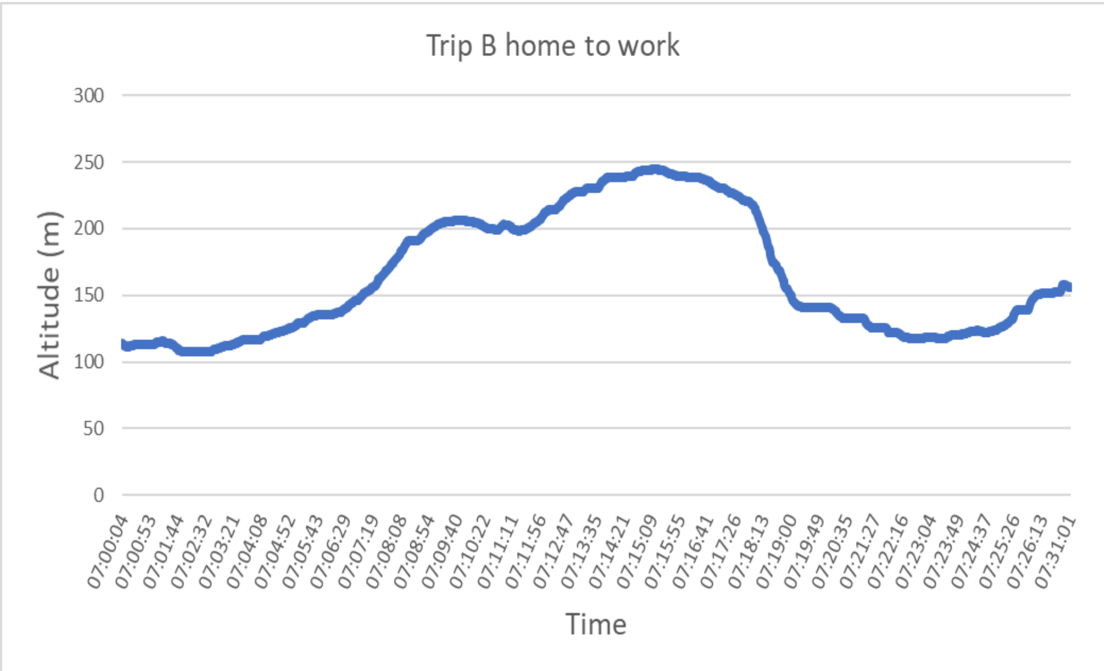


Figure 42. Trip B route from home to work.



(a)



(b)

Figure 43. Altitude changes with time for trip A (a) and trip B (b)

From the information provided in the logger data file, shown in Figure 43, the altitude change for both trips can be compared. The error shown in Figure 43(a) at the beginning of the plot is a result of poor satellite signal from indoor parking. It appears that trip B has longer climbing time than trip A, the distance travelled when EV is going uphill according to the relevant time step is 4.1 miles for trip B comparing with 2.2 miles of that of trip A. The longer uphill journey travelled leads to higher energy consumed. Lower energy consumption for longer distance travelled in trip A can be explained by longer downhill journey, which the EV uses less energy to drive along with more frequent use of brake that recharge the battery via its regenerative braking system.

The experiment was undertaken in a typical cold day as the average ambient temperature of the day is 6℃ [117], and the trips are made on city roads. From the UKEVDB, the standard consumption of the vehicle used for comparison is 440 Wh/mile for city-cold weather from Table 13. Calculate the average of measured EV consumption, gives:

$$U_{EVavg} = (460 + 412) \div 2 = 436 \text{ Wh/mile} \quad (34)$$

This number is very close to 440 Wh/mile, considering the fact that the city of Sheffield has a lot of hills, and the trip consumption of driving in the city varies as a direct consequence of it. Other factors like heating, driver’s behaviour, and traffic conditions could also influence the trip consumption. Thus, the UKEVDB real consumption for EVs are considered to be reasonable and are used in this study.

4.3 System modelling

4.3.1 Domestic energy flow sequence

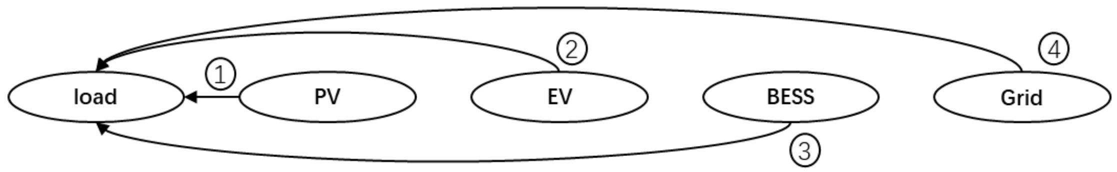


Figure 44. Energy dispatching sequence from load point of view

Following on from the advanced BEMS developed in Chapter 3, here, V2H and V2G are considered to be added into the system to form a comprehensive BEMS. Within the domestic environment, both V2H and V2G are intended to use the EV battery as an extension to the stationary BESS, and connect to the household AC bus via a bidirectional charger, where BEMS is controlling the energy flows between various energy sources and loads within the household. With the EV integrated into the household, from Figure 44, the curved arrows represent the energy flows following the sequential order presented in the circle. The load energy requirement is supplied firstly by PV production, then the energy stored in the EV battery if it is available (e.g. EV is plugged in and has energy left in its battery), the unmet demand requires discharging of the BESS afterward. The grid will cover the rest of the load. The benefit of this dispatching sequence is the domestic renewable energy will be fully exploited, household can achieve energy self-sufficiency at some times of year, which reduces the household bill costs, and make profit via energy export to the grid where possible.

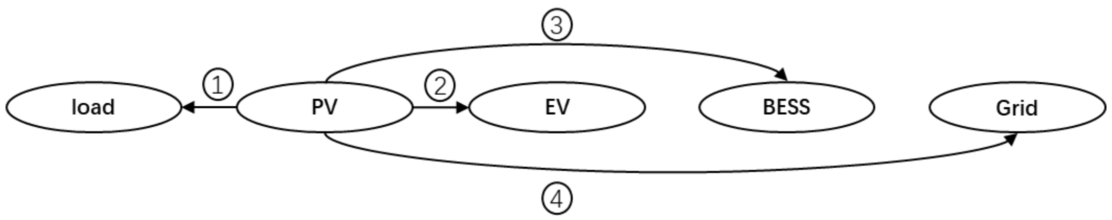


Figure 45. Energy flow from PV point of view

From the PV production point of view, the renewable energy generated is firstly used to support the household load, due to home appliances and lighting, then any surplus energy recharges the EV battery and the BESS in sequence, but the EV has to be plugged into the V2H charger for this to happen, as shown in Figure 45. In the case of either the EV being fully charged, or unavailable, if the BESS is fully charged, the excess energy is exported to support the grid and make profit from the export tariff.

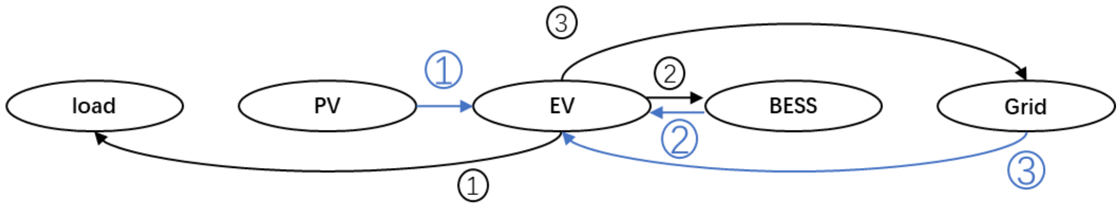


Figure 46. Energy flow from EV point of view

The EV is normally charged overnight at home during Economy 7 off-peak hours if grid energy is used, where the electricity price is around 1/3 of the peak hour's tariff. The comprehensive BEMS ensures the EV uses grid energy to charge to a certain pre-programmed SOC, which is set to be sufficient for the current day's (d) use. In charging mode, as shown in Figure 46, blue arrows and following the sequence presented in blue circles, EV is trying to absorb surplus energy from PV system at the first when it is able to, then it will be charged by the energy provided by the BESS if desired. At the end, if both of the two sources are not enough or unavailable to recharge the EV, EV is charged by grid electricity. Since the EV is used to travel from home to work during the daytime, it cannot provide energy storage for excess PV energy, or V2H and V2G in this period. Thus, only when the vehicle returns home and reconnects to the charging equipment, can it then use any remaining energy in the EV battery for those operations. In the case of the EV is at home during the daytime, in EV discharging mode as presented in black curved arrows, the EV battery can be used as a supplemental stationary energy store, and it can either support the load or recharge the BESS in sequence following the order presented in black circles. Moreover, the EV battery can discharge energy into the grid during high demand periods to perform V2G if energy self-sufficiency is achieved in the household, and the energy in the EV battery is not depleted to its minimum allowed SOC.

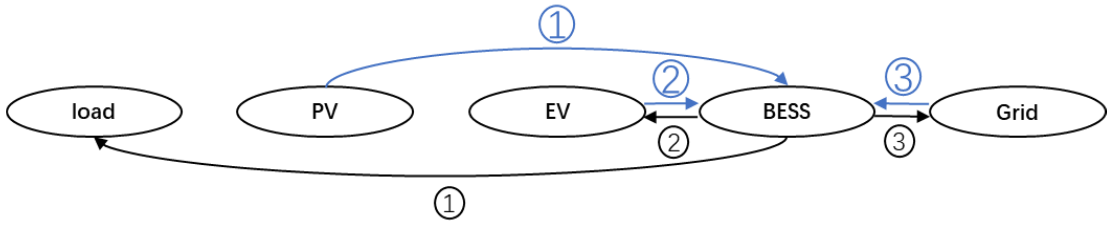


Figure 47. Energy flow from BESS point of view

Figure 47 illustrates the energy flow from household BESS point of view, blue arrows show the charging sequence for the BESS and black arrows show the discharging sequence. The diagram shows the BESS is charged from PV in preference to the EV and the grid. Surplus PV energy is therefore stored in the BESS for later load use. If energy in the EV battery is higher than the targeted value, BESS will also store that extra energy if BEMS allows it to do. Grid energy is stored in the battery during low tariff periods to support the periods of load during periods of high tariff, in order to minimize the bill cost. Once charged, the BESS discharges to provide energy to the load in the sequence described above, followed by the EV battery as a load, and finally, the grid. For instance, if the load is fully covered by renewable energy generation, and the EV is also fully charged by it, or unavailable (e.g., unplugged or left home) at certain time step, then the BESS is used to store the excess PV energy for late use or export (during high export tariff periods). The export of energy also helps in removing the peak demand on the grid.

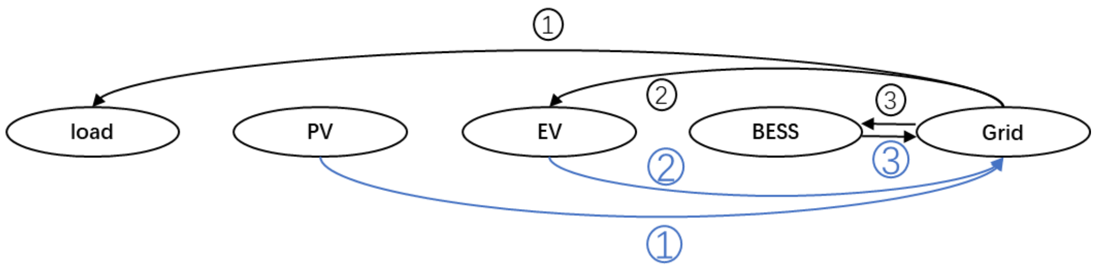


Figure 48. Energy flow from grid point of view

Finally, from the grid point of view, in order to accomplish domestic energy self-sufficiency, the use of grid energy should be minimised, or be as cheap as possible. Therefore, under the Economy 7 tariff scheme, it is better to move all energy consumed from the grid to Economy 7 off-peak hours which the grid is less loaded and the electricity price is cheaper. Hence, in the summer time, where PV production is higher than in winter due to the longer daytime, if given PV array can provide more energy than the daily load requirement, then, the combination of EV battery and BESS can store the renewable overproduction for later use as well as saving enough energy for next day utilisation of the vehicle. Fully exploited renewable energy could potentially reduce the energy import from the grid to zero, thereby achieve energy self-sufficiency. But in winter, due to shorter daylight hours, and increasing demand on heating, the renewable energy generation is not able to cover the daily load, thus, EV battery and BESS are more likely to store off peak grid energy for household use, at the cheaper rate.

4.3.2 Battery aging modelling

Due to increasing volume and maturity of battery and material manufacturing, battery cell prices fell by 87% between 2010 and 2019 [118], Li-ion cells became one of the most common batteries used in the electric vehicles and stationary storage systems because of their characteristics of long life, efficiency and operation. Although battery use is becoming popular in a number of applications, the aging effects of the cells result in battery capacity degradation causing the long-term replacement cost of the battery's use to rise [119]. Thus, it is necessary to integrate aging effects into the system modelling to analyse the overall economic performance of a system.

Battery life is normally categorised by run time, calendar life and cycle life [120]. Battery run time is defined as the time elapsed in depleting a fully charged battery under a given load [121]. Factors affecting battery run time are current drawn by the device connected, physical condition of the battery and the system complexity. High load might be incurred by more complex system due to the use of inverters and wiring for connecting every component, thus reducing the run time. Battery calendar life is defined as the duration over which a battery remains usable, namely before the battery capacity degrades to 80% of its manufactured capacity. It doesn't matter if the battery is used or not during this period, as its aging is affected by the ambient temperature and time [122]. While cycle life is the number of complete charge-discharge cycles a battery can undergo before is operational capacity degrades to 80% of its initial capacity. It is mainly affected by the number of cycles done and the depth of discharge (DoD) of each cycle [123].

The aging mechanism of a battery is due to parasitic reactions taking place within the cells, using the active materials in the battery. The aging is often characterised as the appearance of unfavourable chemical or physical changes, as well as loss of active lithium in lithium-ion battery cells. Additionally, the degraded cells also exhibit electrolyte oxidation and capacity fade [124]. These transformations are irreversible. In this study, cycle life is more of a concern than the battery calendar life, due to both EV and BESS batteries being more likely to undergo deep-cycle operations each day, but both degradation mechanisms are accounted for in the model. The relationship between cycle life (N_{cycle}) and depth of discharge (DoD) can be obtained from Equation (35) [125],

$$N_{cycle} = a \times \left(\frac{DoD(\%)}{14571}\right)^{\frac{1}{-0.6844}} \tag{35}$$

Where a is the cell life constant, and varies for each battery. In this study, the BESS uses a battery with 6000+ life cycles at 90% depth of discharge, and the EV battery is expected to last longer than 15 years or more than 6000 cycles. Thus, both the EV and the BESS battery are considered to have 6000 life cycles at 90% DoD. Given the depth of discharge and its relevant cycle life, thus a can be calculated for the batteries chosen from Equation (35) as:

$$6000 = a \times \left(\frac{90}{14571}\right)^{\frac{1}{-0.6844}}$$

$$a = 3.55 \tag{36}$$

Thus Equation (35) can be rewritten as:

$$N_{cycle} = 3.55 \times \left(\frac{DoD(\%)}{14571}\right)^{\frac{1}{-0.6844}} \quad (37)$$

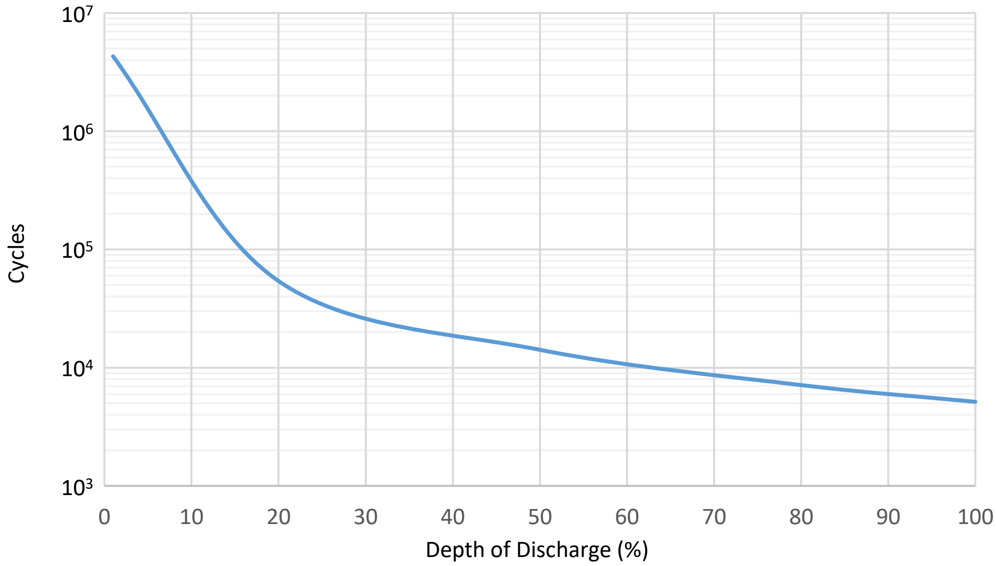


Figure 49. S-N curve of battery cycle life against depth of discharge for Li-ion battery

A plot of S-N curve in Figure 49 is used to visualize the cycling aging trend of the battery. The calculated battery cycle life is different depending on the exact DOD of the battery on each day. As in operation, the battery depth of discharge per cycle is different every day, it is not simple to predict the cycle life of the battery in this way. Coulombic efficiency (CE) is therefore introduced as an approach to determine how much capacity is lost during each charge-discharge cycle, in order to estimate the total battery capacity degradation after a year of operation. The equation of CE is:

$$\eta_{CE} = \frac{E_{discharge}}{E_{charge}} \quad (38)$$

Where $E_{discharge}$ is the capacity of discharge at the end of a single cycle, E_{charge} is the capacity of charge at the start of the cycle. η_{CE} represents how much the charge capacity remaining after completing a full charging and discharging cycle. In the example of a specified battery cell which has a cycle life of 1000, it represents that the battery is expected to lose 20% of its capacity by the end of 1000 charging-discharging cycles. So, the battery cell will lose $\frac{20\%}{1000} = 0.02\%$ of its total capacity for each full charging-discharging cycle completed. Hence $\eta_{CE} = \frac{100\% - 0.02\%}{100\%} = 99.98\%$, Equation (38) can also be modified to:

$$\eta_{CE} = 1 - \frac{20\%}{N_{cycle}} \quad (39)$$

Where N is the cycle life from Equation (37). Coulombic inefficiency (CI) in the opposite way explains how much charge capacity is lost after completing a full cycle. From the Equation (40), $\eta_{CI} = 0.02\%$ for the above example.

$$\eta_{CI} = 1 - \eta_{CE} = \frac{20\%}{N_{cycle}} \quad (40)$$

Since the use of both the EV battery and the BESS are different for each day, as a result, to precisely integrate the battery degradation into the model, Equation (41) is used to calculate the overall battery capacity loss throughout a year, n represents the number of cycles done in a year.

$$E_{loss} = \sum_{1}^{N} \eta_{CI} \times E_{battery} \quad (41)$$

Total capacity loss (E_{loss}) is the accumulation of every day's charge capacity degradation. When taken over a long timeframe such as a year, it gives a reasonable representation of the battery aging. The total loss can be then used to determine whether the system performance is satisfied. CL is calculated for both the EV and BESS batteries, the figures obtained will be evaluated in the result section.

Moreover, as previously described, the levelized cost of energy (LCOE) for battery storage can be derived from the following equation [126], LCOE is defined as the total investment cost of a system over its lifetime divided by the cumulative energy delivered throughout its lifetime.

$$LCOE = \frac{total\ lifetime\ cost}{total\ energy\ delivered} \quad (42)$$

Equation (42) can be rearranged into an expression of battery degradation cost per unit of energy [96]:

$$P_{degradation} = \frac{(P_{battery}+P_{install})}{(N_{cycle}\times E_{battery}\times DoD)} \quad (43)$$

$P_{degradation}$ is battery replacement cost, and as the total cost for replacing a battery includes installation labour cost ($P_{install}$) for hiring certified electrician, the total lifetime costs become $(P_{battery} + P_{install})$. N_{cycle} is the life cycle of the battery which varies according to DoD in percentage, E is the battery capacity in kWh and DoD is the depth of discharge. Labour cost for replacing battery and hard wiring the circuit is around £80 in Sheffield local area [97][98][99], for example. The total cost divided by total energy delivered throughout its life time, gives the degradation cost for each kWh of energy used. Thus, degradation cost per unit of energy multiply by the energy delivered per cycle gives degradation cost per cycle:

$$P_{degradation}(N) = P_{degradation} \times E_{battery} \times DoD \quad (44)$$

From this, the cumulative degradation cost throughout a year can be derived from:

$$P_{degrad\_total}(N) = \sum_{1}^{N} P_{degradation}(N) \quad (45)$$

Based on the equations illustrated above, battery aging model was applied to both the BESS battery and EV battery within the domestic energy system modelled in this work, to precisely evaluate the system ROI over years with real cost considered.

4.3.3 BEMS Control schemes of EV battery

In this thesis, a Mitsubishi Outlander PHEV is combined with the domestic energy storage system to form a comprehensive BEMS. The usable electric capacity of the vehicle is 11 kWh. To date, it only supports type 1 charging in which charging power is limited to 3.7 kW by its onboard charger when connecting to the alternating current (AC) grid, this limitation applies to electrical charging from the grid, PV generation and the BESS. The discharging rate is also taken as being commensurate with this rate, therefore 3.7 kW is taken as the maximum power at which the vehicle can deliver energy from EV battery to the domestic load. A typical type 1 3.6 kW EV charger on the market costs £779 [127], but the government office for low emission vehicles (OLEV) provides £500 grant on approved home charging point, which lowering the cost to £279 plus installation cost. Theoretically, V2H and V2G technology need a bi-directional EV charger to enable both charging and discharging functions for the EV. However, this type of charger is not yet ready for mass production, the latest news indicate that Wallbox published their first V2G charger in September 2020 [128], and a UK based company named "Volta Charge Points Ltd" recently releases the price of the charger is £5628 [129]. It is foreseeable that the cost of such a system is not cheap on the first 3-5 years on the market, the price might go down to an affordable value after mass production. Thus, charging equipment cost is assumed £279 in this research. Due to the logarithmic characteristic curve of charging for Li-ion battery, the actual charging time is not equal to energy divided by power. The charging time of the Mitsubishi Outlander PHEV from empty to full is typically 3.5 hours.

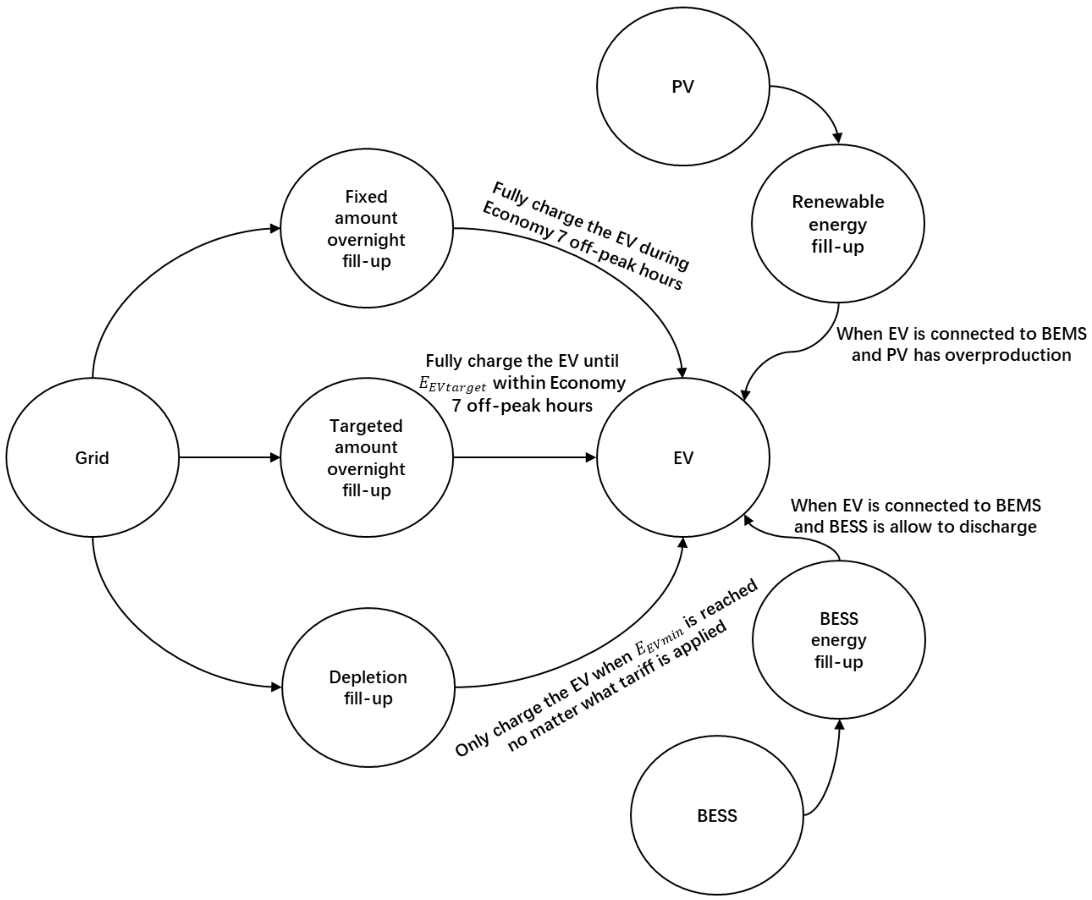


Figure 50. State machine for EV charging schemes

The actual implementation of V2H and V2G needs a series of complex control scheme for charging and discharging the EV battery. Following the drive pattern illustrated earlier, a typical 'employed' household will drive the EV away from home to work at 8:00 and return home at 18:00 on working days, the time interval between these two times being defined as typical daytime. It is important to make sure there's enough energy in the EV battery to cover the trips undertaken in this period. There are five types of charging schemes assessed for the EV battery as shown in Figure 50:

a) Fixed amount overnight fill-up:
   The EV is fully charged to 100% of its SOC using the grid energy overnight no matter whether the vehicle is expected to be used or not.
b) Targeted amount overnight fill-up:
   The EV is charged to a targeted amount of SOC using the grid energy in night-time, the targeted SOC varies according to the prediction of the next day's usage.
c) Depletion fill-up:
   The EV is not charged until the battery SOC drops to or below the minimum SOC, normally set as 10% to prevent sudden change in demand and shorten its life cycle due to a deep-cycle event. It then uses grid energy to charge the battery.
d) Renewable energy fill-up:
   The EV is charged by PV production, this only happens when EV is parked at home and connected to V2G charger. Also, the domestic load needs to be fully covered by renewable energy before charging of the EV can occur.
e) BESS energy fill-up:
   The EV is charged using the household BESS. This only happens when BESS has enough energy stored to cover overnight household consumption. This condition mostly happens in summer time, where there's a large amount of renewable energy overproduction stored in the BESS during the day.

The first 3 of these schemes require energy import from the grid. Fixed amount charging has the benefit that the EV will always have enough energy every day to cover any unexpected travel, but this charging scheme has a dramatic drawback which does not help attain energy self-sufficiency. For example, when the amount of PV energy exceeds the load demand on a typical sunny summer's day, excess renewable energy fills up the BESS which then might be able to recharge the EV fully using the surplus PV energy to cover next day's EV trips. However, fixed amount overnight charging scheme only allows EV battery to be charged by the grid energy, which is not possible to maintain energy self-sufficiency, placing a charging cost on the household.

At the other extreme, the depletion fill-up scheme only charges the EV when the battery SOC falls below the minimum SOC (E_{EVmin}), this type of charging scheme is not user-friendly as there is an increasing possibility that user needs to find a commercial charging point to fill up the EV due to insufficient energy for the upcoming trip. According to the tariff from Shell [130], the recharge cost for using their EV charger is 39 p/kWh, which is more than double that of the home electricity tariff. Hence this charging scheme is not convenient and economical for the EV owner. This research therefore focuses on the EV targeted amount overnight fill-up in combination with renewable energy, and BESS energy charging schemes, on both weekdays and weekends.

The EV is unable to interact with the domestic energy system when it is not plugged in. Therefore, PV overproduction can only be stored in the BESS or directly export to grid if the BESS is fully charged, whereas when the EV is at home and plugged into V2G charger, the EV battery is able to act as an extended stationary energy storage system alongside a household BESS. In order to obtain energy self-sufficiency in a domestic household with PV, BESS and EV integrated, the EV battery is not only used to store the PV overproduction when it is connected during the daytime, but also can pre-charge an extra amount of energy in night-time when tariff is low to cope with the intermittency of renewable energy or high load demand. A more comprehensive BEMS is developed, building on the system covered in the previous chapter, for taking all conditions into consideration. The proposed operating control system analyses the energy consumption information in a domestic household to forecast the energy usage pattern for next day, in addition, the desired target SOC of the EV battery is calculated, to be charged at the night-time, lower cost tariff where required.

The proposed comprehensive BEMS first evaluates the household load demand, three values can be extracted since the household is assumed using Economy 7 tariff: total energy demand (E_{loadT}), Economy 7 peak hour demand (E_{loadpk}) and Economy 7 off-peak hour demand ((E_{loadop}). Accordingly, for PV generation, total renewable energy generated during the Economy 7 peak hours (E_{sunpk}), and that of the whole day (E_{sunT}) is also extracted for evaluation. Daily and peak hour non-renewable energy demands are defined in Equation (46) and (47) respectively.

$$E_{netT} = E_{loadT} - E_{sunT} \tag{46}$$

$$E_{netpk} = E_{loadpk} - E_{sunpk} \tag{47}$$

Where E_{loadT} is total daily load demand, E_{sunT} is total daily PV generation, E_{netT} is daily non-renewable energy required from BESS, EV or grid. Similarly, E_{loadpk} represents load total energy demand during Economy 7 peak hours, E_{sunpk} is total PV generation during those peak hours, E_{netpk} is therefore the non-renewable energy required from other energy sources within the Economy peak hours.

Defining E_{conpk} as the energy required from the grid with the domestic energy system installed within Economy 7 peak hours, it is therefore equal to:

$$E_{conpk} = E_{netpk} - E_{battery} - \left(E_{EVtarget} - E_{EV}\right) \tag{48}$$

Where $E_{battery}$ is the energy stored in the BESS (kWh), $E_{EVtarget}$ is the targeted amount of energy required from the grid to charge the EV battery overnight (kWh), and E_{EV} is total energy consumed by EV for trips made in a day (kWh). The targeted amount of EV battery energy minus the actual usage of the day, gives how much energy is left in the EV battery when vehicle returns home. E_{EV} can be calculated from Equation (31):

$$E_{EV} = \sum E_{trip} \tag{49}$$

Equation (50) shows due to E_{net} in the domestic energy system during Economy 7 peak hours and the total trip consumption of EV (E_{EV}) are certain for a specific day, minimum value of E_{conpk} is only reached when BESS is fully charged to have maximum capacity, and the EV battery is charged to 100% SOC before making trips which obtains maximum leftover energy when EV is plugged back. When E_{BESS} is at its maximum value $(E_{BESS})_{\max}$, term $E_{netpk} - E_{BESS}$ is at its minimum value, and when EV battery is fully charged, the second term $E_{EVtarget} - E_{EV}$ is at its maximum value. Therefore, E_{conpk} would achieve the minimum value.

$$\left(E_{conpk}\right)_{\min} = E_{netpk} - (E_{BESS})_{\max} - \left((E_{EVtarget})_{\max} - E_{EV}\right) \tag{50}$$

Based on the previously discussed EV battery charging schemes, the targeted amount of energy to store in the EV battery is determined at the start of the current day (d) dependent on four conditions based on previous day's (d-1) information, the decision criteria are shown in the flow chart in Figure 51.

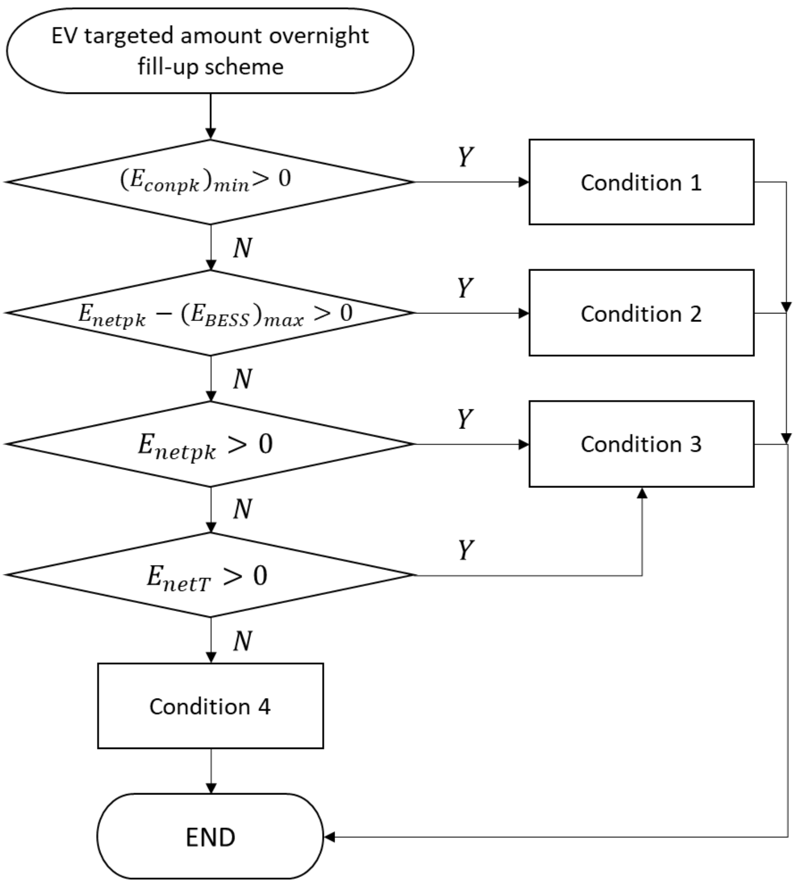


Figure 51. Decision criteria flow chart for EV targeted amount overnight fill-up scheme

Condition 1 is when $\left(E_{conpk}(d-1)\right)_{\min} > 0$. The peak period load cannot be supplied by the domestic energy system alone, including the PV production, a fully charged BESS, and the maximum leftover energy in the EV battery when it plugs back to the charger. This condition typically occurs in winter, where shorter sunshine hours result in lower PV production, while lower ambient temperature results in high load demand due to heating. The mismatch between renewable energy generation and load demand needs the BESS and the EV battery to store as much energy as possible when the electricity tariff is low, then feed this energy back to the load during Economy 7 peak hours, in order to minimize the electricity bill for the household. Under this criterion, the targeted value of EV battery charging is 100% SOC.

Condition 2 is when $\left(E_{conpk}(d-1)\right)_{\min} \leq 0$, $E_{netpk}(d-1) - (E_{BESS})_{\max} > 0$. Here, the peak period load can be supplied by the domestic energy system when a fully charged battery and the leftover energy in the EV battery are utilised. In this case, the EV battery is precharged to a targeted SOC within present day's Economy 7 off-peak hours to cover the daily drive and support domestic energy use, the targeted EV energy required for charge is calculated from:

$$E_{EVtarget}(d) = E_{EV} + \left(E_{netpk}(d-1) - (E_{BESS})_{\max}\right) \tag{51}$$

Condition 3 is when $\left(E_{conpk}(d-1)\right)_{\min} \leq 0$, $E_{netpk}(d-1) - (E_{BESS})_{\max} \leq 0$ and $E_{netpk}(d-1) > 0$. Although the renewable PV energy generation is not enough to cover the load during peak period, but the load can be covered by an extra energy from the precharged BESS. In this case, the EV doesn't need to provide extra energy to support the load for this condition. Thus, energy charged to the EV battery within Economy 7 off-peak hours only needs to fully support the daily EV trips, which gives:

$$E_{EVtarget}(d) = E_{EV} \tag{52}$$

Same condition applies to when $E_{netpk}(d-1) \leq 0$ and $E_{netT}(d-1) > 0$. A zero or negative number for the non-renewable energy required by the load during the peak period means that the PV energy matches the load or is overproducing. As a result, the BESS doesn't need to precharge within Economy 7 off-peak hours, but is used to store any surplus PV generated energy within Economy 7 peak hours. However, since the total daily PV production is less than the daily load demand, there is not enough PV generated energy to recharge the EV battery, hence, the targeted value of charging equals to the energy consumed for daily trips, same as Equation (52), and is charged from the grid during off peak periods.

Condition 4 is when $\left(E_{conpk}\right)_{\min} \leq 0$, $E_{netpk} - (E_{BESS})_{\max} \leq 0$, $E_{netpk} \leq 0$ and $E_{netT} \leq 0$. Here, the household daily electricity consumption is fully provided by renewable PV energy generation, it happens typically in summer when heating is not in use, and longer sunshine duration produces large amounts of energy. If the electric vehicle is away from home during the daytime, the excess energy is only stored in BESS. The available energy $E_{BESS\_available}$ for EV recharging using stored BESS energy is therefore:

$$E_{BESS\_available} = E_{BESS\_EV} - E_{loadop} \tag{53}$$

Where E_{BESS_EV} is the energy stored in BESS when the EV is connected to the V2H charger (Wh), E_{loadop} is the household Economy 7 off-peak load demand (Wh). This is because the domestic energy flow sequence defines supporting load demand is the top priority among others. Defining $E_{surplus}$ as the available surplus energy produced by the PV system from the time the EV plugs into the system, until the end of the day (Wh), Then energy required from the grid to charge the EV overnight is defined as:

$$E_{EVtarget} = E_{EV} - E_{surplus} - E_{BESS\_available} \tag{54}$$

On the other hand, when the EV is parked at home during the daytime, the energy flow sequence defines the excess PV energy as recharging the EV first until it is fully charged, then the rest of the energy is directed to the BESS battery. Thus,

$$E_{EVtarget} = E_{EV} - E_{surplus} \tag{55}$$

Few constraints are made on the EV targeted value, the range of it is within 0% - 100% battery SOC. Any calculated $E_{EVtarget}$ is bounded between its maximum and minimum capacity, if a negative number shows, which implies the EV is fully charged by renewable PV energy, the actual energy required from the grid is 0, thus the value of

$E_{EVtarget}$ is bounded to 0. Meanwhile, if the calculated value is larger than its maximum capacity, which implies the EV battery needs to be fully charged by grid energy, the target is bounded to equal the battery maximum capacity.

The discharging control for the EV battery is restricted to a number of factors: discharging rate, the remaining energy in EV battery, the minimum SOC target allowed to discharge to, and predicted next day usage. Same as charging, the rate of discharging is assumed to be 3.6 kW depending on the charger used. Following the energy flow sequence from the EV point of view, the leftover energy in its battery engages to support the load demand during peak periods, the minimum depth of discharge the EV can discharge to is set as 10% to prevent fast degradation of the battery capacity. If the load demand is matched until the end of the day, and the remaining energy in EV battery is still higher than the targeted reserve for the next day's vehicle use, which usually happens when EV is not in use while storing a large amount of surplus energy during the daytime, it can then discharge to cover the early morning off-peak load period until the targeted reserve energy is achieved.

4.4 Results and discussion

4.4.1 Household case study

In Chapter 3, a domestic energy system with PV only and another with PV generation and BESS were introduced, the first one is controlled by benchmark BEMS while the second system is controlled by an advanced BEMS. In this Chapter, a domestic energy system with PV, BESS and EV is developed, it is controlled by comprehensive BEMS. The example of the modelling of a household load, and PV generation profiles for a single non-pensioner household from the previous chapter are used in this study. The reason of choosing this type of household for evaluation is because an employed household with an EV undertakes more regular travel than the other types of households, in which travel occurs between home and workplace on weekdays (Monday to Friday), and the taking of unsystematic trips such as shopping, leisure, visiting friends occurs at the weekend. Datasets are exported to Excel for coding with a BEMS control programme in VBA. A file of EV information is summarised and created in excel according to UKEVDB, the file digitizes the capacity, charging information, range and EV consumption of most EVs on the market for modelling use. A dashboard is created in Excel as shown in Figure 52, and this is the interface linked to the EV information file where users can select their personal EV. Users can modify their drive pattern, personalising their daily mileage and 'use time' for both weekdays and the weekend on it. Also, the 'cold weather' period is defined as from week 45 to week 9 in this study, according to the 2019-2020 calendar, but it varies for each year, therefore users are able to update this as required. There are 3 types of EV charger with different power ratings pre-set in the tool, which are 3.6 kW, 7 kW and 22 kW. Each of those having a corresponding equipment cost. The input typed into the dashboard sends corresponding EV details to the domestic energy system described previously, which is extended by integrating with the EV control scheme and battery aging model, a complete tool is constructed with comprehensive functions of modelling, payback time calculation and comparison.

As an example, to illustrate the system operation, a Mitsubishi Outlander PHEV with 11 kWh useable capacity and type 1 charging of 3.6 kW is selected. A daily trip distance is configured to 16 miles for working days and 10 miles for weekend travel. For any household without an EV, but having a BESS and PV installed, the Return on Investment (RoI) shows a minimum period when between 5 kWh and 6 kWh of BESS is installed, dependant on the PV array size. Thus, this case study is based on single non-pensioner household with a 5 kWh BESS, 4 kW PV array and the selected EV. Figure 53 (a) and (b) show the simulated PV generation and load profile for typical winter weekday and weekend respectively, along with EV charging scheme. Assume EV battery charging time is in linear with charging power as:

$$T_{charging} = \frac{E_{EVtarget}}{p_{charging}} \quad (56)$$

Where $P_{charging}$ is the power rating of the EV charger, in this case, 3.6 kW.

$T_{charging\_start}$ is used to define the start time of charging process, as shown in Equation (57). Where T_{end} is the target time of finish charging, in this study, all charging processes that require using grid energy are targeted to be finished within the Economy 7 off-peak hours, therefore, $T_{end} = 7am$.

$$T_{charging\_start} = T_{end} - T_{charging} \tag{57}$$

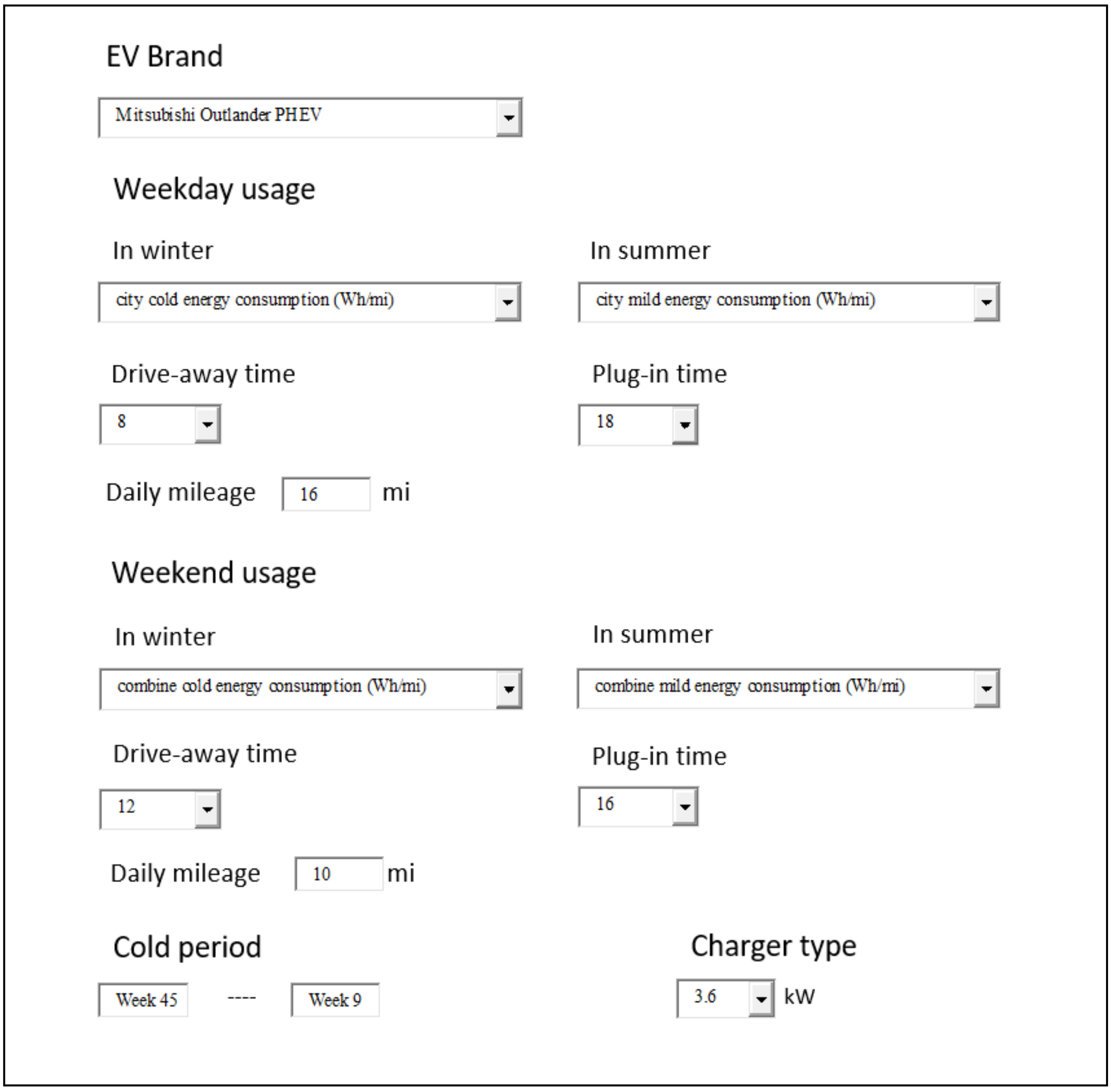
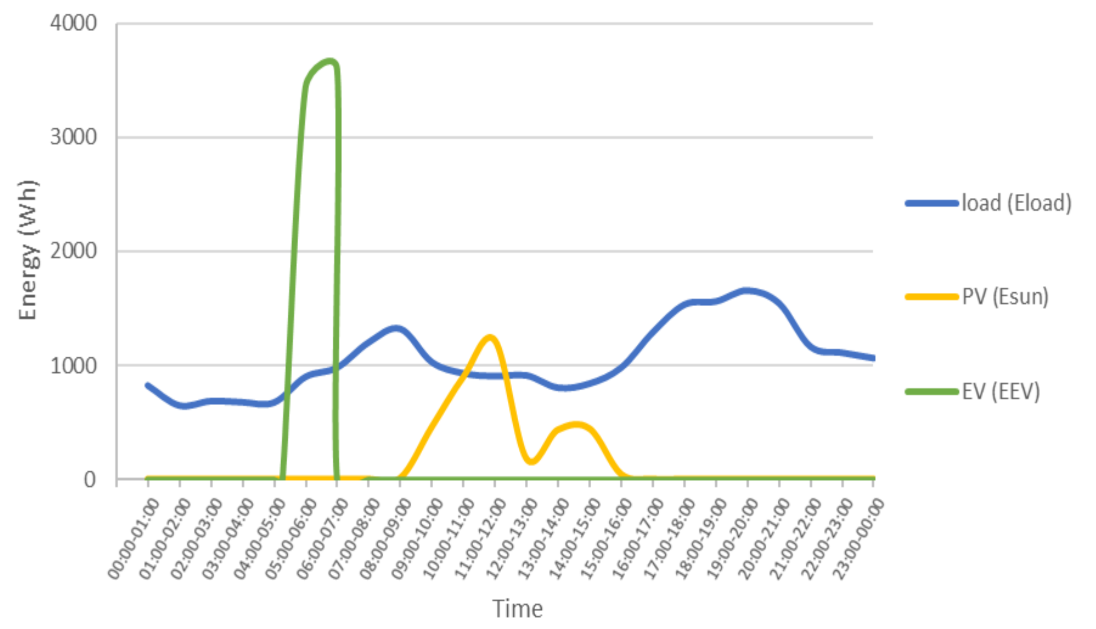


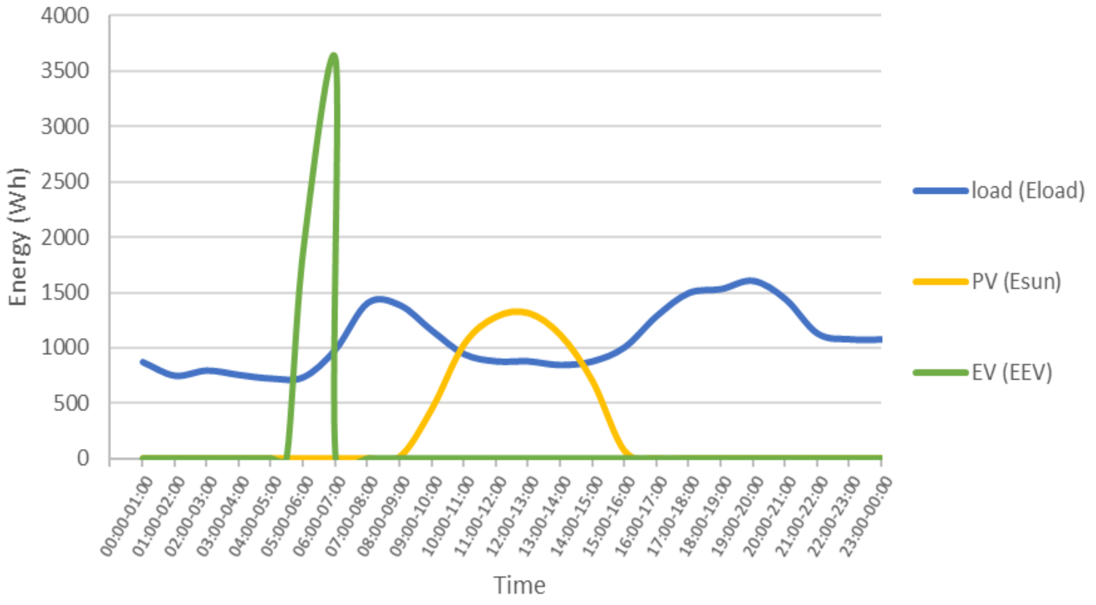
Figure 52. Dashboard of EV information input interface.

For winter weekday (1st Jan) overnight EV charging, a total of 7.04 kWh of energy is required from the grid. Thus, from (60), the starting time of the charging is at 5:02, and the charging duration lasts for nearly 2 hours, until Economy 7 low tariff period ends. Figure 53 (a) illustrates this. Moreover, for winter weekend overnight charging, a total of 5.5 kWh of energy is required, the less energy required, the later the charging starts. Thus, the green curve shown in Figure 53 (b) illustrates the charging process starting at

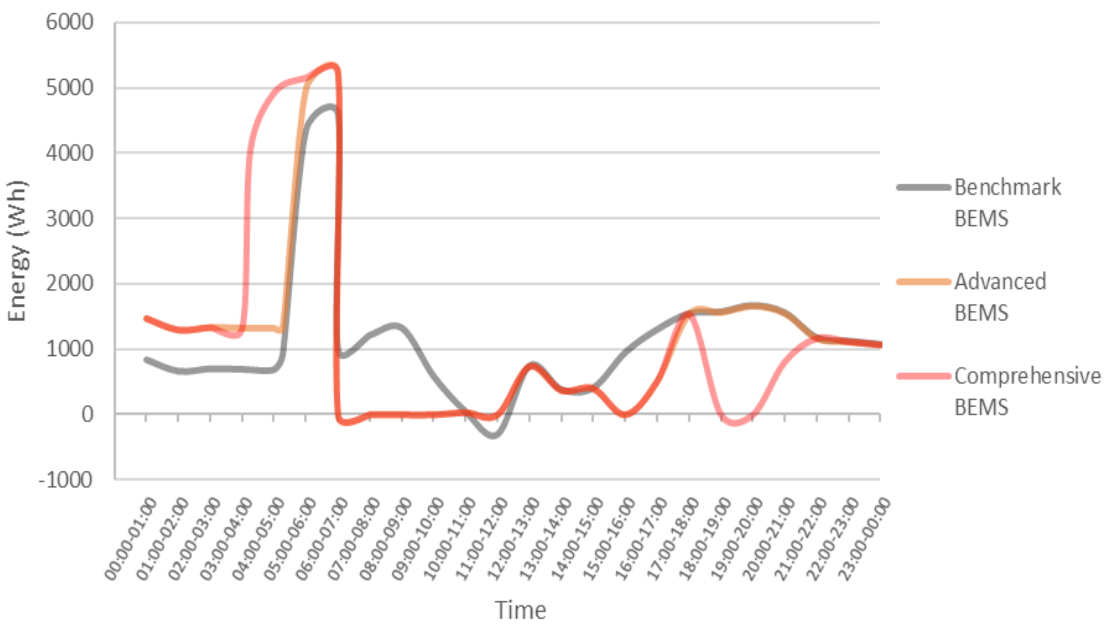
5:28 and lasting for 1 hour and 32 minutes. Both diagrams show that the maximum charging power is 3.6 kW, the charger rating.



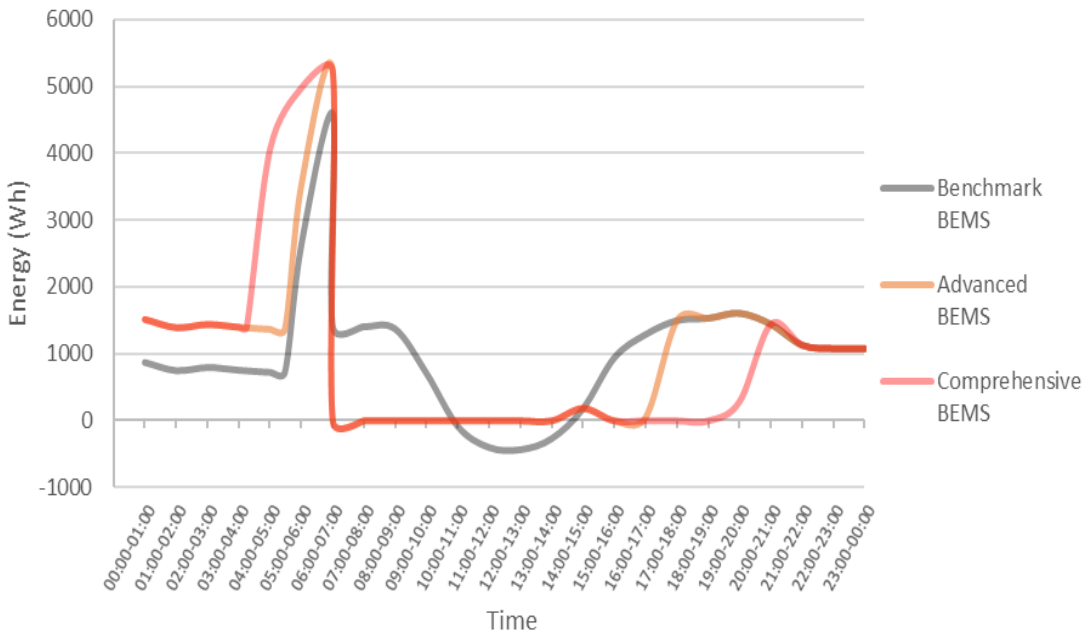
(a)



(b)



(c)



(d)

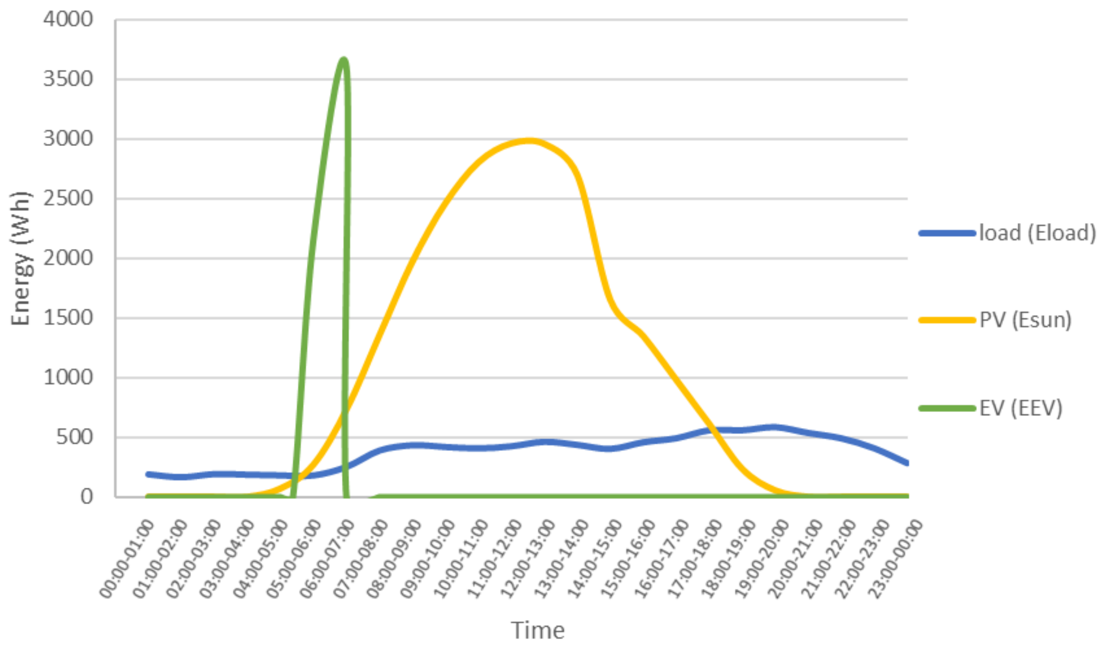
Figure 53. Performance of different domestic energy systems in winter weekday (a)(c) and weekend (b)(d).

Figure 53 (c) and (d) illustrates the performance of the domestic energy system for both working days and weekend days in week 1(2019-2020 calendar) in winter. Grey curves show the benchmark BEMS which only has PV system installed at home. The system uses PV energy to support the load consumption directly, any surplus energy is directly fed back to the grid in this case due to no energy storage equipment is installed. An EV is added to the system, which is charged to only have enough energy for daily trips (7.04 kWh for weekday and 5.5 kWh for weekend). The cost of electricity for household with this primary system on this specific winter working day is £4.08, and that on weekend day is £3.52. In addition, orange curves show the performance of the advanced BEMS, with the energy storage system installed, energy can then be pre-charged into BESS during the low tariff period for solar intermittency support and late load use, in order to lower the overall bill cost, moving the grid energy use from the high tariff period to the low tariff period. Energy used for EV charging is added, since the system doesn't have EV engaged for operation, the EV is only charged to a SOC to cover the daily required trips. The electricity cost for the household with this advanced system installed, including the EV, on a typical winter weekday is £3.46 and that on weekend day is reduced to £2.97, showing a reduction in costs of £0.62 and £0.55 respectively. Red curves represent the comprehensive BEMS with PV, BESS and EV, this comprehensive system enables the EV battery to be used as extended stationary storage in winter. Figure 53 (c) shows EV is fully charged to 100% SOC from 4:15 until 7:00. The EV battery require 9.9 kWh of energy to fully charge, since the minimum SoC the battery can discharge to is 10%, thus, it will have 1.1 kWh remaining in the battery before charging starts. Hence, the pre-charged EV battery further reduces the peak hour energy import from the grid supply, by removing the load demand from the grid completely between 18:00 to 20:00. Therefore, the cost of electricity on a winter weekday is reduced to £3.18. Unlike working days, people don't go to work on weekends, and the EV is parked at home for a longer time during the daytime, thus it has better V2H operation at weekends. Due to lower trip consumption for weekends, most energy stored in the EV battery can be engaged to support household load, thus, peak hour demand is shaved further during 17:00 to 20:00, and the cost of electricity bill on weekend is lowered to £2.49.

The simulation also illustrates summer operation. Figure 54 shows the system performance of the example domestic energy systems for a typical weekday, and during a weekend in summer time. The chosen samples are from week 27 of the year, where a week of sunny days result in maximum daily average PV production, while the average daily load consumption is the lowest. During summer, the PV overproduction occurs for almost every day, as PV overproduction is unable to be stored for later use with a benchmark BEMS lacking a BESS. The loads during the off-peak hours and evening still need grid energy import for summer working days illustrated by the grey curve shown in Figure 54 (c). These demands incur electricity costs even though the PV panels produced sufficient energy for self-consumption due to lack of energy storage in this example. In addition, the energy required for an EV to travel a total distance of 16 miles on summer working day is 5.84kWh, thus the daily cost of energy is £0.94 for this typical summer weekday. A similar simulation result occurs during a summer weekend day, shown in Figure 54 (d). Here the cost of the electricity used by load and recharging the EV is £0.81. The surplus renewable energy is directly exported to the grid from PV-load system, considering the fact that smart meter rollout will be finished before the end of 2024 [131], by which export energy will be metered, more accurately assessing the profit the household can make through selling energy to the grid. The export tariff used in this research is assumed as 5.24p/kWh [25], therefore, the simulated export prices are £ 0.88 and £0.72, with respect to 17.4kWh of energy being exported on weekday and 14.23 kWh exported on the example weekend day in question.

The advanced BEMS enables full exploitation of the PV generated energy, as illustrated by the orange curves, only the EV charging energy is required from the grid. Here, renewable energy generation can cover the load demand of the whole day, therefore, the costs are reduced to £0.41 and £0.31 for weekday and weekend usage respectively. Since the PV overproduction is high during the daytime in summer, the surplus energy after fully charging the household BESS will still be exported to the grid on a weekday. The results show that there is 13.92 kWh of renewable energy exported to grid during the daytime on the weekday, from PV-BESS-load system, and a household can possibly make £0.73 from this export. Figure 44 (d) shows that the exported energy on weekend is a total of 10.83 kWh, and £0.57 may be earned.

For household with a comprehensive BEMS, a 5kWh capacity battery for household BESS used in the original case study is not large enough to contain sufficient PV energy for recharging the EV battery (5.84 kWh is required for a weekday 16 miles daily trip), while the BESS also has to cover the load demand from the household. When the EV is not parked at home during the daytime, it doesn't have the ability to absorb the PV overproduction, therefore, an export price of £0.6 daily is earned from energy exported to the grid when the BESS is fully recharged. Moreover, since the load is matched by PV generation during the daytime, and the evening and off-peak hour usage are covered by stored energy in the BESS, as shown in Figure 54 (c), grid energy is only required to charge the EV battery to the targeted SoC before the end of Economy 7 off-peak hour. The electricity bill cost for using the comprehensive BEMS in specific summer working day is £0.32. However, when the EV is parked at home until 12:00 on a weekend, from the implemented EV charging scheme, $E_{EVtarget}$ is calculated as 0 in this case, therefore, there's no energy required to fill-up the EV battery overnight. As shown by the red curve in Figure 44 (d), the energy from the system recharges the EV battery with a higher priority than the BESS, when load is fully supported by the PV generation. Thus, during the period from 7:00 to 12:00, the EV is recharged by renewable energy. The excess PV energy is then directly exported to grid after EV leaves home until it returns back at 16:00, when surplus energy is again used to recharge the EV as it plugs to the V2G charger. Hence, energy is fully self-consumed within the domestic environment, there's no electricity cost from the grid during the day, and through the energy exportation, the household can earn £0.35 per day.


4000
3500
3000
2500
2000
1500
1000
500
0
Energy (Wh)
00:00-01:00
01:00-02:00
02:00-03:00
03:00-04:00
04:00-05:00
05:00-06:00
06:00-07:00
07:00-08:00
08:00-09:00
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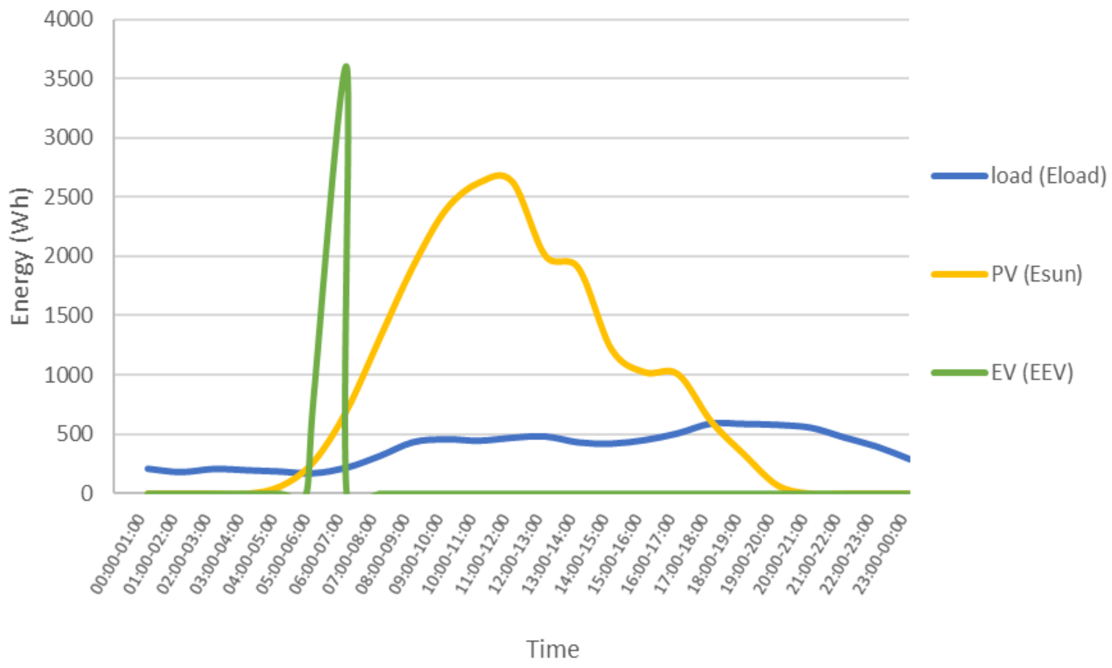
18:00-19:00
19:00-20:00
20:00-21:00
21:00-22:00
22:00-23:00
23:00-00:00
Time
load (Eload)
PV (Esun)
EV (EEV)

(a)


4000
3500
3000
2500
2000
1500
1000
500
0
Energy (Wh)
00:00-01:00
01:00-02:00
02:00-03:00
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04:00-05:00
05:00-06:00
06:00-07:00
07:00-08:00
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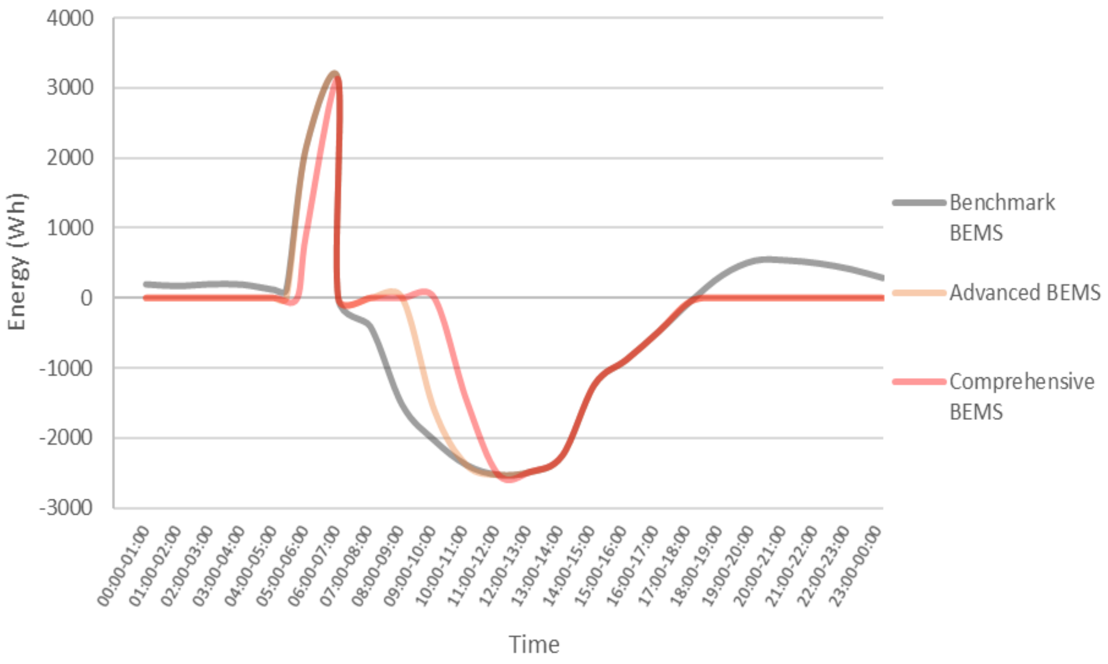
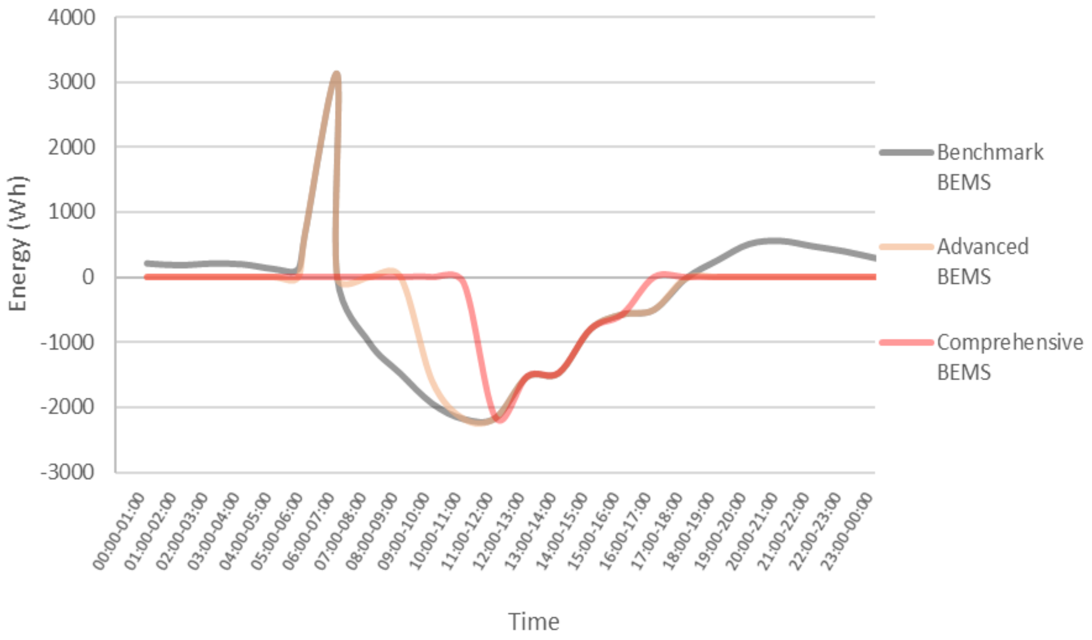
22:00-23:00
23:00-00:00
Time
load (Eload)
PV (Esun)
EV (EEV)

(b)



(c)



(d)

Figure 54. Performance of different domestic energy systems in summer weekday (a)(c) and weekend (b)(d).

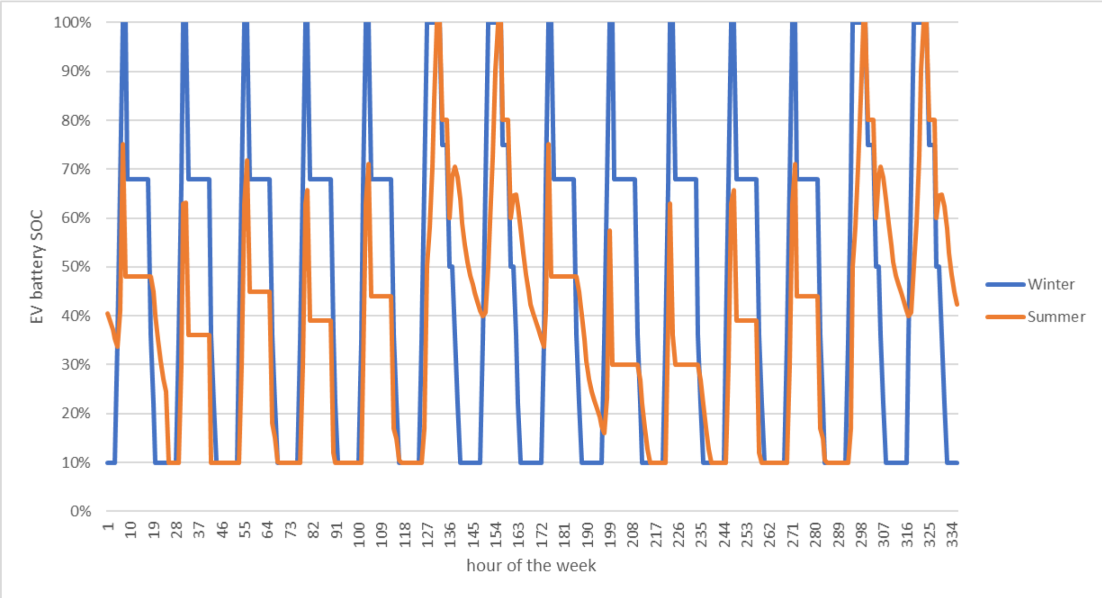


Figure 55. EV battery SOC over 2 weeks period

Figure 55 shows the EV battery SOC over a 2-week period, from the diagram, it is obvious that in winter the EV battery is used mostly as extended energy storage for the household, and is fully charged overnight during the Economy 7 off-peak hours, lowering the overall daily cost of electricity by in effect shifting the household use to the lower rate periods. However, in summer, the EV usually charges to its SoC target overnight using lower cost grid energy to just cover its daily use, unless excess PV energy is available when the EV is parked at home for a longer time, for example on the weekend, leading to better V2H operation. In this case, the EV is recharged by renewable energy and no cost is spent on electricity from the grid supply.

Having examined the daily energy savings and consumption, the system payback period can be used to further evaluate the overall system performance.

$$payback = \frac{P_{systot}}{P_{profit\_tot}} \quad (58)$$

Where

$$P_{systot} = P_{battery} + P_{PV} + P_{install} + P_{charger}$$

$$P_{profit\_tot} = P_{savtot} + P_{export} + P_{FIT} - P_{degrad\_total} \quad (59)$$

The annual profit that a single non-pensioner household with a chosen electricity tariff can achieve can be calculated based on the results of the model. P_{systot} is the total system price including the price of the battery system ($P_{battery}$), PV system (P_{PV}), EV charger ($P_{charger}$) and installation cost ($P_{install}$). P_{profit_tot} is the total profit gained by using the system, p_{savtot} represents the total saving on electricity bills, P_{export} is the total return from energy export back to the grid. Since battery degradation cost is also to be considered, the annual profit must account for that cost. The total cumulative degradation cost for BESS battery throughout a year is £78.70, as the BESS battery degrades 1.13% throughout a year of use. Since the EV battery's degradation cost is accounted for in vehicle return on investment by paying less for charging with electricity than pumping fuel, hence the EV battery's degradation cost doesn't address to the ROI of the domestic energy system. Thus, the total investment including the products and their installation is £8211.63, and annual ROI of the system including the battery degradation cost is £758.42, hence, the payback period on single non-pensioner household with 4kW PV, 5kWh BESS and 11kWh EV battery is calculated as 10.96 years. Comparing with that to a system without the EV integrated to perform V2G, a advanced BEMS has a payback period of 12.23 years, and in addition, the benchmark BEMS with only a PV panel system has a payback period of 12.44 years.

4.4.2 Annual energy and emission savings

Take an example of a single non-pensioner household who commute to work by electric vehicle every weekday, if the household has the comprehensive BEMS installed, it will have an annual energy saving of 1.5kWh comparing with the advanced BEMS, while it have 819kWh of energy saving comparing with the benchmark BEMS. According to the greenhouse gas report published in 2021 [101], the greenhouse gas emission produced for generating 1kWh electricity is 0.231kgCO_2e, therefore, 0.35 kgCO_2e and 189.19 kgCO_2e of greenhouse gas emission are reduced annually from the saved energy by using comprehensive BEMS, comparing with advanced BEMS and benchmark BEMS respectively. Since EV is used in this study to commute on each day, and it produces zero emissions comparing with traditional ICE passenger vehicles, thus the annual reduction on greenhouse gas emission by using EV is calculated.

The average greenhouse gas emission for ICE passenger vehicle driving a mile is 0.28kgCO_2e according to the government statistics of registered vehicles on the road in the UK [17], and in this study, 5248 miles have done in a year by the single non-pensioner household, therefore, a total of 1469.44 kgCO_2e is reduced annually by using EV. As a result, annual overall reductions on the greenhouse gas emission by using the comprehensive BEMS are 1469.79 and 1658.63 kgCO_2e respectively, comparing with the advanced and benchmark BEMS.

This calculation was done for each type of households, and the average annual energy savings by using comprehensive BEMS compare with using advanced BEMS is 1.56kWh, and that compare with using benchmark BEMS is 822.55kWh. Correspondingly, the annual emission savings are 0.44 and 190.00 kgCO_2e respectively.

If a household with EV, but don't have energy management system installed yet, the comprehensive system has the ability to save more than 822.55kWh of energy and 1600 kgCO_2e of emission, depending on the model and make of the EV and how many miles done each day. This is a huge potential for the government to consider, to subsidise the system. With this BEMS installed, household will benefit from bill savings, and the government will benefit from the energy and emission savings as they are accelerating the progress towards net zero.

4.4.3 Sensitivity analysis

Using the same technique described in chapter 3, the sensitivity analysis is carried out on the payback period of the domestic energy system. Figure 46 shows the payback period calculated for various size combinations of PV and BESS for single non-pensioner household with Mitsubishi Outlander PHEV, fully integrated for V2G operation. The minimum payback times for the system with 1kW to 4kW PV system installed are 6.77, 8.97, 10.44, 9.90 years respectively. Those minimum payback times are all shown with less than 5kWh BESS installed according to the diagram.

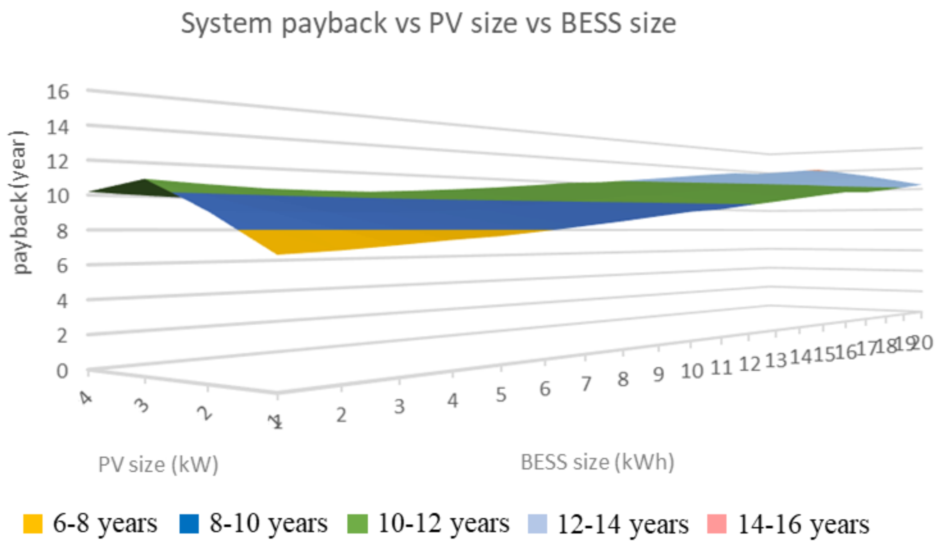


Figure 56. Payback periods of various battery sizes for different sizes of PV system installed in single non-pensioner household

Figure 57 introduces a comparison of how much payback time can be reduced by using comprehensive BEMS compare with advanced BEMS. The reduction on payback time can be calculated by subtracting the payback time of comprehensive BEMS by that of advanced BEMS. The figure shows for smaller sizes of BESS installed, more saving on payback time appears. The battery on electric vehicle enables the household to store more grid energy at a cheap rate in winter by charging EV and BESS within Economy 7 off-peak hour, and then discharge them within the high tariff periods.

The EV battery enlarges the system performance on cost cutting, typically for those households with 1 kWh BESS installed previously in the advanced BEMS, they are unlikely to save a lot of money on electricity bill as the capacity of BESS is too small, however with a 11 kWh EV battery engaged, the system makes cost cut on electricity significant, moreover, in summer, EV can absorb more sunlight energy for household self-consumption, thus reducing the payback period of the system. The maximum reduce on payback time for 1 to 4 kW PV system are 4.83, 3.14, 2.35 and 1.61 years. On the other hand, for those households with large size of BESS system installed, energy self-sufficiency is obtained without the help of EV battery, thus, the difference on payback period is not significant. The result gives that the comprehensive BEMS significantly reduces the system payback time with higher ROI generated each year, for household with less than 12 kWh capacity BESS system installed.

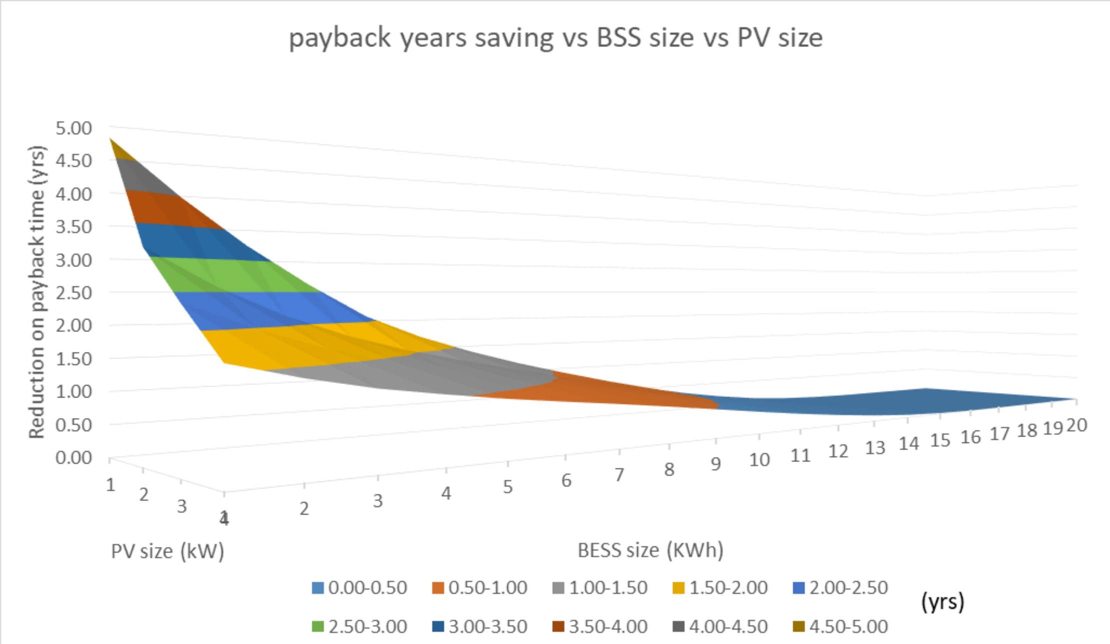


Figure 57. Reduction on payback time of single pensioner household with comprehensive BEMS against with advanced BEMS

Same evaluations apply to each type of households, and the plots are shown below, they show similar results as the single pensioner household, which the reduction on payback time is significant for BESS with smaller than 5kWh size. Then the plots start to saturate, which result in less reduction on payback time.

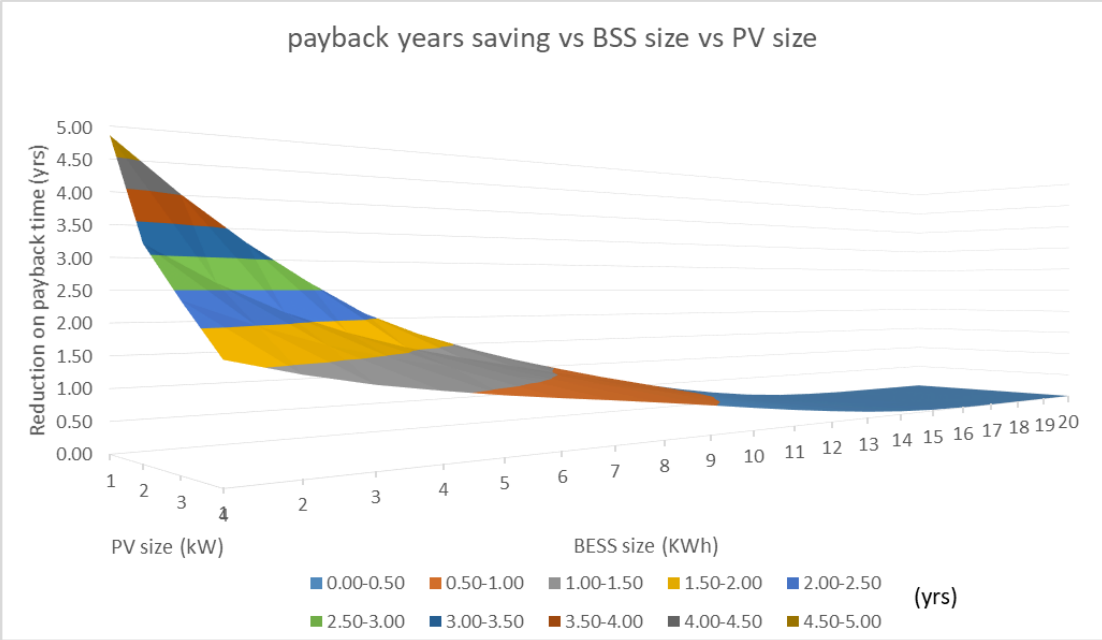


Figure 58. Reduction on payback time of single non-pensioner household with comprehensive BEMS against with advanced BEMS

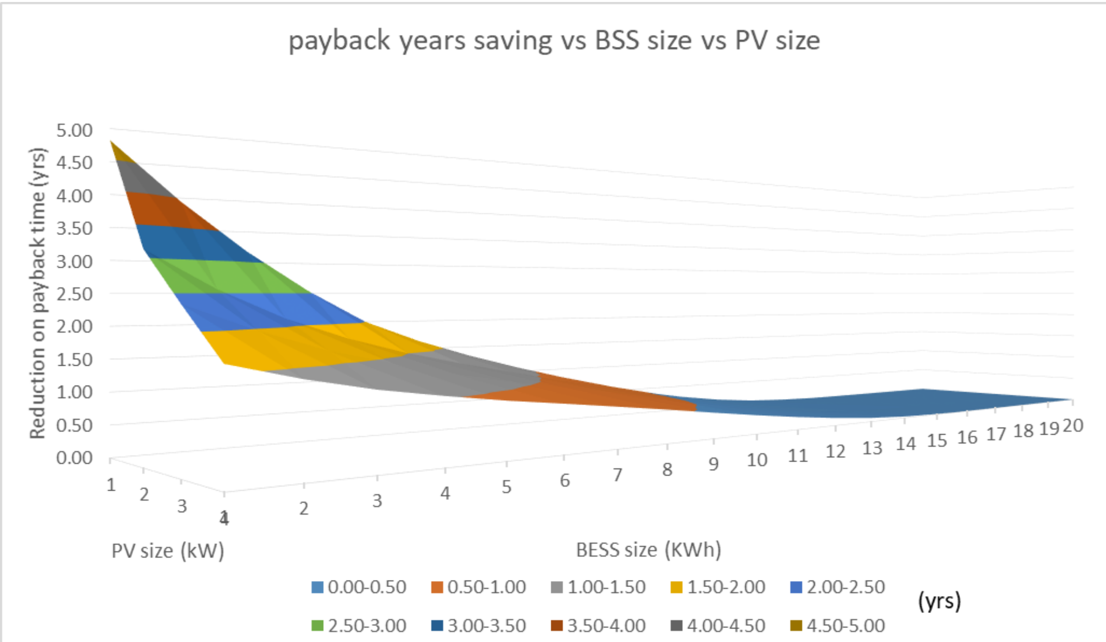


Figure 59. Reduction on payback time of multiple pensioner household with comprehensive BEMS against with advanced BEMS

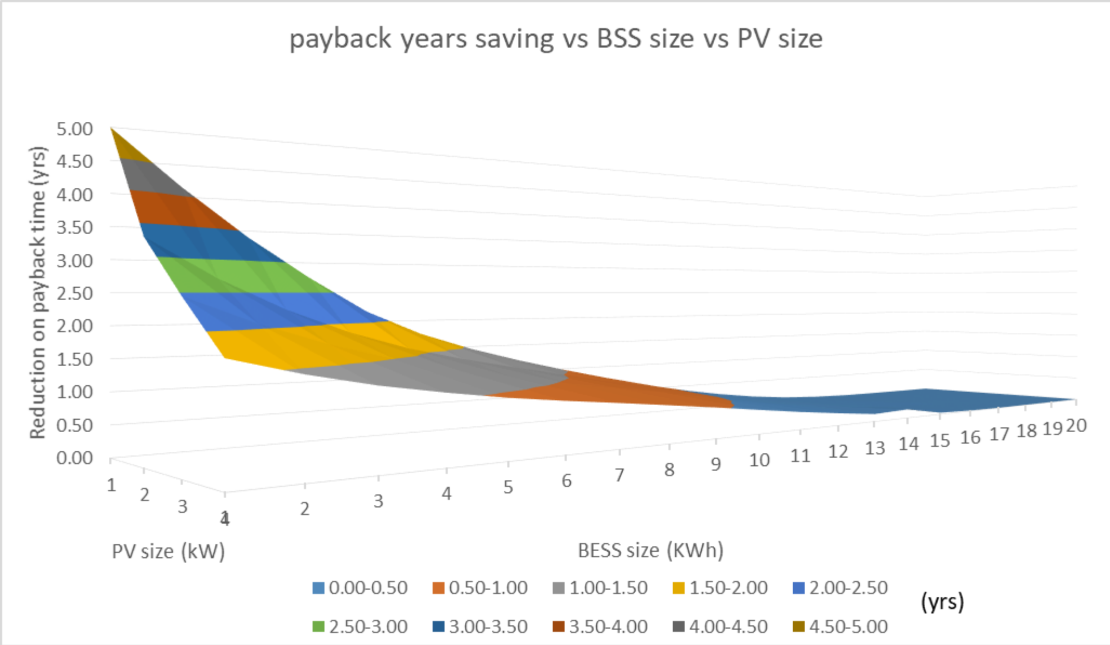


Figure 60. Reduction on payback time of household with children with comprehensive BEMS against with advanced BEMS

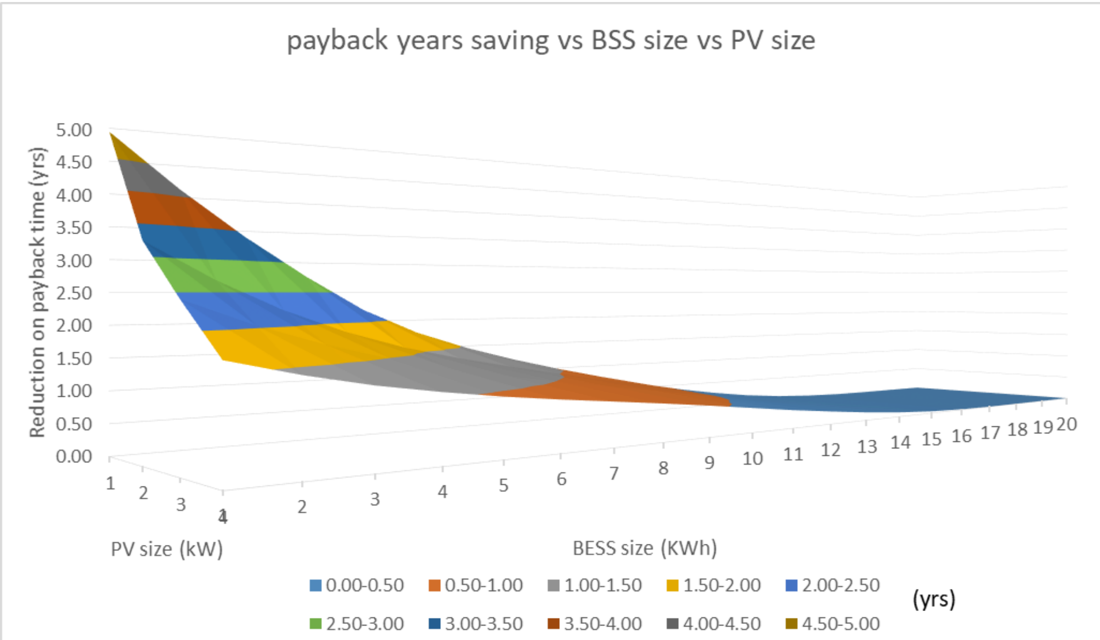


Figure 61. Reduction on payback time of multiple person household with no children with comprehensive BEMS against with advanced BEMS

4.5 Conclusion

This chapter introduces a comprehensive domestic energy system including a PV sub-system, a BESS and an EV. A dashboard was created to enable the configuration of users' own system. By inputting the EV brand and make in dashboard, desired EV information such as EV battery capacity, vehicle range and EV consumption etc. is sent from the linked EV file to the domestic consumption model developed in chapter 3, in order to integrate them and simulate the system.

It also includes various selection choices, such as household type, PV size, BESS size and EV brand etc. which precisely integrate the real-world household models into the system. A control system was also developed to manage the operation of each subsystem. Electricity tariffs are considered to gain lowest price for the minimum energy use scenario for the household, along with the payback period which can be calculated for each variation in PV and BESS sizes.

A battery aging model for both EV and BESS batteries is considered. Since the EV battery is likely to undergo deep-cycle operation for each day driving, the study also addresses concerns about cycle life rather than calendar life. For any household without an EV, but having a BESS and PV installed, the Return on Investment (RoI) shows an shortest period when between 5 kWh and 6 kWh of BSS are installed, dependant on the PV array size.

However, a household with a V2G enabled EV, installed alongside a BESS and PV, shows an improved payback time against that without the EV. Therefore, for small BESS and PV setups, the EV battery can be used as an extra energy storage to enhance the system RoI performance, which in turn maximises the energy self-sufficiency, hence lower bills result in shorter payback time.

Chapter V.

Conclusion and future work

This chapter summarises all the work presented in the thesis, and discusses the overall contributions of the work in comparison with the objectives described in Chapter 1. Possible extensions to this work, described in the future work section are proposed.

5.1 Conclusion

This thesis has proposed a number of control schemes for domestic energy systems that incorporate PV and BESS, with or without EV integration. Chapter 1 states the background and motivation of the work with the aim of obtaining domestic energy self-sufficiency by maximizing the exploitation of photovoltaic (PV) self-generation. To achieve this aim, the study examined how household battery energy storage systems (BESSs) and vehicle-to-grid (V2G) technology could be integrated into the household. These approaches are also identified as two possible solutions to solve the drawbacks brought about by the penetration of PV to the current grid system, in order to promote the transformation towards a smart grid. Therefore, a comprehensive control approach for a domestic energy system needed to be developed. This thesis focusses on how domestic energy systems can help households by lowering expenditure on electricity, whilst accelerating the government's target towards net zero emissions.

Before reviewing the existing literature, basic schemes are first introduced in Chapter 2. Various government policies and targets are introduced in this section, and also the principle of V2G technology. Then the chapter reports the state of the art, and existing studies on home automation and appliance remote control are described. These form part of the household load management strategy which improves the efficiency of use to lower the energy consumption. The use of BESS has been studied in multiple papers for domestic and grid demand peak-shaving, improving grid reliability and maintaining grid frequency. Literatures on using electric vehicles (EV) to support home consumption and grid demand are described based on various models created in previous works. Overall, this chapter outlines what have been achieved and the challenges that need to be solved, as the foundation for later chapters.

The aim of this thesis was to develop and manage the domestic energy system with renewable energy sources and energy storages to obtain local energy self-sufficiency by fully exploiting green energy generation. This thesis first introduces a tool as the foundation for the later research which simulates a household load profile and a PV generation profile. The tool is created in Excel using the simulated hourly household demand data generated from the Goldsim load profile generation modelling, and the simulated hourly PV generation data produced from the System Advisor Model (SAM). Bottom-up approach is used to create domestic load profiling model in Goldsim, a dashboard is created in the model for users to enter various relative inputs such as: household type, household appliances and their quantity etc., then the model retrieves the corresponding hourly consumption data for selected appliances and generates a plot of the daily load profile. Appliance consumption data file was based on government published survey on household energy consumption which monitored in 250 UK households. The survey investigates appliances that most commonly seen in a household and categorises them in seven main categories. SAM is a software created by National Renewable Energy Laboratory (NREL) which can easily provide hourly PV profiles for a selected size of PV system with the integration of weather data files and sunlight data files from the nearest meteorological station. Simulations are validated against practical measured data, and all simulated hourly load and PV profiles are exported individually to an Excel file.

An interface was created in the Excel BEMS simulation tool to link user inputs with those exported data files, and present outcomes in its result section when subsystems are integrated to the tool. As stated in Chapter 3, a BESS is integrated to the domestic energy system. Battery control logics are developed and coded within the tool for the BESS based on the BEMS control strategy described. The BESS and its control logics manage the domestic energy usage, and in winter, the BESS plays the role of moving the peak time load demand to the off-peak period, when the supply electricity tariffs and CO_2 emissions are low. While in summer, the system can fully exploit the PV overproduction by storing it for evening and overnight use. As a whole, energy self-sufficiency can be achieved with this system, it can also effectively support the peak demand of the grid through load shifting and peak lopping. System performances for various sizes of PV system, in different types of households, with various sizes of BESS integration are evaluated under real world tariff rates throughout a year. The tool can automatically run the simulation and output the corresponding annual profits. By calculating system payback period, the shortest payback period represents the best system performance, therefore, the best fit size of BESS for each size of PV system in each type of household is summarised. The shortest payback period is found between the installation of a 5kWh and a 6kWh BESS depending on the PV array size, and household type. Marginal sizes of battery are also determined to ensure the acceptable improvement in total system payback periods.

Chapter 4 introduces the comprehensive building energy management system with both BESS and EV integration. Firstly, the input section of the interface created in chapter 3 is expanded to allow users to configure their own system, and includes the model and make of the possible EV, daily mileage, typical departure and return time, road condition of the trips etc. The inputs of the model and make of the EV can retrieve the corresponding EV information from the individual EV files, which includes EV battery capacity, vehicle range and energy consumption etc., based on the figures provided by UK Electric Vehicle database (UKEVDB). This enables the tool to be as accurate as possible in incorporating the real-world data into the household modelling.

From this, a charging and discharging control strategy for the EV battery was demonstrated, with the consideration whether the EV is available to perform V2G/V2H is coded to the tool (e.g., EV must be plugged in, energy is sufficient to provide load support, enough energy remained to prevent flat battery when needed etc.). EV battery is manipulated to fully exploit domestic renewable generation, therefore it provides energy support to household and grid via a bi-directional V2G charger. Battery aging model is also constructed to the batteries used in the system which are likely to do deep-cycle operations, it is necessary to count the battery degradation cost into the system profit to evaluate the system performance. Thus, the tool can run the simulation and produce the relative annual outcomes such as: bill savings, Feed-in tariff payback, export profit etc. for selected household types with a specific PV and BESS size. Additionally, the total system investment is addressed to evaluate the payback period. It has been shown that a household with a V2G enabled EV alongside a BESS and PV shows a shorter payback time against that without an EV, especially for smaller BESS capacities, which relies more heavily on the EV to function as extended stationary energy storage when it is plugged in.

In summary, the challenges proposed in this research were investigated, solutions were generated and validated by comparing the simulated results with real-world measurements. From the evaluation on system performance, the domestic energy system developed can effectively reduce household bill cost and provide grid peak-shaving support.

5.2 Future work

This thesis presents the extended work based on the state of the art, the work provides improvement on domestic energy system payback with BESS and EV integration. Further studies are suggested in this section which offer potential improvement to enlarge the impact.

Research on connecting households within an area or in a community to construct a large-scale energy system is proposed to be studied in the future. This proposed study can evaluate the impact of the BESS and EV integration at household with PV at a macroscopic level. Current work simulates the performance of domestic energy system within one household for a year, by modelling the situation in which tens or hundreds of households all have such systems installed within an area, the overall effect on local energy self-consumption can be evaluated, in addition, impacts on grid demand and frequency will also be available to be analysed. This project is not only proposed based on cutting domestic electricity cost, but also to help with maintaining grid stability. The large-scale energy system can join the grid reserve service to provide emergency electricity backup with its energy storage capability. This will reduce the operating cost for energy suppliers dramatically without significant impact on customers' normal use. To perform the macroscopic level of control, a communication network to link each household is required. This network will enable the macro-monitoring of the battery SOC in each energy subsystem, then a control system gains the demand information from the utility company and performs algorithms on local energy reserve and grid demand to generate an operation scheme that intending to match the supply and demand.

In addition, with the increased penetration of EVs, more charging facilities are built in commercial areas. It has a bright future to link the large-scale domestic energy system with the nearest commercial center. By selling the household PV overproduction to charge the EV that plugged in the commercial charging station, household can make more profit as the tariff could be higher than feeding back to grid. Thus, this technique fully exploits the PV overproduction when EV is not parked at home during the daytime, helping lower grid demand, and accelerating the government goal on reducing carbon dioxide emission.

Currently, all the results are based on software simulation, experimental validation for domestic energy system with PV and BESS is urgently needed to show the impact in real world. Verification should focus on the reliability of the modelled battery control schemes, load support operation and sequence, PV overproduction export scheme and the economic practicality on system. Validated model can support the future work proposed.

Due to V2G bidirectional charger for EV is not commercially available, performance of the system in a household with PV, BESS and EV is not able to be validated at this time, but in the future, when it has been widely produced, validation is needed to verify the system performance.

Chapter VI.

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