Department of Mechanical and Aerospace Engineering

Energy Management System with PV and Battery to Minimise Energy Costs for Household in UK

Author: Revathy Sivadas

Supervisor: Dr. Nick Kelly

A thesis submitted in partial fulfilment for the requirement of

Master of Science in Sustainable Eng: Renewable Energy Systems and the Environment

2022

Copyright Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

The copyright of this thesis belongs to the author under the terms of the United Kingdom Copyright Acts as qualified by University of Strathclyde Regulation 3.50. Due acknowledgement must always be made of the use of any material contained in, or derived from, this thesis.

Signed: Revathy Sivadas

Date: 10/08/22

Abstract

Energy prices are rising on a daily basis due to the energy crisis, which affecting the living costs of UK households. The reduction of electric energy requirement for the households can reduce energy market crisis and the energy expenses. The deployment of renewable system improves the importance of energy storage system in the network. Its adaptability can reduce the impact of the irregular power generation and energy expenses. The supply to demand balancing is the main issue of renewable integrated home energy system. So, the perfect energy management module with control strategies is necessary for household. Most of the home energy management system concept for the energy cost reduction are focused on the load shifting methodology according to the energy price variations. This project shows the relevance of a residential energy management system with a battery and PV (photovoltaic) system along with a supply-side controller concept that uses weather, load, and electricity price forecasting can reduce energy costs for UK households. Here different way of battery scheduling concepts that reduces the energy cost at the present energy market and future predictive energy market compare and evaluates. The requirement of ESS with a control aspect necessity to utilise the real-time management which considered solar system performance and low-cost energy utilisation for the cost-effective control strategy. An explanation about the future energy market and future challenges in the control strategy for this system is included.

Acknowledgements

First and foremost, I would like to express my sincere gratitude to my supervisor, Dr Nick Kelly, for all of his support and advice for this MSc thesis. I would also like to convey my deepest appreciation to my friends for their important encouragement and support. Finally, I would like to thank my family for their support and encouragement throughout my studies.

Table of Contents

List of Figures

List of Tables

1.0 Introduction

The energy prices have been increasing day by day which affects the living cost of households in UK. According to Ofgem, approximately 2-3 people live in an average household and the average energy bill for a small family is approximately £1600 per year [1]. The energy market in UK is experiencing energy pricing crisis. Gas and electricity prices have risen dramatically in recent months because of the rise of costs for purchasing energy reserves for suppliers. [67]

UK government summary report mentioned that around approximately 64% of the total gas and 40% of the total electricity are consumed by the domestic sector. Domestic buildings consume around 30% of primary energy (Electrical energy and gas supplies are the main sources) [68]. Most of the houses in UK use electricity for lighting, cooling systems, and other electrical appliances, and for heating and hot water systems using energy from gas. Where 80% of kWh energy annual consumption by an average household is from gas and 48% of homes use natural gas for heating. It is estimated that 8% of households used electricity as their main fuel [69]. Low-carbon heating systems are the way of the future in household heating. The majority of houses in UK use fossil-fuel burning equipment to heat their homes. Around 80% of homes are now connected to the gas network, using boilers. In England, around 1.1 million rural homes are not linked to the gas grid and they rely on fossil fuels like oil or LPG for heating [70]. Fossil fuel emits 215grams of CO2 per kWh of heat delivered. 185g of CO2 generated from natural gas burning [27]. So, low-carbon heating alternatives, such as heat pumps, are necessary and the UK government already set a target to install new heating system in all homes by 2035 [72]. Heat pumps utilise heat from the air outside or from beneath to heat home. When compared to a gas furnace, residential heat pumps can reduce carbon dioxide emissions by 38-53% and it can minimise the potential 20-year global emissions by 53-67 percent [2]. Now heat pumps only account less than 2% in UK market. It is expected that in the future, heat pump will replace boilers for the net zero transition world [71]. After considering the relevance and importance of low carbon thermal energy production, electric consumption of heat pump is considered instead of gas consumption of gas boilers, for the selected households in this study.

For the UK net zero transition target, the portion of the UK energy market must have to eliminate extra carbon content from the air than they release. So, electricity consumption increasing faster than other energy sectors because of the electrification of energy uses. So, more adaptability of renewable systems is required. According to renewable studies, wind, solar, wave, hydro and biomass are the main source of natural energy in UK, overall accounting for 39.3% total electricity generation [25].

Renewable energies, notably solar energy, have improved rapidly during the previous decade. Rooftop solar PV(Photovoltaic) is the best renewable energy source for residential applications. According to the UK government's 2020 report, around 3.3% of UK homes installed PV modules [26]. The decrease of air pollution and the falling cost of solar photovoltaic (PV) technologies are the primary reasons for its strong integration in power systems (Cost of solar PV module fell by 82% within the last decade [24]). So, the global capacity of residential solar PV is anticipated to rise in the next years.

Now, the world is going to more digitalised, and the future electricity supply will be 100% renewable. This leads to the possibility of blackouts in the network due to their intermittency. But the perfect assistance to RES with the help of digitalisation can reduce the risks. The possibility of balancing issues between the supply and demand in a large overall system can be mitigated by using a local energy production network or the development of a microgrid. Microgrids are combined energy systems composed of different loads, Storage devices (ESS), and Renewable Resources (RES). The growing deployment of RES has enhanced microgrid efficiency and lowered global CO2 emissions [88].

A System for Energy Storage has the ability to reduce the intermittent nature of photovoltaic Solar energy output while also managing peak loads. The cost-effective size of PV and ESS may be established to save capital costs while providing adequate storage to benefit the building load. To increase the stability of a microgrid, several software and algorithms are employed [88]. Thus, a forecasting and scheduling algorithms required to attain the full benefits of Battery ESS. An ESS forecasting algorithm is used to predict when peak load occurs and how much power is required. That information is critical to schedule the system. Peak shaving, power pricing, and solar PV output must all be addressed when creating an efficient energy storage plan. Customers are installing solar panels on their rooftops with an ESS to offset rising power rates and environmental concerns. The inability to formulate a correct cost function can impair the efficient utilisation of battery energy. This work presents a cost function that integrates restrictions with the charging component of the function to efficiently manage battery energy through charging/discharging behaviour management. [89].

Now microgrids are emerging to reduce load consumption, integrate intermittent renewable energy supplies, and prevent long-term power disruptions. To achieve this, it should be able to monitor and regulate loads and energy resources placed in the building [44]. But for this thesis, a house with its own managing and monitoring possibility concept is considered. Increasing reliability for RES integrated microgrid system is challenging, for the smart operation, existing power systems have to improve to the smart grid by updating new requirements and new communication technologies for the electricity consumer and utility [45]. The main problem with the renewable integrated power system in households is energy management issues and energy price variation. So, energy management systems for home are developed as a remedy. A well-designed HEMS enables electricity consumers to achieve better levels of energy controls. Different traditional techniques (mathematical optimisation), model predictive control techniques, Heuristic & Metaheuristics, Appliance scheduling, and other techniques used in HEMS are detailed in different research papers are reviewed in [46]. Most research papers mainly focused on the demand side response algorithms and load shifting according to the price. In this thesis, a grid connected home with solar system and energy storage system with cost-effective battery control patterns according to the electricity real price and renewable energy performance are evaluated and future green tariff price-based energy cost reduction calculations are obtained.

1.1 Aim and Objective

Aim: The goal of this research is

- A study on the concept of home energy management system for grid connected home with PV and ESS to supply the house loads.
- To create and test algorithms concepts that uses climate, load demand, and electricity price forecasts to reduce energy consumption from the grid and the net cost of electricity by increasing and utilising self-consumption.
- To show a future energy system that uses a 100% renewable green tariff for battery control which suitable for a UK residential building.

Objectives:

- A detailed background study about the energy management system, and its relevant components and terms for a household. Show the relevance of an energy management system using weather and electricity forecast services for reducing net annual electricity cost for a household.

- Sizing and modeling of Battery and PV according to the load and the importance of these components for the energy cost reduction for households.
- Develop an equation-based control supply-side energy management concepts evaluation in matlab/Simulink as a modeling software by considering the constraints of the components, system requirement and the electricity price. Select a cost-effective battery control strategy which reduces total electricity expenses.
- An overlook into the home energy system with the developed cost-effective battery charging/discharging control strategies on the basis of onsite excess solar energy generation and future 100% renewable electricity supply rate (green tariff).

2.0 Background study

This section is intended to provide insight into relevant project areas while also supporting the technical assessment methodology. A wide range of literature will be mentioned and explained in order to give a full and comprehensive understanding of main points. The first step is to investigate future residential plans and home electrical systems in the United Kingdom and the relevance of the energy management system in the Home. Secondly, the components of the home energy system relevant to the future development will be investigated.

The following steps after this background study are system modeling, system component selection, and developing and comparing different algorithms concept for controlling battery charging/discharging periods based on solar power generation and energy tariff to select the best cost-effective control model for residential buildings in the UK.

2.1 Smart Grid

A smart grid is an electrical network that builds on digital technology that uses two-way digital communication to deliver smart electricity to users. This system can analyse and perform itself as a problem solver, update information regarding the faults or issues to the operator before it happens, and it can divert or redirect electricity automatically to reduce areas affected by the blackout [7]. The advanced and smart grid system is one of the solutions for the drawbacks of an existing system and the deployment of new technologies. Smart grid uses 2-way communication, smart meter, smart appliances, renewable resources, etc. Two-way communication and two-way flow of electricity improve the distribution network [73].

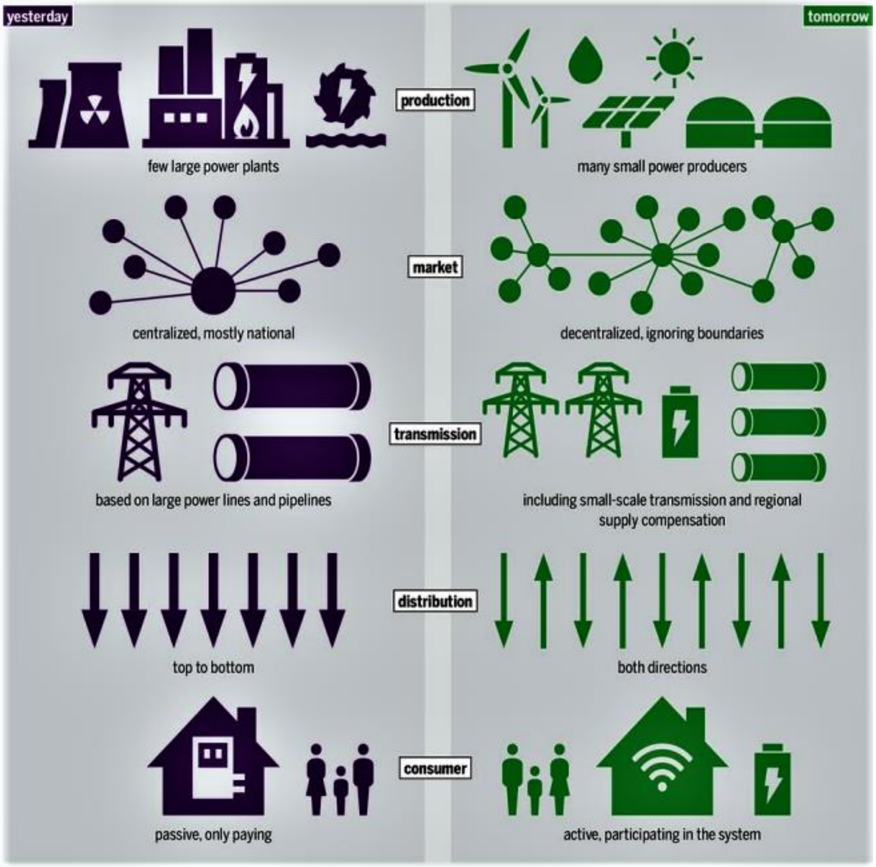


Figure 1 Grid system before vs future [7]

The future technologies of the smart grid are, Energy management systems, Advanced metering infrastructure, IoT programs, Big-data, EV points, etc [73,74]. The smart grid's goal is to transmit real-time information to improve efficiency and reduce the possibility of burnouts, blackouts, and surges, etc. smart grid technologies will allow to the management of high-frequency switching devices and unpredictable renewable outputs [7]. Figure 1 shows the electric grid system before and in future.

2.2 Energy Management System (EMS) for Home

This section provides an overlook into the concept of EMS in residential building. Energy management in residential buildings increasingly important to integrate more sustainable energy resources. The main concept of EMS is to connect or disconnect source components like, grid, battery and PV to the home load, and manage the power flows between smart loads, renewable generators, electrical storage, and the power grid [81]. The energy management is the process of saving energy by monitoring or controlling the system components. Energy monitoring shows energy consumption, solar energy output, battery state, electric price etc. The practical system module main components of EMS are smart electrical panels, monitoring modules, control programs and applications, smart electrical circuits etc. The goal of EMS is to reduce peak demand charges and to optimise the scheduling of the BESS to charge and discharge economically in the presence of electricity price and develop power exchange programmes by considering excess or deficit power value of solar power generation and predict the energy purchase from and energy sell to the grid. Due to the intermittent nature of renewable energy sources, a forecasting algorithm is necessary to correct for uncertainties and give high precision data for load and generation characteristics [7].

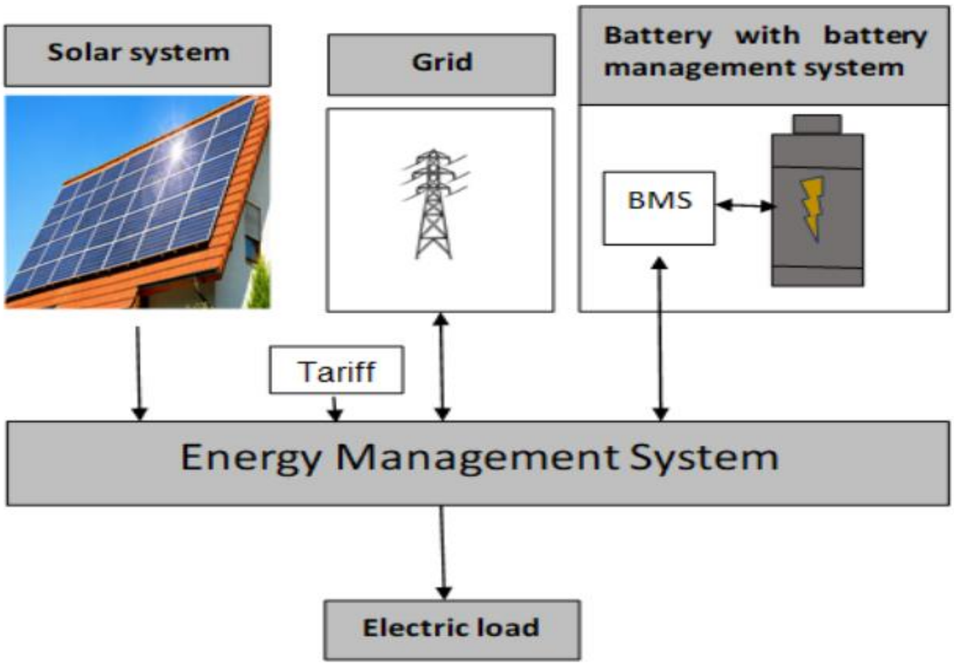


Figure 2 EMS (Energy Management System) [9]

Figure 2 depicts an EMS that controls energy to ensure the residential building's balance of power criteria throughout time periods via power exchange programmes with grid and solar system power output. [89]. Here the EMS uses PV as its primary source of energy. The objective to manage the power flow in this system, real-time energy management process is applicable in practical applications. Where, real-time data by using sensors can be used to schedule the components. But for an accurate control historical datas are required to predict the data. If we have the historical datas of the energy consumption, climate datas and the size of battery it is possible to make an analysis by considering battery model in a software with necessary scheduling program. Which can create the practically relatable output and state of battery. By using this information, effective control module with necessary predictive operation from big data processing. So, statistical analysis is really important to develop a control system.

2.2.1 The architecture of HEMS

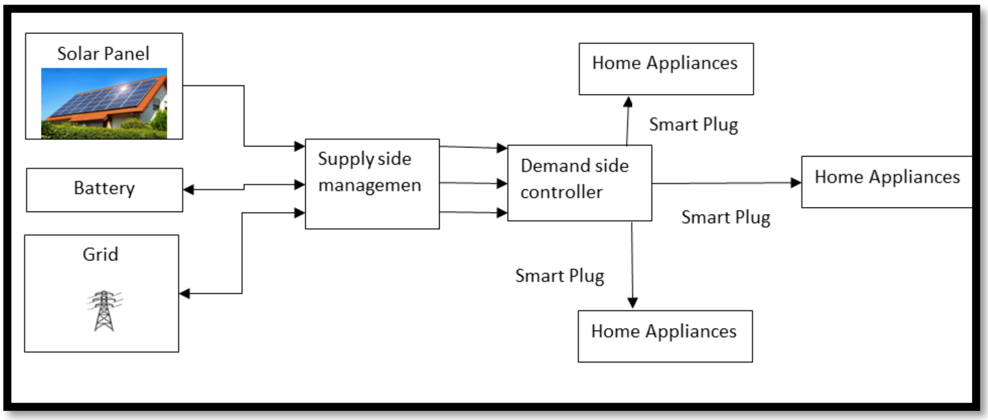


Figure 3 HEMS architecture [76]

Practical EMS in the home consists of an active hub device for maintaining communication between necessary home functions, the households, and the utility or energy provider company. The majority of HEMS are designed with the goal of controlling power consumption, improving smart grid performance levels, demand optimisation, enabling devices in residential buildings, and so on. HEMS could automatically monitor and adjust power use via smart metres, smart plugs, smart devices and appliances resulting in better power and improved management. [23,76].

The figure 3 shows the simple architecture of HEMS. Where, two methods are used to reduce energy consumption and energy cost; 1) supply-side management by integrating alternative power generation such as renewable energy supply and battery systems; 2) management of load by categorizing schedulable and non-schedulable loads and controlling schedulable loads to reduce cost (not practicable in the case of fixed tariff). A detailed explanation and comparison of these methods are included in the article [37] and it is emphasised the advantages of demand side management and supply side management for an energy bill reduction. The power balance issue between demand and supply is the main challenge in the operation of grid-connected system. The key parameter of effective generation planning, and power management are power generation and load predictions [38]. The EMS works with the help of Artificial Intelligence and Optimisation Programming algorithms to achieve electricity bill reduction and the reduction of uncertainty in power exchange between utility and end user. In previous research [36], 3.23% reduction in electrical energy bills were achieved. In [39], a review concepts for electricity consumers in microgrids related to Building automation and Control Systems, energy management systems, and Home energy management systems (HEMS), with the mission of increasing energy performance are included. Which give an overlook concept regarding the EMS for home. In the article [40], affordable energy management structures show demand response programs for residential buildings in the UK. Where, 3 stages of optimisation are obtained, first, day-ahead load shifting according to the electricity fluctuating prices, second, supply and load balancing, and finally, integration of power flow which provides real-time energy supply during minimising cost. Day head optimum scheduling techniques for a grid-connected system based on an storage strategy proposed by [42]. Where optimal scheduling of ESS to reduce running costs and technical properties of battery is taken into account for the control methods. An enhanced dynamic programming approach is used to solve optimisation model.

2.2.2 Smart Home Energy Management System (SHEMS):

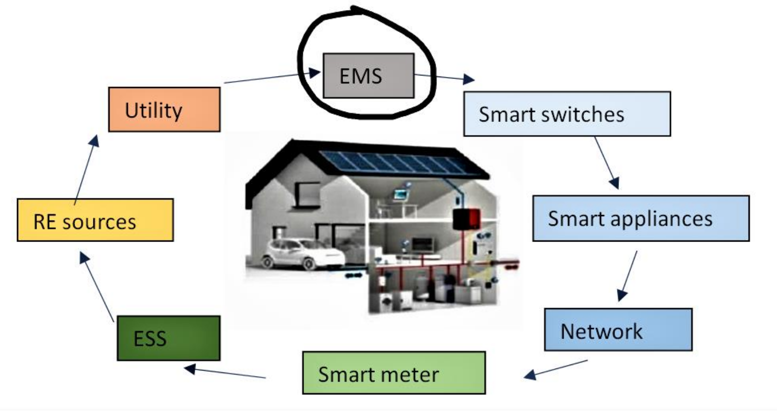
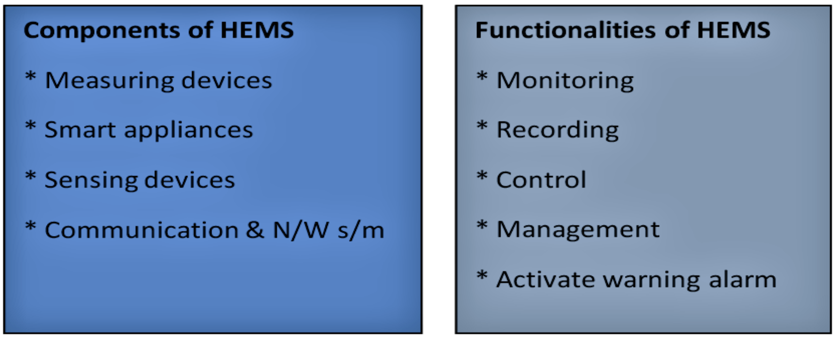


Figure 4 Elements of smart Home with EMS [7]

From the perspective of the consumer, the objective principle of SHEMS is to lower their total power consumption/ bill without changing their needs. SHEMS's main purpose is to control components at home according to the real-time price, climate data, load preferences, etc. Here, the practical side details about the future developed energy system are explaining in detail. Home energy management systems depends advanced metering infrastructure (AMI) devices to enable the communication between energy supplies and residential building. This communication channel created the path for the inclusion of anticipated incentives for a smart house for supply-side resource management as energy consumption reduction method for shifting energy consumption from peak load hours to lower electricity bill hours [20,45]. Smart home connected to the smart grid will maintain perfect interaction and which will support energy providers and households to manage energy in useful ways.



Components of HEMS

* Measuring devices

* Smart appliances

* Sensing devices

* Communication & N/W s/m

Functionalities of HEMS

* Monitoring

* Recording

* Control

* Management

* Activate warning alarm

Figure 5 components and features of SHEMS [20]

Figure 4 shows the elements of smart home. The features of HEMS are, monitoring, recording, controlling, management and activating warning mechanisms. Monitoring real-time information of all equipment's and components in the system is the main functionality of EMS. The user can access device information via a web interface. In its most basic form, device control should be offered to the user manually. Control can be automated if the management system supports smart scheduling [19]. Another specification of home EMS is seamless communication between different devices by using different technologies, such as ZigBee, CTA-2045, wi-fi, Z-wave, etc. In this case, the system should be capable of facilitating communication across multiple components independent of their communication capabilities [20]. CTA 2045 port adapter and the unified communication manager (software) communicate with water heater and HVAC systems to react and work intelligently for the necessary condition and it works as a mediator between these devices and control module [19] .The Zigbee is a Low rate, low power and wireless network device can transmit data over long distances.

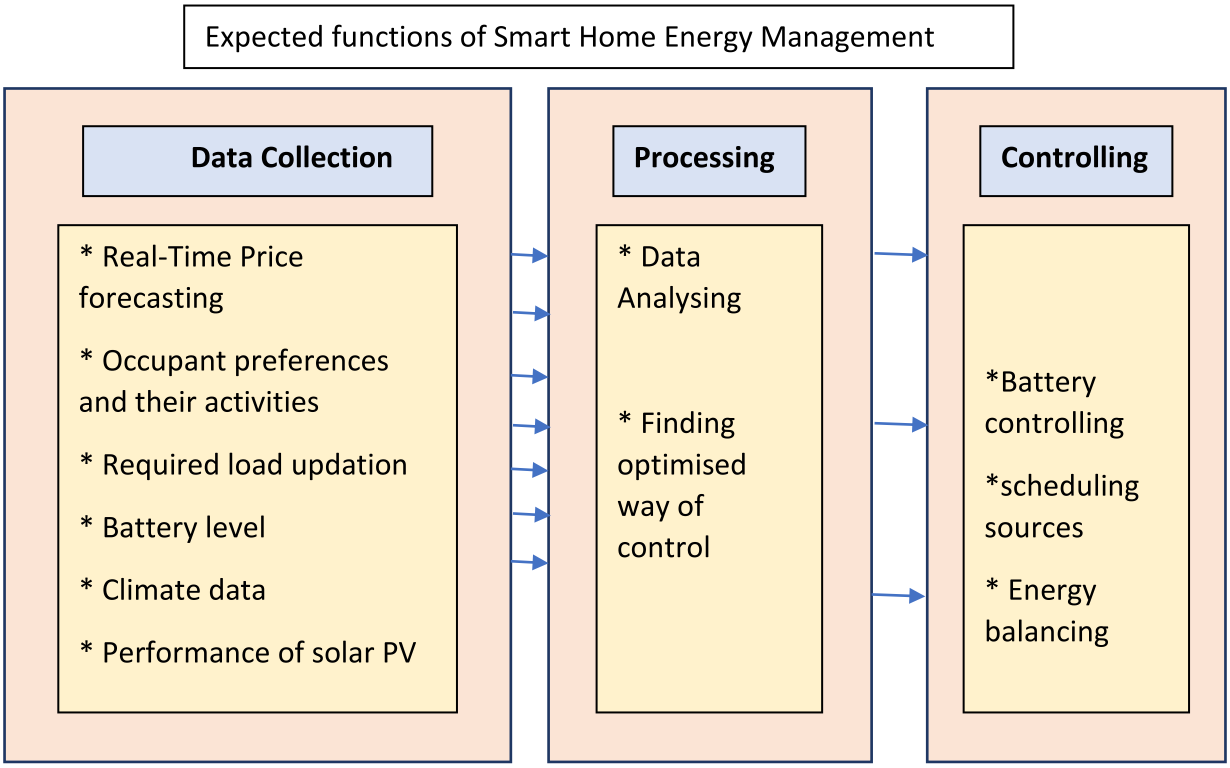


Figure 6 Functions of Smart Home Energy Management

As illustrated in the figure 6, the primary functions of the expected SHEMS are: 1) Collect information and messages such as Real-time pricing, Occupant preferences, their activities, Load status, Climate data, Battery performance status, Solar PV performance, and other relevant notifications; 2) Analyse the collected data and generate the optimal control strategy; 3) Controlling the battery operation according to the processing stage operations based on the automatically generated strategy; 4)Send feedback and other relevant information to control algorithms [35].

For the Real-time price data collection, for reading and collecting real-time tariff data from energy providers, an internet connection is necessary. So, the ethernet module should be included in the SHEMS module. Communication and updates like weather alerts, electricity availability alerts, and scheduled or perfect outage periods from energy providers are necessary. Data collection module in EMS with Ethernet or internet connection can improve the system performance. The processing module is the brain of SHEMS, collected data for processing is wired to appropriate equipment to get connected. This module will process the data obtained from human actions or motions, battery level, load preferences, tariff data, climate data, and other necessary information, which will be employed in machine learning and optimisation algorithms to induce behaviour modifications, and power flow control, and further load optimisation. The function of the controlling part includes load control and battery control according to the optimised way processed by a processor on the basis of real-time prices and the real-time status of all appliances

2.3 Energy Storage Systems

The deployment of renewable energy resources challenges the energy balancing and flexibility of future energy systems. Energy storage systems are capable for improve the reliability and flexibility of the renewable integrated system [80]. It is a critical component of a power system that includes renewable systems. Its adaptable operational capabilities can mitigate the impact of intermittent power generation as well as operational costs. They are used to store energy for a period and used later to do some useful operations. It can reduce energy costs for the consumer, be useful for renewable integrated systems and help to reduce environmental problems.

2.3.1 Classification of Energy storage system

Different types of Energy storage methods are Hydrogen, Compressed air energy storage, flow battery, pumped hydro, electrochemical batteries, etc. Each device has different characteristics, including energy density, power density, specific power, rated power, rated energy capacity, response time, discharge time, storage duration, lifetime, response time, impacts, etc. Electrical energy cannot be stored on large-scale projects due to the technical limitations of thermodynamics. It is more accessible and sustainable than chemical, mechanical, and thermal energy storage methods. Selecting the best technology, power and energy criteria can be used to classify ESS [11]. ESSs are playing an important role in enhancing operational abilities of a microgrid. There are several types of ESS available but not all of them can be efficiently used in MGs. The most common type of energy storage options for heat is thermal stores and heat batteries. Thermal store ESS is expensive if it is connected to renewable sources. Heat batteries are more expensive than hot water cylinders and their space efficiency relation is high. But it can store energy from the heat source and other electricity sources.

BESS is one of the primary power source in micro-grids due to its high-power density and quick response. Fly-wheel Energy Storage, Super-conducting Magnetic Energy storage and Supercapacitor technologies are often utilised to maintain power quality because they have high power density and life [11]. Electro-chemical energy storage systems are selected in this study because of their property to save energy for a long time and suitability in solar integrated system.

To balance power generation and demand, the storage system can mitigate the effect of RESs' stochastic nature on the microgrid. This can be accomplished by charging and discharging the storage system during excess and deficient RES energy, respectively. Battery charging and discharging intervals for residential buildings can be regulated based on solar power output and real-time energy costs. The battery's performance is determined by the storage system's parameters. Different types of BESS are classified here,

Table 1 Classification of Electro-Chemical Energy Storage Systems (ESS) [10,11]

ESS type	Lithium ion	Lead-Acid	NaS battery	Redox flow Vanadium battery	Hydrogen fuel cell
Capacity(kWh)	250-2500	250-5000	<300000	<250000	33kwh/kg
Power (MW)	upto 100	up to 100	up to 50	up to 50	~1
capital cost(£/kW)	300-600	50-150	250-400	100-1000	45-50
Response time	<1s	<1s	<1s	<10min	<1s
Discharge time	<1h	<4h	~6h	~8h	>1h
efficiency %	~90	~75	~80	~80	35-45
Lifetime (Years)	~15years	~20	~15	~10	1-1.5
Cycles	<10000 times	2000 time	2500-6000	10000-16000	50,000
Adv.	High efficiency, Low maintenance	less costly compared to Li-ion	extended life and great power density	Not explosive	Reliable, less harmful to the environment, and less noisy

Disadv.	Ageing	excessive upkeep and efficiency less than 80%	High maintenance	low density for stored energy	Hydrogen storage is expensive, and there are some safety issues.

The chemical energy is transformed to electrical energy and made available as an electric current at a predetermined voltage in electro-chemical storage devices. The primary benefit of this sort of storage is that devices of any size may be developed and built based on Voltage-current availability [10,11]. Classification of different electro-chemical ESS are shown above. Where the lead-acid battery has been around for over a century and is presently the most common rechargeable storage technology. It can be used for an uninterruptible power supply because of its efficiency, cell voltage property, and inexpensive advantage. With low specific energy and short cycle life, traditional lead-acid batteries need periodic maintenance, and they can fail unexpectedly due to a chemical reaction called sulphation. These batteries are very quiet simple to recycle, but lead is a toxic material that can harm the environment [77].

Lithium-ion batteries (LiBs) have been the most extensively utilised technology in electrochemical energy storage since the 1990s [10]. LiBs have a high energy density, a high efficiency (~90%), a quick response and an attractive self-discharge rate (refer table 1) [12]. Lithium's rapid reaction and nature of less weight make it ideal for battery production. But the drawbacks included are low depth of discharge (DoD) cycle, and the high cost of the materials is an issue [11]. The cost and safety issues factors are the problem when using this in the power system. The Tesla company developed the powerwall lithium-ion rechargeable battery that can stores energy in an advanced way and it can detect outputs automatically, and so can reduces reliance on the grid [15,16]. They are claiming that their new battery has 100% depth of discharge and a 20-year lifespan. Tesla's advanced battery research department published an article on a nickel-based battery that last 100 years while charging with high efficiency [90].

Hydrogen fuel cells (HFC) have grabbed the interest of both academics and industry due to its promise for zero-emission energy generation [13,11]. In [14,11], it is mentioned that

Hydrogen has a high specific energy (142 MJ/kg), and the water vapour the only by-product of Hydrogen storage cell. The benefits of the use of hydrogen as an energy vector are, sustainable development, energy security, etc. The barriers are increased production cost, liquid hydrogen storage, etc. The unavailability of an efficient hydrogen infrastructure, high-risk factors like complexity of the integration into the energy system, burning properties of hydrogen in the presence of air, system integration issues, and high cost are the disadvantages [17]. In [43], ratio of self-sufficiency and Net Present Value is compared between Battery and hydrogen storage system, and the results show that battery storage are more self-sufficient than battery under the same cost function as hydrogen storage, and the ratio difference between these two systems grows when the NPV decreases. At last, this study suggested that hybrid battery and hydrogen storage can adopt the benefits of both system. So, Hybrid batteries and hydrogen systems are the best options for future energy systems. Future energy storage systems for residential applications have to be above 90% efficient and should have good switching properties. But in this study, the characteristics of lithium-ion battery is considered for the analysis because it efficiency and high energy density. .

2.3.2 Challenges and problems of ESS

1. Size & cost: Sizing is critical for assuming ideal and cost-effective microgrid operation. If the energy storage capacity is insufficient, it might not be able to deliver the required economic advantages. If it is larger than the required size, then it would impose a higher cost. The right sizing of ESS will justify the investment and benefits over time. Total cost of ESS= Operational expenses + Capital Expenses [78,11].

   Capital expenses increases linearly as the size increases and Operational cost expenses decreases with increasing size. The optimal size of ESS is the lowest value of total cost.

   The implementation challenges of ESS are the cost and size. The size and cost characteristics of the battery storage system are shown in table 1. The cost of the system depends on the material used for manufacturing, operation time, capacity, and life cycle. But the optimal scheduling or operation of ESS can reduce the cost challenges. [78]

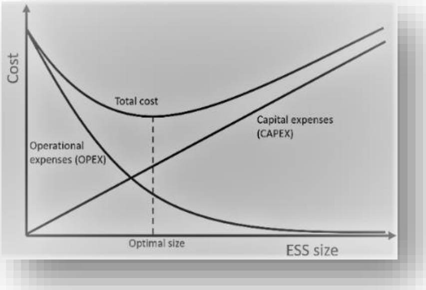


Figure 7 Optimal Sizing of Battery [11]

2. Materials availability: Materials availability challenges faced due to the concerns about the sustainable supply of the materials and the difficulties encountered because of high geopolitical concentrations and the availability of environmentally friendly materials. [77]

3. Environmental impacts: Despite their overall positive impact, ESSs have little impact on the environment in terms of air, water, or soil pollution during manufacturing, disposal, and recycling. This is especially true for technologies based on electrical energy systems. The majority of the environmental impact is attributed to the mining of its raw materials, such as cobalt and lithium. Furthermore, the post-processes cause a variety of respiratory, neurological, and pulmonary diseases [11,18]. As a result, proper safety precautions and new technologies in the manufacture, maintenance, and disposal of ESSs are required because in [79] it is mentioned that cobalt lithium materials mining causes lots of environmental impacts so this material using for the manufacturing of ESS also leads to environmental issues.

2.3.3 BMS (Battery Management System)

In this section, the relevance of BMS, its type, and its expected developments are explained. The performance of Electro-chemical batteries used for PV application is relying on chemical reactions. The battery pack will be consisting of different battery cells which have their own properties like internal resistance, capacity, etc and this property may change due to the temperature and load current which may impact the present state of individual cells. An uncontrollable self-discharging inside the battery cell may increase the temperature inside the cell connection (because weak cell can discharge energy quickly than others). This temperature variation lead to thermal run way affect. The small variation in the cell will not lead to increase temperature more but the discharging efficiency will reduce gradually. To maintain the battery operation, to protect them from damages, and for the power balancing issues mitigation, BMS is necessary. It is a system control unit that is designed to assure the battery pack's safety operations [47]. The usage of BMS can increase the life cycle of the battery. If the ESS is a lithium-ion battery then the battery should charge and discharge within the 20 to 80% energy level, otherwise, there is a chance to occur blasting. By limiting the batteries state of Charge (SOC) within this constraints, battery life can increase. Cell imbalance is a major problem in big-size battery packs that reduces the battery performance (State of Health). When the battery pack discharges energy below its limit, the weakest cell in the combination of cells discharges the energy very quickly which causes hazards and thermal runaway. The BMS consists of circuitry to monitor the voltage and temperature across each cell. This monitoring analysed by the balancer inside the BMS. Based on the SOC (state of Charge), cell balancing is classified into two methods: passive and active cell balancing [49,52]. Where passive balancer is the most commonly used type in the present case. The Future BMS balancer will be an active balancer. The different balancing simple image is shown below. The passive cell balancing method equalises the SOC of each cell by dissipating energy from high SOC cells to the resistor and maintaining the cells with same level of charge. Likewise, the active cell balancing method is a non-dissipate balancing technique that uses storing elements to equalise the level of charge in each cell by transferring energy from the cell in the battery with highest level of charge to the cell with lowest. The passive cell balancing method is applicable for low power applications because of its less amount of heat dissipation and extended balancing period and the active cell balancing method is applicable for high power applications because of its lower speed for balancing and higher efficiency [37].

So, an active battery monitoring and managing system (BMS) is required to extend battery life, sfety of the device, and monitor of each cell's voltage and energy levels is necessary [48].

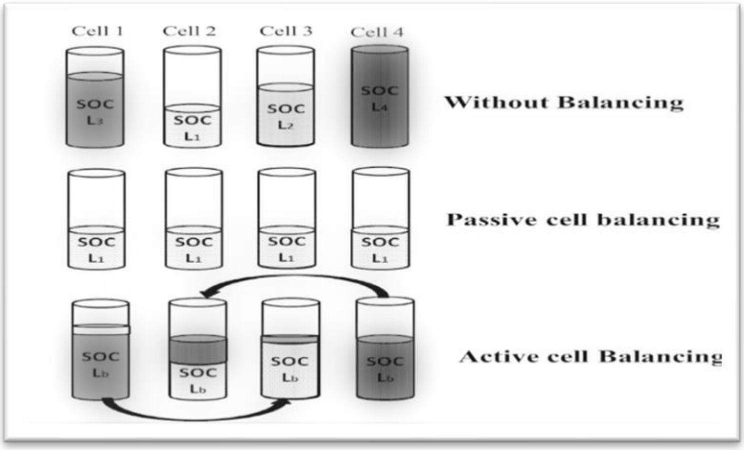
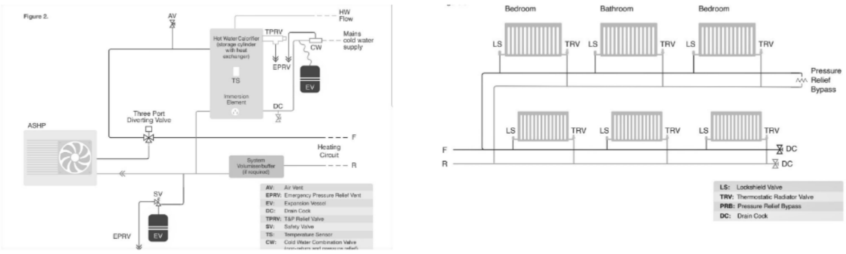


Figure 8 Battery Balancing concept based on SOC of Li-ion battery [49]

In future BMS for the home applications will be use active balancing method with smart control techniques to improve the life of battery, the perfect operation will reduce the safety issues and the operational cost and expenses can be reduced. The future BMS can communicate with the home energy management system for the perfect utilisation of stored energy in the battery. This is an unavoidable module for smart control applications in the future energy system or home network.

2.4Heat pump

Due to rising fuel costs, government policy, and the shift towards net zero transition domestic heat pumps installed in Uk have increased gradually over the last years (installing around 20000 heat pumps every year) [92]. The general working of the heat pump is, taking energy from the air, the ground, or water and delivering this energy as heat through hot water or a heating system. The type options are Space heating Heat pump (SH HP), Domestic Hot Water Heat Pump (DHWHP), and Combined Space Heating (SH) and Domestic Hot Water (DHW) Heat Pump. Among them combined heat pumps are the most installed type of HP (refer Figures 7 a & b)).



a) DHW b) SH

Figure 9 Combined heat pump [28]

Heat pumps are well-suited for fully functional smart controls. That means, enabling and disabling the equipment is possible according to the supplier's signals on the basis of grid information. This information can be in terms of variable tariff, time, etc.

Main space heating controls are Time controls, Temperature controls, ambient air temperature load correction, and optimised controls. The intermittent time-controlled heating, to return the building to design conditions, the plant is turned OFF at the end of the predicted building occupancy period or occupancy activity and turned ON before the next period of predicted occupancy. [28]. The continuous time control system has no particular time control, and its control system is ON for all time, but its operation depends on the temperature sensor. The combined intermittent and continuous time control is an effective way of control, the system with this control is continuous and enabled all the time but the temperature settings change during the daytime. Both controls in one will determine the working of the system. Weather compensation or ambient air temperature load correction efforts are used to improve the efficiency of the HP during seasonal operation by temperature flow reduction. Different temperature controllers for SH are, set point controllers (simple user interface control), radiators with trimming control, individual room temperature control called underfloor heating, etc. Where HP operation is controlled with the help of thermostatic devices [28]. Possible future smart control of heat pumps will be influenced by the spot price of electricity. Such smart control would enable systems to store heat in a domestic water cylinder or other heat storage system, during low demand periods with lower electricity prices and lower emission factors. By doing this, consumers such as household energy cost bills can be reduced, and this method will be useful for the net zero transition world. In this thesis, heat pump control is not included. But effective control of heat pump can reduce energy consumption or cost by minimising the thermal energy into the minimum border level during the high peak energy cost times.

2.5Tariff

An energy tariff is a fee that an energy provider charges a customer for the use of gas and electricity. Tariffs are classified into two types: fixed rate and variable rate. A fixed-rate tariff locks in the cost of energy for a set t period of time, typically one year or more, whereas variable tariff prices fluctuate with the market [21]. In this section, different type of tariff and the selection of the perfect tariff for a household is explained. For the components control, cost reduction, and performance analysis, octopus Time of Use tariff rates are considered for importing energy, and fixed outgoing rate for export energy is considered. At last, for the future energy system cost analysis, green tariff rate provided by Octopus energy is selected.

2.5.1 Fixed tariff

The fixed tariff guarantees consumers energy price for a set period of time (usually 1- 2 years). After this period, it's free to switch again, but the supplier can charge an extra fee if the customer leaves before the agreement. The fixed tariff rates help to keep customers' budgets without confusion and that rate will be lower than standard tariff rates. For example, due to the energy crisis in the UK caused gas and electricity prices to skyrocket. These price changes will not be affected if the consumer has a fixed rate tariff and the cost per kWh will remain unchanged. Most fixed rate tariffs become more expensive now than the variable tariff and the fixed rate may vary by region and meter type.

2.5.2 Variable tariff

Energy prices for this type of tariff can fluctuate depending on the market and can be inexpensive. This can be advantageous when energy prices are falling, but the customer must pay more when they rise. Variable tariffs can be a major issue if the energy market experiences a sharp increase.

2.5.3 Export tariff

This type of tariff applies to what energy companies pay to the consumer. It applies only if the consumer of energy company generates their own power, such as with solar panels. Feed-in-tariff rates may vary on the capacity of installed PV. The government's feed-in-tariff program ended for new solar panel installations. But outgoing smart export tariff of Octopus can pay customers for the export energy. For a home with PV and a battery, the outgoing

Octopus smart export tariff is a perfect option. They have two options, one is, a flat unit price and another is a half-hour day ahead of the wholesale price of energy at the time.

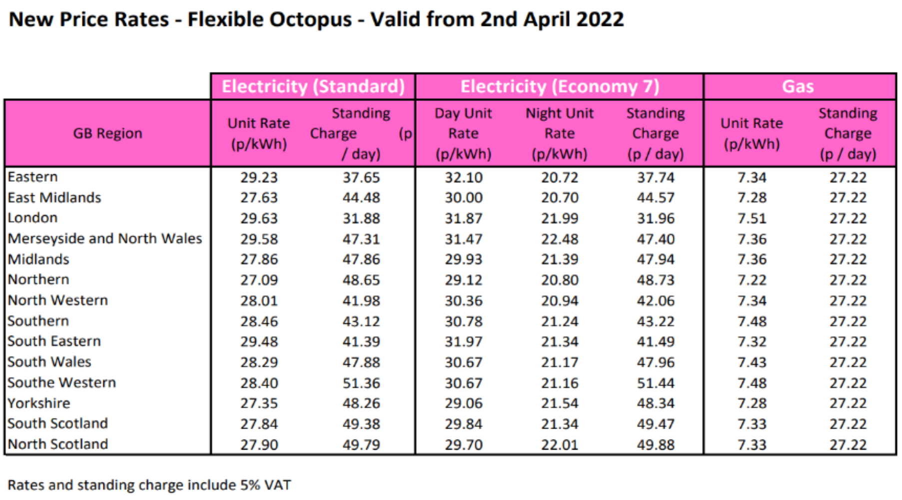
2.5.4 Time of Use tariff (ToU)

If Economy 7, Economy 10, or time of use tariff taken for consumers, they will get cheaper 'off peak' energy for either 7 hours or 10 hours a day.

Economy 7: - midnight and 7am

Economy 10: - spreads its cheaper hours set time throughout a day

Customers in the energy market have two primary charging policies: Real Time Pricing (RTP) and Time of Use (ToU) tariffs. RTP deals with both retail and wholesale power pricing. Tariffs under the TOU provide the client with two or three pricing tiers (peak, and off-peak prices) [34]. Off-peak rates are cheap, but energy rates other than the off-peak period rates are high. If the smart way of usage arranged by the consumer can reduce energy costs as much as possible. The cheapest Economy 7 period of time is the 7-hr span between 23:00 to 8:00 am (From 23:00 to 6:00 is selected for this thesis [32]). Other than peak and offpeak rate, the standing rate per day will chargeable for every day whether or not the consumer use electricity. The best energy supplier for 2022 is Octopus Energy and their new price rates of flexible octopus are shown in figure 10. The rates changes and value depends on the Great Britain region [31]. For the analysis, the electricity price of the north- Eastern England Eco 7 electricity price for import energy, and fixed feed-in-tariff rate for outgoing energy are selected.



New Price Rates - Flexible Octopus - Valid from 2nd April 2022

	Electricity (Standard)		Electricity (Economy 7)			Gas	
GB Region	Unit Rate (p/kWh)	Standing Charge (p / day)	Day Unit Rate (p/kWh)	Night Unit Rate (p/kWh)	Standing Charge (p / day)	Unit Rate (p/kWh)	Standing Charge (p / day)
Eastern	29.23	37.65	32.10	20.72	37.74	7.34	27.22
East Midlands	27.63	44.48	30.00	20.70	44.57	7.28	27.22
London	29.63	31.88	31.87	21.99	31.96	7.51	27.22
Merseyside and North Wales	29.58	47.31	31.47	22.48	47.40	7.36	27.22
Midlands	27.86	47.86	29.93	21.39	47.94	7.36	27.22
Northern	27.09	48.65	29.12	20.80	48.73	7.22	27.22
North Western	28.01	41.98	30.36	20.94	42.06	7.34	27.22
Southern	28.46	43.12	30.78	21.24	43.22	7.48	27.22
South Eastern	29.48	41.39	31.97	21.34	41.49	7.32	27.22
South Wales	28.29	47.88	30.67	21.17	47.96	7.43	27.22
Southe Western	28.40	51.36	30.67	21.16	51.44	7.48	27.22
Yorkshire	27.35	48.26	29.06	21.54	48.34	7.28	27.22
South Scotland	27.84	49.38	29.84	21.34	49.47	7.33	27.22
North Scotland	27.90	49.79	29.70	22.01	49.88	7.33	27.22

Rates and standing charge include 5% VAT

Figure 10 Flexible Octopus according to the region [31]

2.5.5 Green tariff

Green, 'eco,' or renewable tariffs can work in a variety of ways. One option is that whatever amount of energy households use is 'given back' to the National Grid by the supplier of renewable energy. Alternatively, they may provide your home with 100 percent renewable energy, a mix of renewable and non-renewable energy, or they may contribute to environmental projects instead [21]. The greenest tariffs, according to the Energy Saving Trust, are those in which the energy supplier purchases renewable electricity directly from generators such as UK wind or solar farms. It claims that this will benefit the UK renewable industry significantly [21]. Future tariff will be Eco or renewable tariff, apart from the current electricity tariff rate variation, future tariff price will be completely weather depended and cost will be high in winter and night times. The energy cost for the upcoming year will hike more, because of the huge deployment of decarbonised sector and which leads to the increase development cost, so, energy cost for consumer (refer Appedices II) [91].

2.6 Forecasting

This section explaining about different data forecasting and its importance in energy management systems. Forecasting is essential for efficient scheduling of power distribution and for controlling renewable energy system in microgrid. It is a strategy for predicting future energy requirements to establish demand-supply balance [51]. Forecasting techniques are mainly classified into three, these are, short –term, medium term and long-term forecasts. The short-term forecast represents the forecasting of required data for time interval of a few hours to a few days, the medium-term forecast represents the forecasting of required data for time interval of a few months and the long-term forecast represents the required data forecast over a time for years [57]. The accurate short-term energy generation and consumption forecasts improve unit commitment by creating unit operation schedules & operating planning, increasing dispatch efficiency, reducing reliability issues, and therefore reducing the operational requirements in the system [56]. For energy cost reduction, the power generation and consumption forecast method for real-time dispatch application is suitable.

2.6.1 Load forecasting:

Electrical generation should follow the electrical load demand for an optimal operation and scheduling. Predicting fluctuations in electrical load is extremely difficult. In an electric network, supply and demand must be synchronised in terms of frequency and power, so, forecasting the load consumption is necessary. As a result, energy providers and microgrid energy management system modules utilise electric load forecasting algorithms. Load forecasting is a technique for anticipating future load demand based on physical features of the network such as temperature, losses, and others. An unwanted power supply may be avoided with the aid of this forecasting method. That means, electrical failure such as blackouts and breakdowns caused by excessive loading can be avoided if sufficient attention is given to the load demands [50]. The block diagram below is developed as a concept and it is expected that these are the inputs needed to predict the load. were, sensor data can be consisting of the occupancy and state of each electrical equipment.

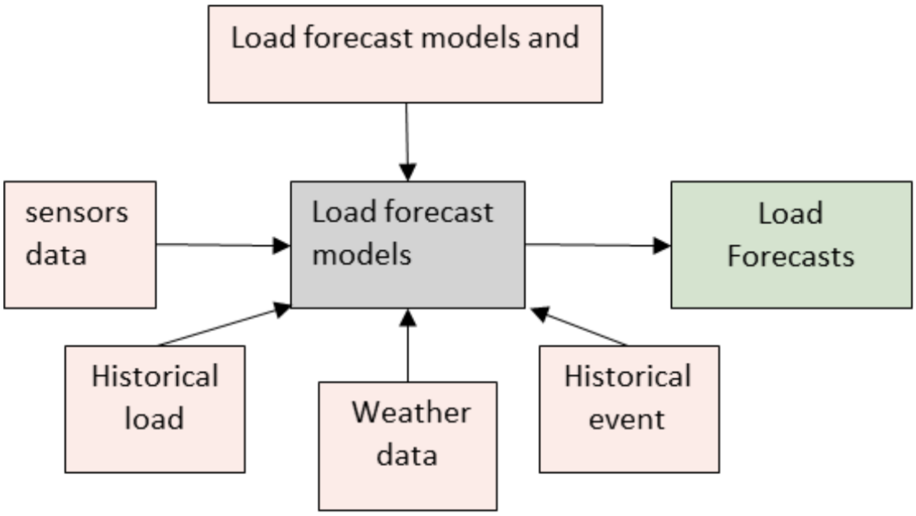


Figure 11 concept based load forecasting

2.6.2 Weather forecasting:

Weather predictions are mostly used to forecast RES generation in microgrid or HEMS. Weather data is a critical input for scheduling the components. Previously, some studies analysed the prediction of solar generation directly taken without using weather forecasts datas. In general, projections are made by adding stochastic behaviour into historical PV production series with the help of meteorological variables, or PV power estimates are obtained from forecast services or derived using time-series forecasting algorithms from local power data. Some examples of time-series forecasting techniques are, autoregressive method, ANN, etc [53]. The PV power estimations are derived from weather forecasts and the meteorological data transformed into power estimates by using PV models (model based on real PV panels [54] or theoretical PV power equation [55]). In most cases PV power production depends on the typical meteorological parameters such as irradiance and temperature. Advanced weather forecasting systems use live and historical meteorological data and create forecasts using developments in digital technology such as artificial intelligence (AI) and big data [56].

Figure 12 shows how the weather forecast can be used to predict the solar power output. With the help of big data of historical weather of the particular site and numerical forecast models, the air temperature and solar irradiance are predicted by comparing the sensor data after the bigdata processing. From the forecasted weather data, by considering the practical system characteristics and its availability power generation can be forecast.

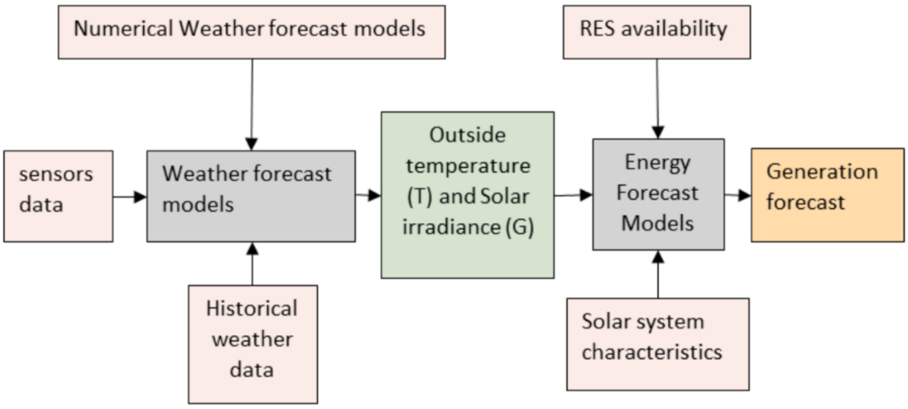


Figure 12 weather forecast and Solar power forecast [56]

2.6.3 Battery level forecasting:

For an optimal, reliable, and smooth smart control application for batteries, forecasting models are used. The most important aspects of battery management is predicting the State of Charge of a battery. The internal chemical processes of lithium-ion batteries are complicated; its SOC (State of Charge) prediction has significant nonlinear properties. Forecasting models for SOCs are mainly used to calculate the realistic charge and discharge schedules for cost-effective and efficient operation [61].

2.6.4 Electricity price forecasting:

Electricity price forecasting is necessary to perform an optimal control operation for home applications. The factors affecting the future electricity price variations depend on the weather (temperature, wind power, humidity, precipitation etc) and the variations in the daily activity which influence electricity consumption and pricing (off-peak, peak and weekend, etc). The instability of electricity prices is caused by the inability of electrical energy to be stored and the variation in energy demand [58]. Anyway, octopus provides their agile API to utilise energy greener and cheaper, which can be utilised for smart control applications [59],[62]. API or application programming interface is a way to communicate between computer programs. It is possible to make an API if we have the required data. The different methods for API creation are included in [60].

2.6.5 Forecasting technique relevant for future energy systems for residential applications

This section explaining about an overlook into a forecasting technique for an understanding of the relevance in future system. Different forecast techniques are available such as linear regression, state space method, Knowledge-based expert approach, Artificial Neural Network (ANN), etc, among them, ANN is a highly accurate and useful technique, and this can be used for the future controller [50]. In this thesis, the training and data analysis that uses ANN is not included but it will be suitable for future works. Here, a detailed explanation of this technique is included.

In artificial intelligence, a non-linear model called ANN has a future in energy systems because it is a scientific computing network that mimics the properties of the human brain [64,65]. Now ANN have been widely employed in a various field to solve complicated issues which requires optimization, power balancing and forecasting. Which the help of machine learning software, datas can be trained to solve complex and confusing situations [66].

For load forecasting, battery level forecasting, and renewable power forecasting in home energy management systems, ANN-based controller module can be used. For a perfect data prediction, training in big data input-output performance is necessary. So, before installing a management system with forecast techniques, historical performance and events bigdatas are required. This controller can predict any of complex combination of power variations so, the energy management system can avoid upcoming complexity due to faults, blackouts, or deficiency of energy in the network.

The basic processing component of the ANN is neurons that are programmed to receive input, process input, and predict the output. The schematic diagram of ANN neuron is shown above. In most cases, the real number of signal connections between neurons with the help of non-linear function of its input combinations calculates the predictive output [50]. So, this technique is suitable for load forecasting, Solar PV power forecasting and SOC forecasting.

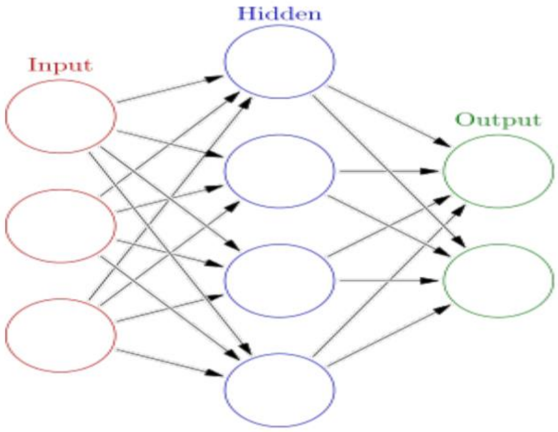


Figure 13 ANN technique [50]

2.7Summary

Following the background research on EMS, it is apparent that it will play an important role in the future system. To lower a household's energy costs, two control strategies are available: supply-side management and demand-side management (section 2.1.0). The majority of the studies focused on load shifting control and the scheduling strategy of energy storage devices. The supply-side management component is taken into account for this project. Following an examination of the devices' adaptability and usefulness for the future smart system, the potential of source scheduling in practical application is accepted as an understanding. Solar systems are flexible renewable energy systems for residential applications, and in order to utilise their output, an energy storage system is required (explained in section 2.2). Because of their appropriateness in solar integrated systems, electro-chemical storage technologies are used. Following a rigorous evaluation of several energy storage systems, hydrogen storage has a future in the net-zero transition world, but due to efficiency, affordability, and safety concerns, the specifications of a lithium-ion battery were chosen for this study. Its efficient charging and discharging schedules can help to save energy costs. The necessity of heat pumps in the future system is discussed, as well as their potential for energy reduction strategies. As a result, heat pumps for both space heating and water heating will be included in the study of household power use. Energy rates in the energy market are evaluated to determine the optimal cost-cutting technique. For this study, the Time of Use tariff rate for import and fixed price for outbound were adopted for the investigation of current market costs. The significance of various forecasting methods and the ANN approach for future development is examined for comprehension. The importance of different forecasting and the ANN technique for the future development is carried for an understanding. In the next section modelling and the how different control aspect can help to reduce the energy consumption from grid are mentioned in detailed.

3.0 System Modelling methodology

This area includes component selection, calculations, and modeling or control processes that aid in the evaluation of supply-side management strategies. Where demand side management and accurate forecasting techniques are absent. The emphasis is mostly on the importance of ESS in the future energy management system for cost-cutting objectives and its control strategies according to the energy price for reducing energy purchase from utility. To evaluate the real electricity consumption from grid, and to develop battery performance according to the renewable energy availability, big data like load consumption, weather data and energy price rates are needed. For this required data, CREST simulation tool [3] is selected to generate data set.

This study is concentrated for a single-family house in UK with electrical and thermal load. So, the stochastic load patterns are based on single-family house data extracted from CREST simulation tool [3]. The inputs that are given to generate required per day load profile are, equipment preferences, occupancy rate, house type, location, date and month, and weekday or weekend day selection (to predict the activity). According to the finding preferences, energy consumption and weather datas are taken from this tool. But it is difficult to extract per year datas from this tool so, for a simplicity, 7 days datas for every 4 season is considered and that repeated for each seasonal weeks and it is take it as an annual data. This method is not a perfect way to show an actual analysis. But this is the method I have carried out for the annual analysis because of the time limit to process big data. After considering the load consumption next step is to model the system components. For that, battery and solar PV equation-based models are selected and rated values for this component are calculated by considering per day average value of energy consumption

3.1Residential building

Flats, terraced, semi-detached, and detached buildings are the four primary property kinds, a look at the UK landscape as a whole indicates that semi-detached properties are now the most common residence, accounting for slightly over 30% of the total national housing stock and 60% of population living in this type of property [82].

Here Improved semi-detached residential building with 87m^2 floor area for 2-3 residentials is considered as an example model [3].

Table 2 Residential Building Parameters [3]

Building Type	Improved Semi-detached
Floor area, living space	87m^2
Height, living space	4.2m

The appliances for generating the electric load profile selected from CREST simulation tool these are fridge, TV, oven, Microwave, kettle, dishwasher etc. The main data collected is thermal demand for both for water heating and space heating and calculated the corresponding electrical demand with the help of Coefficient of performance (COP) and the efficiency of the boiler(80%) is taken (because I simulated the semidetached house with 2-3 people and using boiler for the thermal energy).

Electric demand of WH or SH = Thermal demand in W/COP*0.8

The value of COP in pleasant weather is 4, and when the temperature falls below 0 degrees, the number drops to 2.8. This is thought to account for the production of electric demand. The load consumption data for control strategies is the combined electrical demand of appliances and the electrical demand of HP is estimated from the thermal demand required.

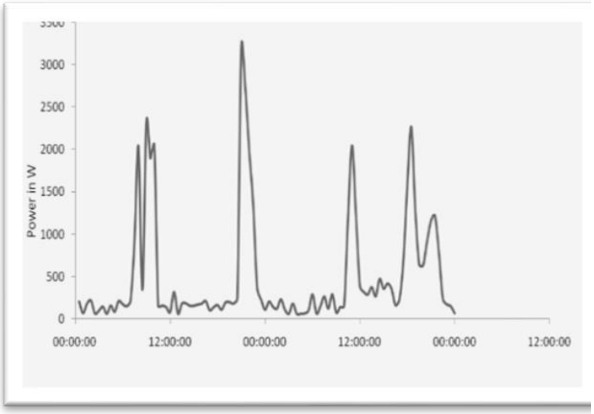


Figure 14 Summer Electric load demand in W [3]

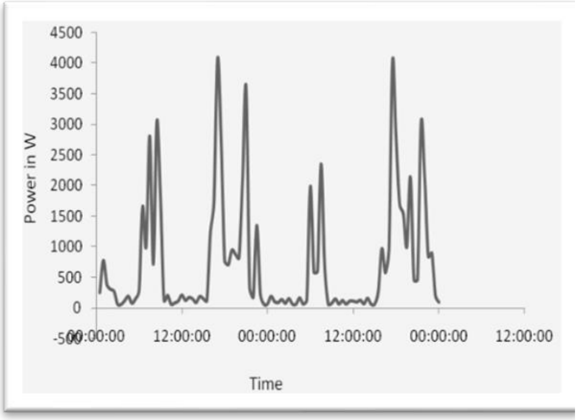


Figure 15 Winter Electrical load demand in W [3]

Based on the location, occupancy, and climatic data presented above, a load profile was created using the CREST simulation programme. [3]. Figures 14 and 15 depict the two-day electric load profile of a residential building on summer and winter weekdays, respectively. It has been discovered that the most activity happens at night or early in the morning (cooking and similar hobbies are popular before going to bed). The usage of electricity for thermal energy is also covered here. Due to the high energy consumption requirements for space heating and water heating, electric use is particularly high during the winter season.

3.2Energy Storage System

Uncontrollable operation of ESS may lead to some safety issues (refer section 2.3.3). This section explaining about the battery constraints, equation models and the rated size calculation for the battery system.

3.2.1 Battery Constraints and Equation model

Equation based models for charging and discharging are represented here. [9]

During battery charging time battery energy level can be represented as:

$$Eb_{lev(t)} = Eb_{lev(t-1)} + (Pb_{ch(t)} * time\ resolution) \tag{1}$$

During battery discharging time battery level can be represented as:

$$Eb_{lev(t)} = Eb_{lev(t-1)} + (Pb_{dis(t)} * time\ resolution) \tag{2}$$

In Equation 1 & 2, actually battery charging and discharging efficiency have to be multiplied with the charging and discharging powers but for a simplicity these values are taken as 1.

The battery energy limits should be below and above of the battery maximum and minimum limits respectively. i.e.,

Battery constraints: [78]:

Battery energy level limits:

$$Eb_{lev_{max}} < Eb_{lev(t)} > Eb_{lev_{min}} \tag{3}$$

Battery Power limits:

$$Pb_{ch_{max}} > Pb_{ch(t)} > 0 \tag{4}$$

$$Pb_{dis_{max}} < Pb_{dis(t)} < 0 \tag{5}$$

$Pb_{ch(t)}$, $Pb_{dis(t)}$ = Battery charging and discharging power at t^{th} time.

$Eb_{lev_{max}}$, $Eb_{lev_{min}}$ = Maximum and minimum energy level of battery in Wh

$Pb_{ch_{max}}$,$Pb_{ch_{min}}$ = Maximum and minimum battery charging power in W

$$Eb_{lev_{max}} = SOC_{max} * Battery\ size \tag{6}$$

$$Eb_{lev_{min}} = SOC_{min} * Battery\ size \tag{7}$$

For a smooth operation, state of charge (SOC) of battery should be within maximum and minimum percentage. i.e, SOC_{max} =80% and SOC_{min} =20%

3.2.2 Battery selection

In this thesis, the combination of batteries is considered to make a battery system. Where the average electrical load of the residential building per year is calculated (by taking 7 days energy consumption from crest tool for each season separately and that converted to annual energy consumption) is approximately $5000\ kWh$. So, total kWh energy required from battery = per day average electrical load = $13.7KWh$

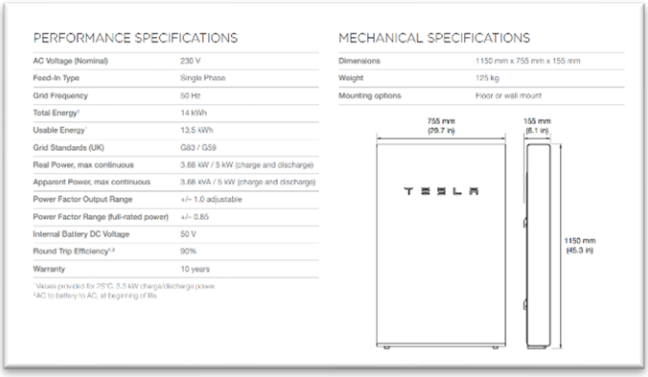
Battery size calculation equation taken from [86],

Assumptions: $Days\ of\ Autonomy = 2days,\ \ Depth\ of\ discharge\ (DoD) = 80\%\ (Li - Ion)$.

$$\text{Battery size needed} = \frac{Days\ of\ Autonomy * Per\ day\ average\ electrical\ load}{DoD} \quad (8)$$

$$= \frac{13.7 * 2}{0.8} = \sim 35kWh$$

So, 3 batteries of 12 kWh rating have to be taken. To check the area required to install the battery, Tesla's Powerwall 2 datasheet is considered. The performance and mechanical specification of Tesla battery is shown below (figure 16 [83]).



PERFORMANCE SPECIFICATIONS

AC Voltage (Nominal)	230 V
Feed-In Type	Single Phase
Grid Frequency	50 Hz
Total Energy[1]	14 kWh
Usable Energy[1]	13.5 kWh
Grid Standards (UK)	G83 / G59
Real Power, max continuous	3.68 kW / 5 kW (charge and discharge)
Apparent Power, max continuous	3.68 kVA / 5 kW (charge and discharge)
Power Factor Output Range	+/– 1.0 adjustable
Power Factor Range (full-rated power)	+/– 0.85
Internal Battery DC Voltage	50 V
Round Trip Efficiency[1,2]	90%
Warranty	10 years

[1] Values provided for 25°C, 3.3 kW charge/discharge power.
[2] AC to battery to AC, at beginning of life.

MECHANICAL SPECIFICATIONS

Dimensions	1150 mm x 755 mm x 155 mm
Weight	125 kg
Mounting options	Floor or wall mount

Figure 16 Specifications of Tesla Powerwall [83]

According to their specification, thickness, width and height of a 14kWh battery is only 6.1inch, 29.7 inch and 45.4 inch respectively. So, its sufficient to fix 3 batteries in a normal home wall (outside or inside) and utilisable energy from 3 Powerwall battery is 40.5kWh. For this analysis, 35-36 kWh battery only needed, so three 12 kWh battery is enough for this model and it is expectable that the size less than that of tesla's powerwall.

3.3Solar Power system

Solar power generation is depending on the solar irradiance(G), outside temperature(T), and size of the photovoltaic panel. Solar irradiance varies in different locations and is expressed as W/m^2. The PV panels can be operated in MPPT mode which uses maximum energy. MPPT examines the PV module's output, determining the best power that the PV module can produce and converting it to the best voltage to obtain the maximum current as needed.

3.3.1 Solar System equation model

If a PV system with Npv no of modules considered, then the power generated from the solar system at a particular outside temperature (T) and solar radiation (G) is calculated by using an equation provided in [9],

$$Ppv\ (t) = Npv * Prated * A * Effpv\ (G(t)/1000) * (1 - (T(t) - 20)) \qquad (9)$$

Here,

$Ppv\ (t) =$ PV power output in kW at tth instant

$G(t) =$ Solar irradiance in W/m^2 at tth instant

$T(t) =$ outside air temperature in ^{0}C at tth instant

$A\ =$ area of PV panel in m^2

$Effpv =$ Overall efficiency of PV system

The power generated by photovoltaic panels also depends on the maximum rated power of solar panel and other climate conditions and its specifications. The efficiency of commercial solar panels varies from 15% to 20% and the researchers have develop PV cells with approximately 50% efficiency [87]. But in this case, PV technology with 20% efficiency is selected for the calculation and analysis [63].

The solar irradiance and temperature for summer and winter selected is shown in figure below. Where the time resolution is 30 min (Here, x-axis 0.02 span =30min (refer appendices I table 10)). Solar irradiance and temperature are less in winter season. In figure 19 and 20, X-axis is the days and y-axis shows the temperature in degree C and in figure 17 and 18, y axis shows the solar irradiance in W/m^2. The solar power generation for the data analysis, equation 9 is considered to generate solar output model for every half-hour time.

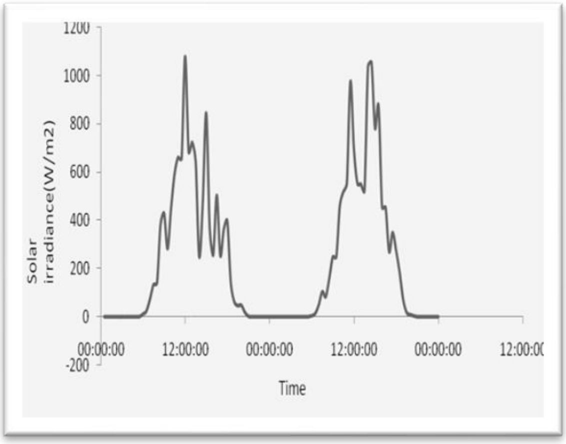


Figure 17 Solar irradiation during summer days

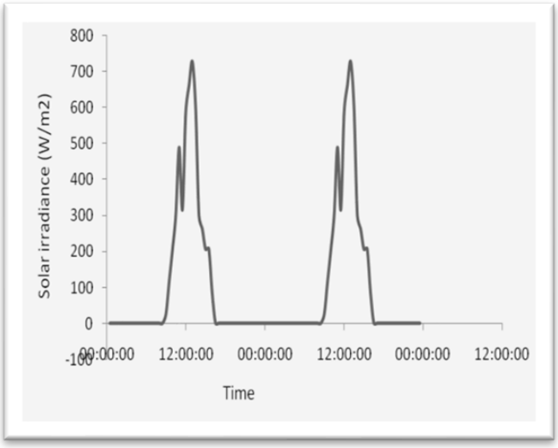


Figure 18 Solar irradiance during winter days

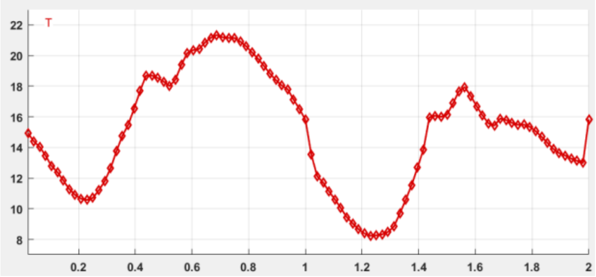


Figure 19 Summer temperature) [3]

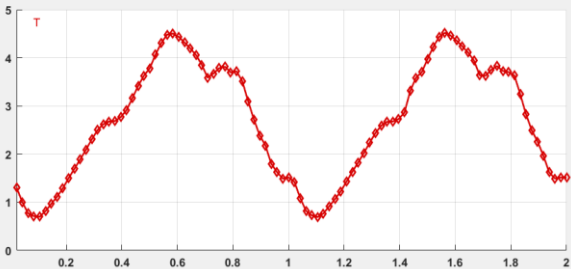


Figure 20 Winter days temperature [3]

3.3.2 Power rating and the size of Solar PV

The size and number of solar panels for this home are determined by considering the area of the roof of a residential building. Solar panels are installed in arrays, with the number of panels varying according to the available roof space and the rated power to be generated from PV. Most common individual solar panel area is 1.6 m2. These panels can then be linked together to cover the areas and generate more power. If a house needed 6 panels, then the area covered by that solar system is 9.6m^2, and the rated power is around 1.3kW [5].

Ground-based solar panels are an option if the building doesn’t have available roof space or a south-faced roof. But this method is not really recommended because of the shading problem and this option is suitable for the residential building with a large garden area.

Energy production prediction is critical for the design and installation of the PV system. Free software tools are available for predicting PV energy production, these are, Solar Advisor Model, PVGIS, PVSyst, etc.

PV selection

To figure out the size of the solar system required, first determine how much power is required from the solar system on a daily basis. The amount of daylight hours in the site region, as well as the size of the roof space, are other important factors to consider.

The normal size of one PV panel is $250Wp$ its area is considered as1.6m^2. The average load consumption of a small home is $13.7kWh$. Average annual daily sun hour of UK will not be exceeded 5hrs. According to statista's research, 4.7 hours was the average daily sun hour in the year of 2018 [85].

Rated power of PV = Electrical load consumption/Average daily sun hour = 13700/4.7=~3000W

For this project, approximately 16 Nos of $250Wp$ rating panels are selected. And its parameters are shown in Table 3.

Table 3 Solar panel parameters

One PV panel size	250
Area for one PV	1.6m^2
Suitable roof area of house (considered)	30m^2 [5].
No of panels (appropriate)	16 nos (25.6m^2) [5].
Rated power output of the whole system	3.5kW [5].

4.0 Supply-side control strategy and results

To visually analyse component performance, equation and performance-based ideas are created in Matlab/Simulink, where system component performances are parameterized to closely reflect the practical specification of energy system components. The input data for this study include electrical load, heat pump use, electricity price, solar irradiation, outdoor temperature, and PV and battery size. The cost study is based on the UK marketplace's energy costs. Assume that a house that relies only on the electric grid is linked to the PV and a battery to fulfil supply-demand power balancing and cost reduction. The performance of supply components in the energy network is discussed for houses with and without PV and batteries, as well as the projected consumption of energy for load from grid. To do this analysis, many instances are as follows:

1) A home energy system in which the electric load is powered only by the solar system and the electric grid. (case1)

2) Electric load power consumption from the solar system, electric grid, and energy storage system in a home energy system. Where the battery charges extra PV energy after taking into account load requirements and discharges energy at other times. (case2)

3) Home energy system with solar system, grid, and energy storage system electric load power consumption Where the battery charges low-cost grid electricity and discharges energy during peak periods. (case3)

4) Home energy system with the combination of case 2 & 3, where the battery charges low-cost energy from the grid and excess energy from the solar panel, and discharges energy at other times. (case4)

5) Future home energy system based on the green energy tariff rates. But the battery control concept same as in case 4. (case5)

In 1,2,3 and 4th cases, electricity cost calculation is done by using at present tariff rates.(Appendices III)

4.1Case 1: with 3 system components (grid, load, and PV)

A residential house load with PV and batteries is explored in this scenario. The major goal of this part is to demonstrate the relevance of PV for residential applications in terms of energy cost reduction. The load consumption in this case is just from PV and the grid.

If in any instant of time, solar power becomes more than the electric load, then the excess amount of power is directly sold back to the grid. Otherwise, a deficit amount of power will be taken from the grid supply.

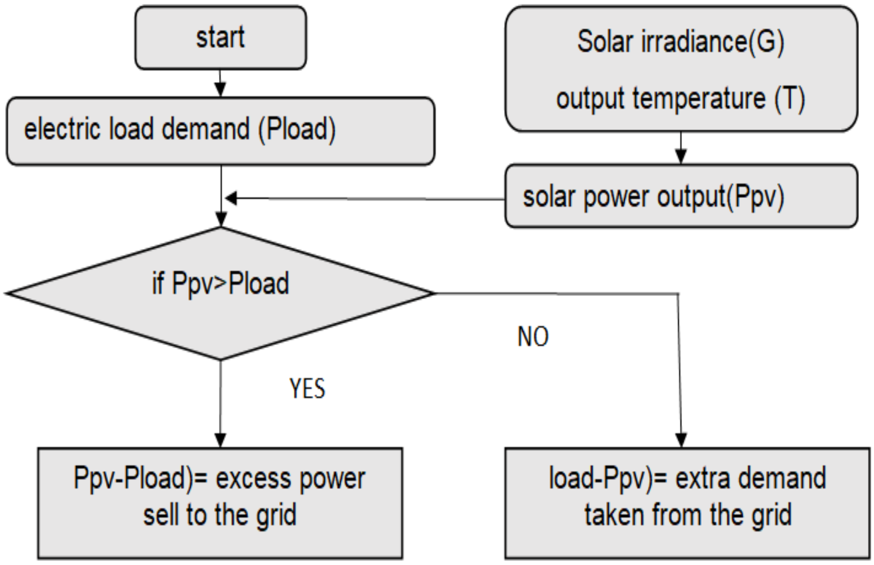


Figure 21 Flow chart - case1

Equation-based control strategy developed in MATLAB/Simulink by fetching data from excel sheets. Practically, output of solar systems are direct current but the load required ac power so, relevant converters are required, but here inverter parameters are not considered. The Flow chart shows the power management strategy that the energy management unit have to follow in this case. Where solar power generation is developed using Equation 9 with the help of Solar irradiance (G) and outside temperature(T) datas for every half hour instant. This PV power output is the main source for electric loads and the deficit amount will be analyse by the system controller program and according to the deficit value, necessary information will take to consume sufficient energy to balance the power to demand. Flow chart (figure 21) is developed before making the modelling in software.

The power balance equation in this case is,

$$P_{load}(t) = P_{grid}(t) + P_{pv}(t) \tag{10}$$

$$P_{grid}(t) = P_{load}(t) - P_{pv}(t) \tag{11}$$

$P_{load}(t) =$ Load power at t^{th} time in W

$P_{grid}(t) =$ Grid power at t^{th} time in W

$P_{pv}(t) =$ Solar power at t^{th} time in W

If $Pgrid(t)$ power sell to the grid is taken as a negative value for the cost analysis

If $Pgrid(t)$ power purchase from grid is taken as positive value for the easiness in calculation

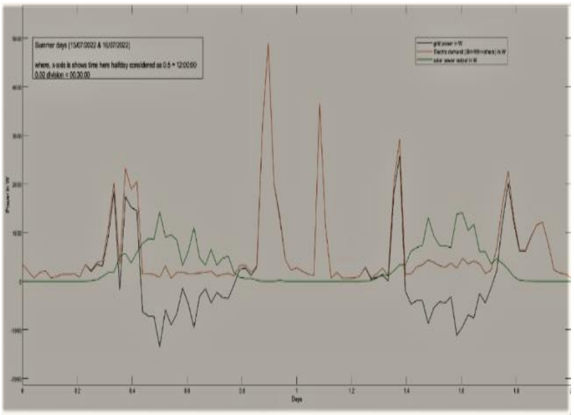


Figure 22 Summer power demand and consumption profile

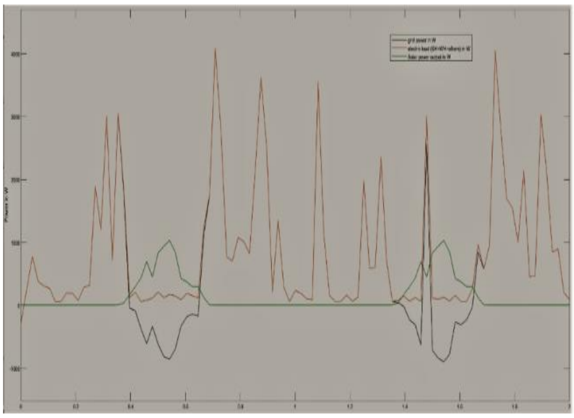


Figure 23 winter power demand and consumption profile

Figures 22 & 23 shows the power flow of PV output (Green graph), grid electricity (Black graph), and household energy consumption (Red graph) during summer and winter days (with data resolution is on half-hourly basis). This electrical load consumption is very low from 9 am to 5 pm due to the low occupancy activity rate during this period (these two days datas are of weekday occupancy prediction so, less occupancy in day time). during the daytime solar PV output is high, Occupancy independent load uses only this PV power output and excess will sell back to the grid.

The consumer with tariff plan of Eco 7 octopus tariff rates for importing energy from the grid is taken, Night (23:00 to 06:00) unit rate: 21p/kWh, Morning unit rate: 31p/kWh, and standing rate; 45p/kWh [31]. For outgoing energy, the octopus energy providing a rate of 7.5p/kWh. Standing charge is the fixed daily amount that the consumer has to pay every day and this rate does not depend on the energy used by the consumer. The consumer must pay this amount daily even if they didn't consume energy from the utility. According to this tariff rates, annual energy cost variation is calculated after adding 3.5 kW PV panel with the help of climate data and load consumption for a working family. Here, 4 seasonal separate one-week consumption taken to calculate the annual cost. The Table 4 shows the total expense comparison of the residential home with and without PV. This shows that after installing 3.5 kW PV system, selected household consumption can reduce 17% electric energy cost.

Table 4 Total energy expenses - case1

	Cost for total energy purchase from grid	Income after selling the energy to the grid	Total spent money for electricity by consumer
without PV	£1,608	£0.00	£1,608
With PV	£1,417	£80	£1337

4.2Case 2: with 4 system components (grid, load, PV and battery). Battery control based on excess and deficit solar power.

The goal of this example is to demonstrate the change in the system and energy expenditures after including an 36kWh Energy Storage System (ESS) into the prior scenario. Section 2.3discusses the various ESS and battery system options for this thesis, as well as an explanation of BMS. In this scenario, the solar power output controls battery charging and discharging. The load immediately consumes the solar power produced. If the PV generates more power than the intended load power, the extra power is immediately accepted by the battery, and it begins to charge up to its maximum limit level. This charged energy will be discharged at night or when solar power does not satisfy the needed load power.

Here power balance equation while discharging the battery is,

$$Pload(t) = Ppv(t) + Pgrid(t) + Pbat(t) \qquad (12)$$

If $Ppv(t) > Pload(t),$ then, $(Ppv - Pload) = P\_excess =$ excess amount from solar panel is stored by battery if the battery energy within its limits. (Battery SOC should be between 20% to 80% charge to reduce battery blasting issue)

Expected Battery power while charging,

$$Pb\_ch(t) = Ppv(t) - Pload(t) \qquad (13)$$

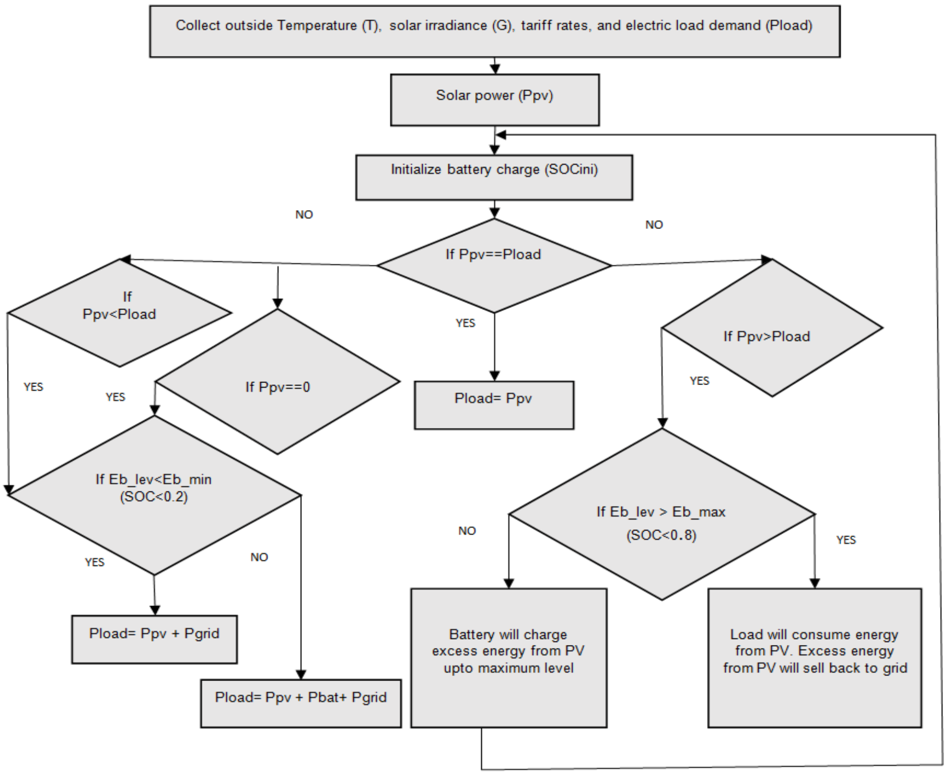


Figure 24 flow chart- case2

If P_excess value within the battery charging power and energy level limit (refer section 3.2.1), then this excess power charge by the battery within its limits or otherwise it will directly fed into the grid. i.e., if excess power from the solar system is generated while the battery is fully charged then this excess energy will sell back to the grid. Detailed flow chart is developed here (refer figure 24).

Expected Battery power while discharging,

If the battery level is within limitations and $\boldsymbol{Pload(t)}$ exceeds $\boldsymbol{Ppv(t)}$, the, expected battery power when discharging is, $\boldsymbol{Pb\_dis(t) = Pload(t) - Ppv(t)}$. If the battery level reaches its lowest, the battery should cease draining and demand power should be drawn from the grid after using PV power.

Figures 25 and 26 illustrate the two-day power values of the battery (blue graph), grid (black graph), load (red graph), and solar system (green) during the summer and winter seasons with half-hourly resolution. Figures 27 and 28 depict the battery's state of charge (SOC). To read state of battery from the graph, the positive power value when charging and the negative power value when discharging. Thus, battery power $\boldsymbol{Pbat}$ is the sum of charging and discharging power.

Table 5 Annual electric energy cost- case 2

	Annual Cost for total electric energy purchase from grid	Annual Income after selling the energy to the grid	Total spent money for electricity by consumer
without PV	£1,608	£0.00	£1,608
Case1: With PV	£1,417	£80	£1337
Case 2: with PV &battery	£1169	£26.56	£1142.44

Table 5 shows the overall yearly energy expenditure (electricity price same as previous case). As a result, it is concluded that combining PV and batteries in a residential building with 'case 2 control operation' may cut energy bills by around 29%.

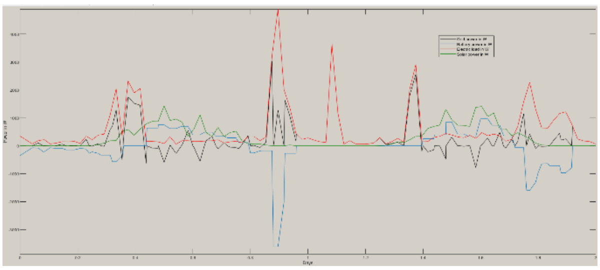


Figure 25 Summer days - power flow graph- case2

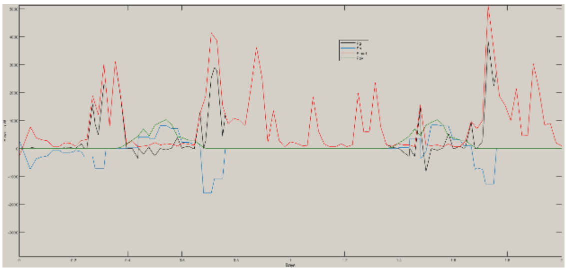


Figure 26 Winter days - power flow graph - case 2

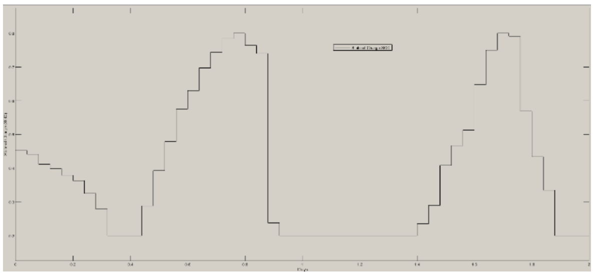


Figure 27 Summer days battery state of charge graph - case 2

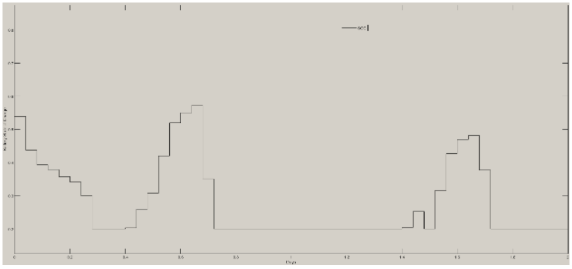


Figure 28 Winter days battery State of Charge - case2

Because the battery stored energy is very low during the winter season due to the lower power output from the solar system, the energy cost reduction value during this season is quite low. To make better use of battery operation for energy cost reduction during low air temperature seasons, battery control based on electricity cost fluctuation is discussed in the next section (4.3).

4.3Case 3: with 4 system components (grid, load, PV and battery). Battery control based on the electric price.

In this situation, battery scheduling is solely based on the cost of energy. The battery is not directly linked to the solar PV in this case. PV power generation is sent directly to the load, with any excess power sold back to the grid at any time. Battery charging is solely determined by the cost of electricity at the time of use (same rate as in case1). When the electricity price is very low, the battery charges energy and discharges that energy to load when the electricity price is at a peak cap. The flow chart is developed which showing the correct dispatching.

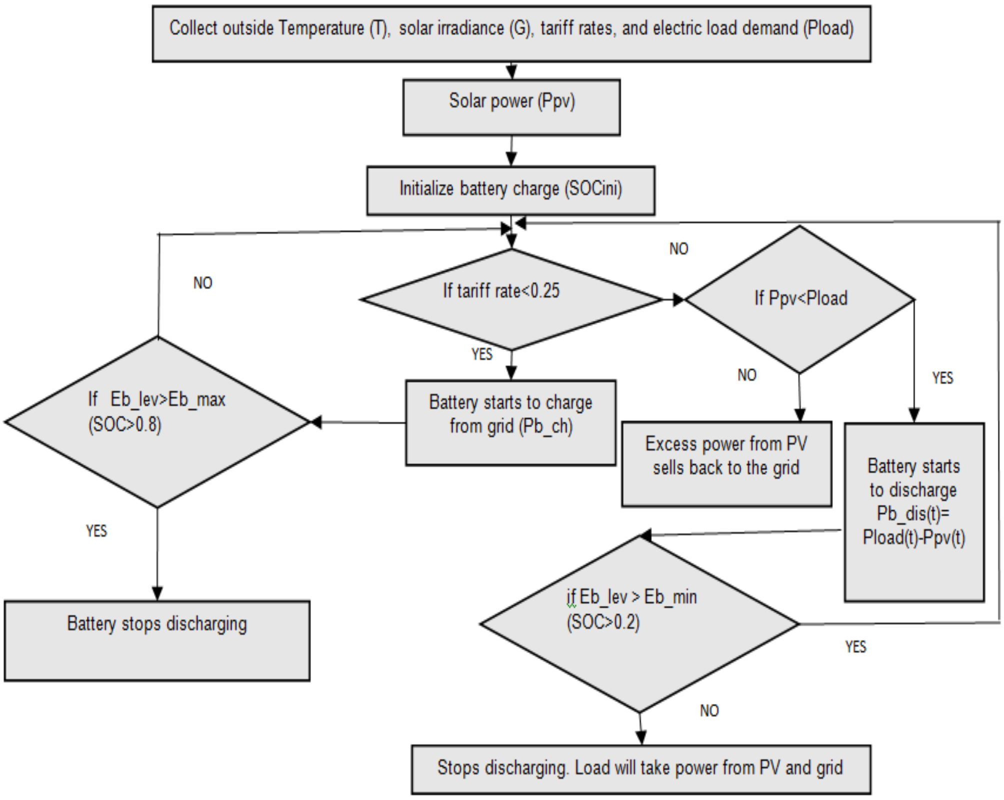


Figure 29 Flowchart- Case 3

After considering the input half hourly electricity price value, threshold values are generated and the battery will start to charge if the electricity price below threshold minimum tariff price (0.25p/kWh) and will discharge other time. But in algorithm used for modelling is considered 0.30p/kWh as the highest threshold tariff rate. When the electricity price become above 0.30p/kWh then the battery will start to discharge up to its minimum level energy value. The supply and demand consumption graph and corresponding battery state of charge graph during two days in summer and winter days shown below. In the both cases, battery charging up to its maximum value.

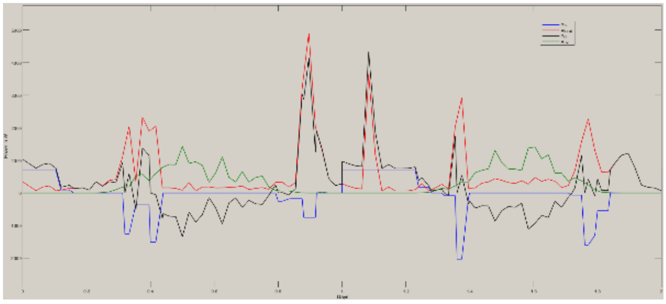


Figure 30 Summer power demand and consumption profile - Case 3

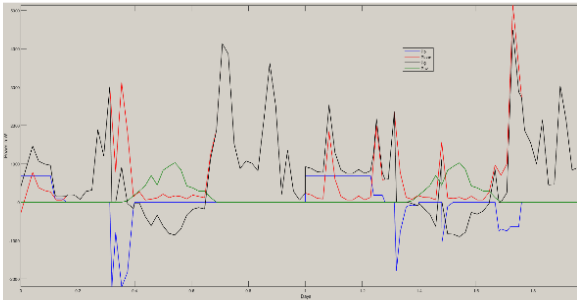


Figure 31 Winter power demand and consumption profile - Case 3

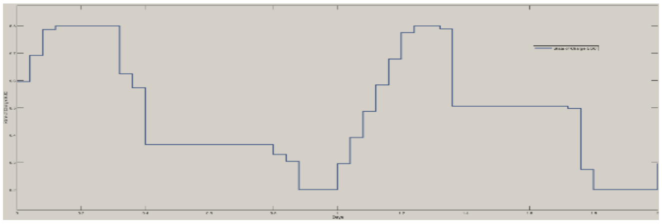


Figure 32 Summer days battery State of charge - Case 3

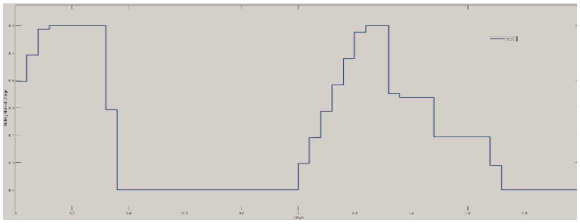


Figure 33 Winter days battery State of Charge- Case 3

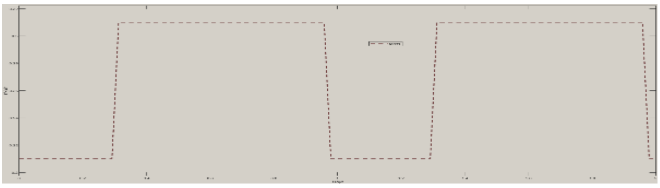


Figure 34 ToU tariff rates- case 3 [31]

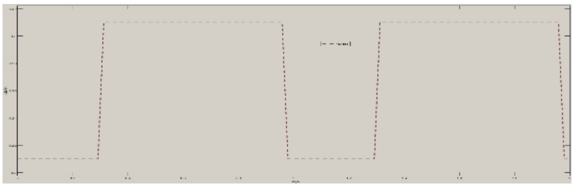


Figure 35 ToU tariff rates- case 3 [31]

Table 6 shows the annual energy expenditures incurred by employing this battery scheduling technique. Case 3 battery operation lowered energy costs by 22%. Because of the rise in grid buy rate and poor battery operation, this cost reduction value is less than the preceding instance.

4.4 Case 4: with 4 system components (grid, load, PV and battery). Battery control based on Time of use tariff and excess PV generation.

Case 4 is a hybrid of cases 2 and 3. Battery charging is planned in this situation when the PV generates surplus power or when the grid distributes electricity at a lower cost per kWh. Where the threshold value for the minimum tariff rate is the same as in example 3. However, the discharge period is not specified in advance. The battery cannot be charged and discharged at the same time, and their operation is completely governed by the battery management system. In this situation, the BMS and EMS work together to govern the charging and discharging of the battery. The system first analyses the performance of the other components and then operates in an optimised manner. Simulink was used to build the combined equation and rule-based algorithm. The combined equation and rule-based algorithm was created in Simulink. The graph of the power output from energy suppliers and load consumption of residential home during summer and winter days is shown below.

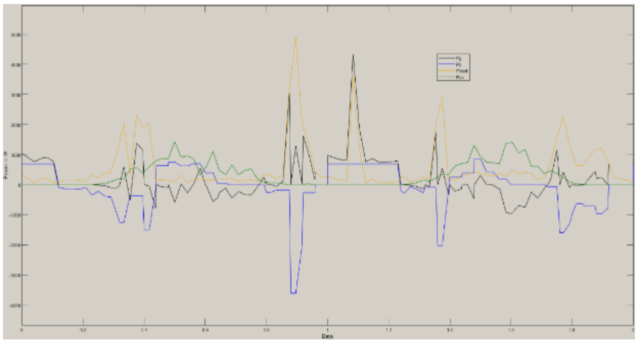


Figure 36 Summer days power demand and consumption profile

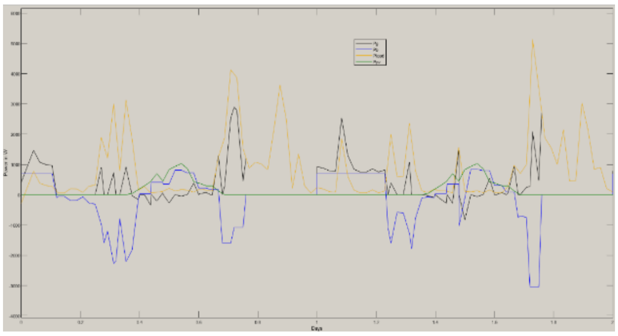


Figure 37 Winter power demand and consumption profile - Case 4

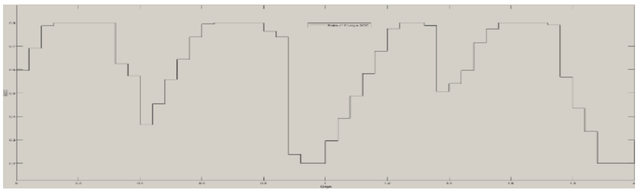


Figure 38 Summer days battery State of Charge - Case 4

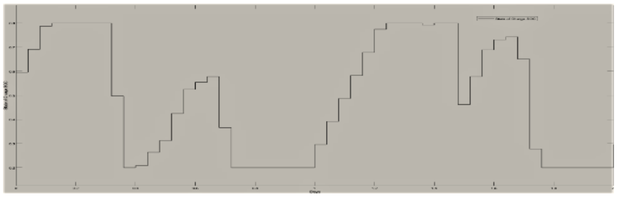


Figure 39 Winter days - Battery State of Charge - Case 4

Table 6 Total energy expenses - Case 4

Annual expenses	Annual Cost for total electric energy purchase from grid	Total spent money for electricity by consumer	Annual Income after selling the energy to the grid
without PV	£1,608	£1,608	£0.00
case1 (with PV only)	£1,417	£1337	£80
Case2 (with PV &battery)	£1169	£1142.44	£26.56
Case3 (with PV &battery (tariff based))	£1,338	£1258	£80
Case 4 (combination of Case 2& 3)	£1029	£988	£41

Annual energy expenses data by using this battery scheduling scheme is shown in this table. The case 4 battery operation reduced ~ 39% of energy cost.

Table 7 Energy consumption from grid and energy sell back to grid in kWh

	Annual energy purchase from grid in kWh	Annual energy sells back to grid in kWh
Base case	4977.45 kWh	-
Case1: With PV	4361.85 kWh	1063.22 kWh
Case 2: with PV &battery (Algorithm 2)	3501.00 kWh	352.10 kWh
Case 3: with PV &battery (Algorithm 3)	4284.80 kWh	1063.04 kWh
Case 4: with PV &battery (Algorithm 4)	3215.25 kWh	544.05 kWh

In each scenario, Table 7 provides the yearly energy consumption and annual outbound energy values. When each is compared, it is evident that case4 is the optimal control method for supply side management in the home energy management system. This regulation lowered utility energy use by 36%.

4.5 Case 5: Case 4 with future green energy tariff

The future energy system will share decarbonised energy. So, in this case, home energy system operation according to the green tariff is explained in detail.

The idea of the future energy management system (FEMS) must anticipate real-time half-hourly fluctuating tariff data and record it in its memory, and the system will transmit information to the controller inside based on the dayahead or yesterday's tariff rate. This FEMS system will feature a programmed system that can take expected power, compare projected prices, and adjust the low and high tariff rate thresholds. These figures indicate that the battery may be charged and discharged successfully. This strategy is only appropriate if the energy price for tomorrow is available now. The threshold value setting algorithm is not shown in this thesis because, first, I took the mean of whole day halfhourly electric rates to divide the price rate as low and high, but its operation is tricky, and whenever the real time tariff varies greatly, the mean value becomes a little high, which does not provide an effective cost reduction. Furthermore, abruptly shifting tariff prices complicate system operation. In the future, electrical energy will be generated entirely from renewable sources, and energy companies refer to this as a green tariff rate.

Green, 'eco,' or renewable tariffs can now operate in a variety of ways. Octopus Energy Group, formed in 2015, is a renewable energy firm focused on sustainable energy. They offered a lot of information regarding the future tariff or green tariff on their website. As a result, Octopus green energy tariff rates are used in the analysis. Tariffs based on renewable energy are heavily reliant on climatic data. 'Octopus energy' offers two options: a fixed time based option and a half-hour day ahead Octopus Agile option (refer figure 40). ‘Octopus weather depend Agile’ is different for different locations. Agile outgoing Vs Agile import rates of England for every half hour are shown below [34]. Export and import real-time half hourly rate high during morning and evening peak and at the same time, weekdays domestic energy consumption also high for a working family. So, Battery fully charge the PV generation and shift its discharging to the night time can be cost effective. Switching of battery on the basis of real time rates is complicated, so, time of Use rate again considered in this case with green tariff rates. This greenest energy tariff rate is available from Octopus, and they only charge if 100% energy from renewable sources is supplied [30].

According to super green octopus 12Month eco 7, electricity rates are;

$$Day\ unit\ rate: \mathbf{64.86\ p/kWh};\ Night\ unit\ rate: \mathbf{46.38p/kWh};$$

$$Standing\ charge: \mathbf{49.47\ p/day}\ [30], \tag{14}$$

$$Fixed\ rate\ of\ outgoing\ energy\ is\ \mathbf{7.5\ p/kWh}$$

$$offpeak\ time\ span\ is\ 7\ hours(\ from\ 23:00\ to\ 6:00\ )$$

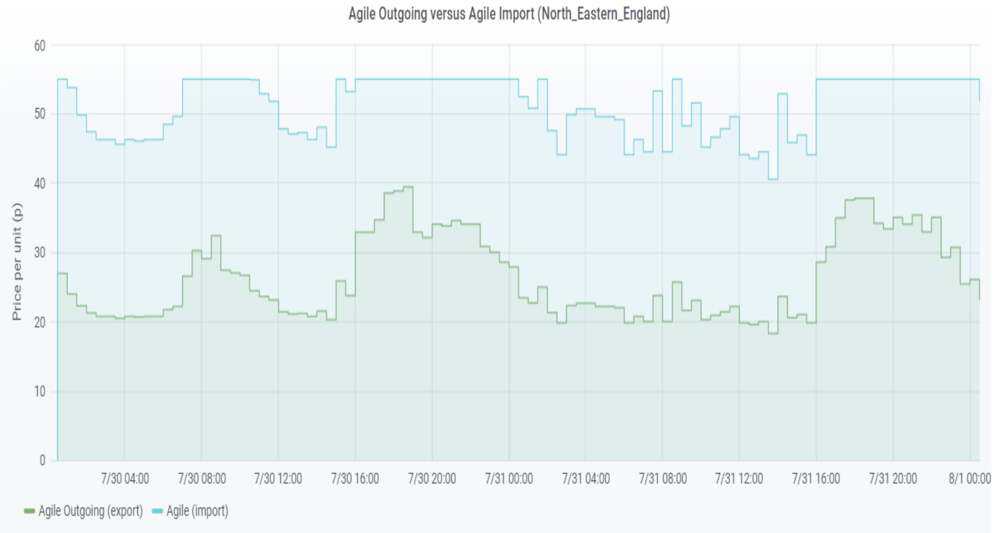


Figure 40 Octopus agile outgoing and Agile import rate [34]

Most of the energy consumption in the home is high during the morning and evening hours and the energy rate in the case of agile octopus is low comparatively to the eco 7 energy rate not only that the energy providers can vary the rate of energy price according to their energy supply production and weather conditions. So, during winter season, there is a chance to rise the energy rate. In such conditions, fixed eco 7 energy rates are adaptable for the consumer.

But while considering the energy sell back to the utility, real time energy sell rates per kWh is more effective; the values are;,

per day average p/kWh of agile octopus= approximately 50-53p/kWh ;

per day average p/kWh of eco7 =59.47p/kwh

But some days agile imports have no more variations in the price its looks like a constant tariff rate with slight variations. Because of the optimal unpredictability of setting threshold value, huge or less variation in the half-hourly electric price and necessity of modern algorithms, scheduling of system components according to this value is quite complicated. In this case, two rate electricity price for import energy and fixed outgoing tariff for exporting energy is considered.

Table 8 Comparison of the system considering green tariff

	Annual energy purchase from grid in kWh	Annual energy sells to the utility in kWh	Annual energy purchase cost in £	Annual energy sells cost in £
Base case without PV and battery	4958.55 kWh	-	£2919.15	-
Case 5 with green tariff	3183.75 kWh	781.79 kWh	£1961.53	£58.63

Data on residential building energy use and energy costs are compared to green energy tariff data. It was discovered that the system with PV, battery with battery control and excess solar power output saves 36% of the energy usage in kWh from the grid (refer figure 8). But the base case annual cost is estimated on the basis of the present market. The renewable based tariff is really high and it is expecting to hike more in coming years because of the deployment of new system. So, 18 % energy expense is increased even if the energy consumption decreased to 36%.

4.6 Comparison

Figure 44 shows a comparison of import and export annual energy in kWh in all cases. It is predicted that the per unit energy cost for upcoming decarbonised energy will be increases than the present rate and will gradually decrease in the future. But the energy purchase in kWh from the utility was reduced after considering the control of the system according to the green tariff. The future supply-side management and demand side management in the energy management system in home will be based on the climate and green tariff rates. Which can reduce more energy consumption for households.

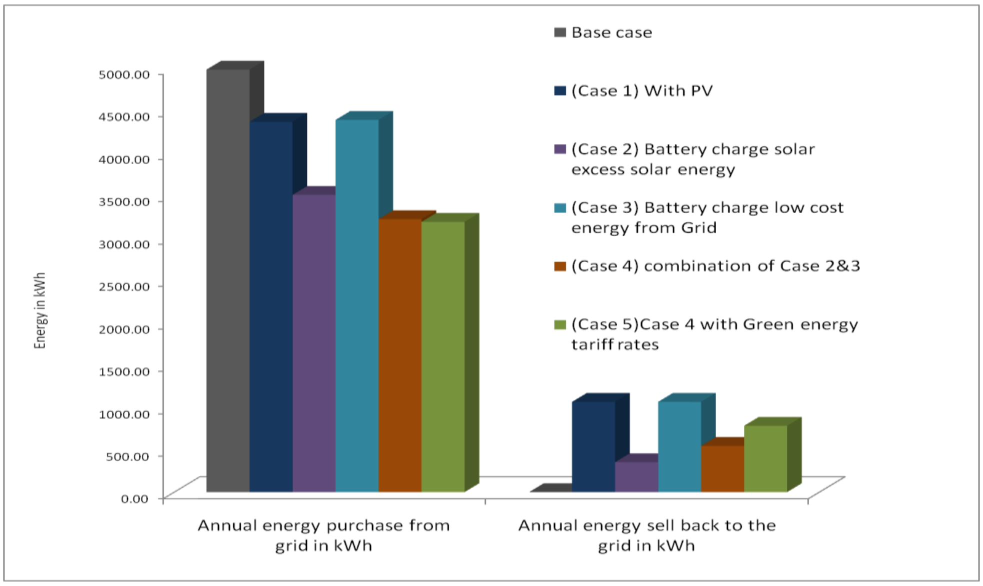


Figure 41 Annual energy import and export in all cases

5.0 Limitation

In addition to the primary components described in this work, other components such as an inverter, supporting modules, connecting cables, electric switches, monitoring devices, and so on must be included for supply management analysis. Because each system has its own efficiency and problems. This will have an impact on system performance. Small variations in frequency and power can disrupt the energy system. As a result, comprehensive and thorough analysis and data gathering are essential to achieve future energy system modelling and accurate data analysis. In the case of batteries, scheduling without sufficient monitoring might generate a slew of problems in the system.

The paucity of data and the simplicity of the mathematical model of the components lowered the accuracy of the data. The suggested control aspect in this situation has some practical concerns because there is the possibility of the synchronisation charging and discharging based on both PV power supply and low tariff rate, which would complicate battery management (battery cannot be charge and discharge at a same time). If future energy suppliers establish the energy price to be totally half-hourly changing, the suggested regulation will be ineffective. Only a completely digitalised smart world will be able to address these concerns.

6.0 Conclusion

The relevance of energy management with PV and battery with perfect forecasting as a concept is explained in this thesis. Here a study of HEMS and relevant system components and its terms for the future energy system are included. This thesis focused on the supply side management strategy among two management strategy of HEMS by considering ESS as a main component. Performance of ESS and different battery scheduling algorithm strategies and equation-based data analysis are evaluated and finalised that battery that stores both excess solar generating output and low-cost energy can reduce approximately 36-39 % of energy cost expenses annually. A simple overlook into Octopus energy tariff rates is done and it is concluded that perday mean value of future energy green agile tariff is less than fixed time of use tariff and they providing the API to collect tariff data for users to implement smart controls, but the half-hourly varying rate can complicate the battery control on the basis of tariff threshold rate updation. As a result, for the final case system performance evaluation, eco 7 green tariff for import energy and fixed tariff for outgoing energy are considered. It is determined that the adaptability of future energy management system module taking green tariff and a battery control approach based on electric price fluctuations, as well as solar power output, might minimise kWh utility energy usages.

7.0 References

[1] "Licence and sectoral publications", *Ofgem*, 2022. [Online]. Available: https://www.ofgem.gov.uk/energy-policy-and-regulation/policy-and-regulatory-publications/licence-and-sectoral-publications. [Accessed: 02- Jul- 2022].

[2] T. Pistochini, M. Dichter, S. Chakraborty, N. Dichter and A. Aboud, "Greenhouse gas emission forecasts for electrification of space heating in residential homes in the US", *Energy Policy*, vol. 163, p. 112813, 2022. Available: 10.1016/j.enpol.2022.112813.

[3] "CREST Demand Model", figshare, 2022. [Online]. Available: https://repository.lboro.ac.uk/articles/dataset/CREST_Demand_Model_v2_0/2001129. [Accessed: 27- May- 2022].

[4] E. McKenna and M. Thomson, "High-resolution stochastic integrated thermal–electrical domestic demand model", *Applied Energy*, vol. 165, pp. 445-461, 2016. Available: 10.1016/j.apenergy.2015.12.089.

[5] G. Started, C. Power and S. Calculator, "Solar Calculator", *Sunwatts.com*, 2022. [Online]. Available: https://sunwatts.com/solar-calculator/. [Accessed: 12- Jul- 2022].

[6] D. González-Peña, I. García-Ruiz, M. Díez-Mediavilla, M. Dieste-Velasco and C. Alonso-Tristán, "Photovoltaic Prediction Software: Evaluation with Real Data from Northern Spain", *Applied Sciences*, vol. 11, no. 11, p. 5025, 2021. Available: 10.3390/app11115025.

[7] Yadu Krishnan, "Smart Home Energy Management - the Future of Energy Conservation: A Review", *International Journal of Engineering Research and*, vol. 9, no. 07, 2020. Available: 10.17577/ijertv9is070134.

[8] T. Morstyn, B. Hredzak and V. G. Agelidis, "Control Strategies for Microgrids with Distributed Energy Storage Systems: An Overview," *in IEEE Transactions on Smart Grid*, vol. 9, no. 4, pp. 3652-3666, July 2018, doi: 10.1109/TSG.2016.2637958.

[9] M. Hossain, H. Pota and C. Moreno, "Real-time Battery Energy Management for Residential Solar Power System", *IFAC-PapersOnLine*, vol. 52, no. 4, pp. 407-412, 2019. Available: 10.1016/j.ifacol.2019.08. 244.

[10] H. Chen, T. Cong, W. Yang, C. Tan, Y. Li and Y. Ding, "Progress in electrical energy storage system: A critical review", *Progress in Natural Science*, vol. 19, no. 3, pp. 291-312, 2009. Available: 10.1016/j.pnsc.2008.07.014.

[11] G. Chaudhary, J. Lamb, O. Burheim and B. Austbø, "Review of Energy Storage and Energy Management System Control Strategies in Microgrids", *Energies*, vol. 14, no. 16, p. 4929, 2021. Available: 10.3390/en14164929.

[12] G. Graditi, M. Ippolito, E. Telaretti and G. Zizzo, "Technical and economical assessment of distributed electrochemical storages for load shifting applications: An Italian case study", *Renewable and Sustainable Energy Reviews*, vol. 57, pp. 515-523, 2016. Available: 10.1016/j.rser.2015.12.195.

[13] N. Rashid, W. Choi and K. Lee, "Optimization of two-staged bio-hydrogen production by immobilized Microcystis aeruginosa", *Biomass and Bioenergy*, vol. 36, pp. 241-249, 2012. Available: 10.1016/j.biombioe.2011.10.024.

[14] S. Niaz, T. Manzoor and A. Pandith, "Hydrogen storage: Materials, methods and perspectives", *Renewable and Sustainable Energy Reviews*, vol. 50, pp. 457-469, 2015. Available: 10.1016/j.rser.2015.05.011.

[15] "System Design | Powerwall Support", *Tesla*, 2022. [Online]. Available: https://www.tesla.com/support/energy/powerwall/learn/system-design. [Accessed: 18- Jul- 2022].

[16] "Powerwall | Tesla", Tesla, 2022. [Online]. Available: https://www.tesla.com/en_GB/powerwall. [Accessed: 10- Jul- 2022].

[17] R. Felseghi, E. Carcadea, M. Raboaca, C. TRUFIN and C. Filote, "Hydrogen Fuel Cell Technology for the Sustainable Future of Stationary Applications", *Energies*, vol. 12, no. 23, p. 4593, 2019. Available: 10.3390/en12234593.

[18] L. Gaines, "The future of automotive lithium-ion battery recycling: Charting a sustainable course", *Sustainable Materials and Technologies*, vol. 1-2, pp. 2-7, 2014. Available: 10.1016/j.susmat.2014.10.001.

[19] H. Zandi, T. Kuruganti, E. Vineyard and D. Fugate, "Home Energy Management Systems: An Overview", *Osti.gov*, 2022. [Online]. Available: https://www.osti.gov/biblio/1423114. [Accessed: 20- Jul- 2022].

[20] Yadu Krishnan, "Smart Home Energy Management - the Future of Energy Conservation: A Review", *International Journal of Engineering Research and*, vol. 9, no. 07, 2020. Available: 10.17577/ijertv9is070134.

[21] 2022. [Online]. Available: https://www.comparethemarket.com/energy/content/energy-tariffs-explained/. [Accessed: 20- Jul- 2022].

[22] "Are green energy tariffs cheaper than standard deals?", *TheMoneyEdit.com*, 2022. [Online]. Available: https://www.themoneyedit.com/household-bills/green-energy-tariffs. [Accessed: 20- Jul- 2022].

[23] A. Dimeas et al., "Smart Houses in the Smart Grid: Developing an interactive network.", *IEEE Electrification Magazine*, vol. 2, no. 1, pp. 81-93, 2014. Available: 10.1109/mele.2013.2297032.

[24] "Solar PV costs fall 82% over the last decade, says IRENA", *Solar Power Portal*, 2022. [Online]. Available: https://www.solarpowerportal.co.uk/news/solar_pv_costs_fall_82_over_the_last_decade_says_irena. [Accessed: 25- Mar- 2022].

[25] "UK energy in brief 2021", GOV.UK, 2022. [Online]. Available: https://www.gov.uk/government/statistics/uk-energy-in-brief-2021. [Accessed: 25- Mar- 2022].

[26] "How Many People Have Solar Panels in the UK? - The Eco Experts", *The Eco Experts*, 2022. [Online]. Available: https://www.theecoexperts.co.uk/solar-panels/popularity-of-solar-power. [Accessed: 25- Mar- 2022].

[27] "Heat Pumps vs Gas Boilers: Cost, efficiency and carbon-footprints", *Heatable.co.uk*, 2022. [Online]. Available: https://heatable.co.uk/boiler-advice/heat-pumps-vs-gas-boilers. [Accessed: 25- Jul- 2022].

[28] Mcscertified.com, 2022. [Online]. Available: https://mcscertified.com/wp-content/uploads/2020/07/Heat-Pump-Guide.pdf. [Accessed: 26- Jul- 2022].

[29] "BIEMMEDUE SPA - HOW TO CALCULATE THE THERMAL POWER NECESSARY TO HEAT A BUILDING", *BIEMMEDUE SPA*, 2022. [Online]. Available: https://biemmedue.com/en/news-and-events/2017/9/18/how-to-calculate-the-thermal-power-necessary-to-clean-a-local. [Accessed: 27- Jul- 2022].

[30] "Introducing Agile Octopus: The 100% green smart tariff with Plunge Pricing", *Octopus Energy*, 2022. [Online]. Available: https://octopus.energy/agile/. [Accessed: 01- Jun- 2022]

[31] Octoenergy-production-media.s3.amazonaws.com, 2022. [Online]. Available: https://octoenergy-production-media.s3.amazonaws.com/documents/Flexible_Octopus_April_2022__PDF_VAT.pdf. [Accessed: 13- Jun- 2022].

[32] "Introducing Outgoing Octopus: The UK's first smart export tariff", *Octopus Energy*, 2022. [Online]. Available: https://octopus.energy/outgoing/. [Accessed: 31- Jul- 2022].

[33] "What is an Economy 7 meter and tariff? | Octopus Energy", *Octopus.energy*, 2022. [Online]. Available: https://octopus.energy/help-and-faqs/articles/what-is-an-economy-7-meter-and-tariff/. [Accessed: 28- Jul- 2022].

[34] "Octopus Agile Outgoing Export Southern Scotland - Energy Stats UK", *Energy Stats UK, 2022*. [Online]. Available: https://www.energy-stats.uk/octopus-agile-outgoing-export-North_Eastern-scotland/. [Accessed: 23- Jul- 2022].

[35] Q. Hu and F. Li, "Hardware Design of Smart Home Energy Management System With Dynamic Price Response", *IEEE Transactions on Smart Grid*, vol. 4, no. 4, pp. 1878-1887, 2013. Available: 10.1109/tsg.2013.2258181.

[36] G. La Tona, M. Luna, A. Di Piazza and M. Di Piazza, "Towards the Real-World Deployment of a Smart Home EMS: A DP Implementation on the Raspberry Pi", *Applied Sciences*, vol. 9, no. 10, p. 2120, 2019. Available: 10.3390/app9102120.

[37] A. Aoun, H. Ibrahim, M. Ghandour and A. Ilinca, "Supply Side Management vs. Demand Side Management of a Residential Microgrid Equipped with an Electric Vehicle in a Dual Tariff Scheme", *Energies*, vol. 12, no. 22, p. 4351, 2019. Available: 10.3390/en12224351.

[38] S. Wang, X. Xue and C. Yan, "Building power demand response methods toward smart grid", *HVAC&R Research*, vol. 20, no. 6, pp. 665-687, 2014. Available: 10.1080/10789669.2014.929887.

[39] A. Ożadowicz, "A New Concept of Active Demand Side Management for Energy Efficient Prosumer Microgrids with Smart Building Technologies", *Energies*, vol. 10, no. 11, p. 1771, 2017. Available: 10.3390/en10111771.

[40] Chen, X.; Weng, K.; Meng, F.; Mourshed, M. Smart Energy Management for Unlocking Demand Response in the Residential Sector. Proceedings 2018,2, 1136.

[41] Y. Levron, J. Guerrero and Y. Beck, "Optimal Power Flow in Microgrids With Energy Storage", *IEEE Transactions on Power Systems*, vol. 28, no. 3, pp. 3226-3234, 2013. Available: 10.1109/tpwrs.2013.2245925.

[42] X. KONG, L. BAI, Q. HU, F. LI and C. WANG, "Day-ahead optimal scheduling method for grid-connected microgrid based on energy storage control strategy", *Journal of Modern Power Systems and Clean Energy*, vol. 4, no. 4, pp. 648-658, 2016. Available: 10.1007/s40565-016-0245-0.

[43] Y. Zhang, A. Lundblad and J. Yan, "Comparative Study of Battery Storage and Hydrogen Storage to Increase Photovoltaic Self-sufficiently in a Residential Building of Sweden", *Energy Procedia*, vol. 103, pp. 268-273, 2016. Available: 10.1016/j.egypro.2016.11.284.

[44] M. Ganji and M. Shahidehpour, "Development of a residential microgrid using home energy management systems", 2022.

[45] H. Dinh, J. Yun, D. Kim, K. Lee and D. Kim, "A Home Energy Management System With Renewable Energy and Energy Storage Utilizing Main Grid and Electricity Selling", *IEEE Access*, vol. 8, pp. 49436-49450, 2020. Available: 10.1109/access.2020.2979189.

[46] I. Gomes, K. Bot, M. Ruano and A. Ruano, "Recent Techniques Used in Home Energy Management Systems: A Review", *Energies*, vol. 15, no. 8, p. 2866, 2022. Available: 10.3390/en15082866.

[47] V. Pop, H. Bergveld, D. Danilov, P. Notten and P. Regtien, "Adaptive State-of-Charge Indication System for Li-ion Battery-Powered Devices", *World Electric Vehicle Journal*, vol. 1, no. 1, pp. 38-45, 2008. Available: 10.3390/wevj1010038.

[48] J. Zich and J. Jandik, "Active Battery Management System for Home Battery Energy Storage," *2020 21st International Scientific Conference on Electric Power Engineering (EPE)*, 2020, pp. 1-4, doi: 10.1109/EPE51172.2020.9269172.

[49] H. S, "Overview of cell balancing methods for Li-ion battery technology", *Energy Storage*, vol. 3, no. 2, 2020. Available: 10.1002/est2.203.

[50] "Load-Forecasting/Load Forecasting.pdf at master · Warptron/Load-Forecasting", *GitHub*, 2022. [Online]. Available: https://github.com/Warptron/Load-Forecasting/blob/master/Load%20Forecasting.pdf. [Accessed: 05- Aug- 2022].

[51] E. Sharma, "Energy forecasting based on predictive data mining techniques in smart energy grids", *Energy Informatics*, vol. 1, no. 1, 2018. Available: 10.1186/s42162-018-0048-9.

[52] K. See et al., "Critical review and functional safety of a battery management system for large-scale lithium-ion battery pack technologies", *International Journal of Coal Science & Technology*, vol. 9, no. 1, 2022. Available: 10.1007/s40789-022-00494-0.

[53] J. Palomares-Salas and O. Florencias-Oliveros, "Weather forecasts for microgrid energy management: Review, discussion and recommendations", *Applied Energy*, vol. 228, pp. 265-278, 2018. Available: 10.1016/j.apenergy.2018.06.087.

[54] G. Liu, M. Starke, B. Xiao, X. Zhang and K. Tomsovic, "Microgrid optimal scheduling with chance-constrained islanding capability", 2022.

[55] T. Bogaraj and J. Kanakaraj, "Intelligent energy management control for independent microgrid", *Sādhanā*, vol. 41, no. 7, pp. 755-769, 2016. Available: 10.1007/s12046-016-0515-6.

[56] "Advanced forecasting of variable renewable power - [PDF Document]", *vdocuments.net*, 2022. [Online]. Available: https://vdocuments.net/advanced-forecasting-of-variable-renewable-power-.html. [Accessed: 27- Jul- 2022].

[57] M. Shapi, N. Ramli and L. Awalin, "Energy consumption prediction by using machine learning for smart building: Case study in Malaysia", *Developments in the Built Environment*, vol. 5, p. 100037, 2021. Available: 10.1016/j.dibe.2020.100037.

[58] "Price Forecasting: Applying Machine Learning Approaches to Electricity, Flights, Hotels, Real Estate, and Stock Pricing", *AltexSoft*, 2022. [Online]. Available: https://www.altexsoft.com/blog/business/price-forecasting-machine-learning-based-approaches-applied-to-electricity-flights-hotels-real-estate-and-stock-pricing/. [Accessed: 31- Jul- 2022].

[59] "How to hack your home for cheaper, greener, energy with our open API", *Octopus Energy*, 2022. [Online]. Available: https://octopus.energy/blog/agile-smart-home-diy/. [Accessed: 28- Jul- 2022].

[60] A. Walling, "20+ Tutorials on How to Create Your Own API (by Programming Language) | RapidAPI", *The Last Call - RapidAPI Blog*, 2022. [Online]. Available: https://rapidapi.com/blog/20-tutorials-on-how-to-create-your-own-api-sorted-by-programming-language/. [Accessed: 28- Jul- 2022].

[61] Y. Guo, Z. Zhao and L. Huang, "SoC Estimation of Lithium Battery Based on Improved BP Neural Network", *Energy Procedia*, vol. 105, pp. 4153-4158, 2017. Available: 10.1016/j.egypro.2017.03.881.

[62] "Octopus Energy APIs — Octopus Energy API 1.0 documentation", *Developer.octopus.energy*, 2022. [Online]. Available: https://developer.octopus.energy/docs/api/#electricity-meter-points. [Accessed: 29- Jul- 2022].

[63] "Photovoltaic Energy Factsheet", *Center for Sustainable Systems*, 2022. [Online]. Available: https://css.umich.edu/publications/factsheets/energy/photovoltaic-energy-factsheet. [Accessed: 18- Jun- 2022].

[64] N. Liu, V. Babushkin and A. Afshari, "Short-Term Forecasting of Temperature Driven Electricity Load Using Time Series and Neural Network Model", *Journal of Clean Energy Technologies*, vol. 2, no. 4, pp. 327-331, 2014. Available: 10.7763/jocet.2014.v2.149.

[65] P. Mandal, T. Senjyu, N. Urasaki and T. Funabashi, "Electricity Price and Load Short-Term Forecasting Using Artificial Neural Networks", *International Journal of Emerging Electric Power Systems*, vol. 7, no. 4, 2006. Available: 10.2202/1553-779x.1360.

[66] K. Ye, G. Demirezen, A. Fung and E. Janssen, "The use of artificial neural networks (ANN) in the prediction of energy consumption of air-source heat pump in retrofit residential housing", *IOP Conference Series: Earth and Environmental Science*, vol. 463, no. 1, p. 012165, 2020. Available: 10.1088/1755-1315/463/1/012165.

[67] 2022. [Online]. Available: https://researchbriefings.files.parliament.uk/documents/CBP-9340/CBP-9340.pdf. [Accessed: 29- Jun- 2022].

[68] Assets.publishing.service.gov.uk, 2022. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1094025/UK_Energy_in_Brief_2022.pdf. [Accessed: 04- Jun- 2022].

[69] "Energy Follow Up Survey (EFUS) 2017 reports", GOV.UK, 2017. [Online]. Available: https://www.gov.uk/government/publications/energy-follow-up-survey-efus-2017-reports. [Accessed: 11- Jun- 2022].

[70] Assets.publishing.service.gov.uk, 2022. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1026356/domestic-offgg-consultation.pdf. [Accessed: 09- Jun- 2022].

[71] K. Woodward, "The future of heating in the UK: heat pumps or hydrogen?", Energy Saving Trust, 2022. [Online]. Available: https://energysavingtrust.org.uk/the-future-of-heating-in-the-uk-heat-pumps-or-hydrogen/. [Accessed: 09- Jun- 2022].

[72] "Plan to drive down the cost of clean heat", GOV.UK, 2022. [Online]. Available: https://www.gov.uk/government/news/plan-to-drive-down-the-cost-of-clean-heat. [Accessed: 18- Jul- 2022].

[73] F. Abrahamsen, Y. Ai and M. Cheffena, "Communication Technologies for Smart Grid: A Comprehensive Survey", Sensors, vol. 21, no. 23, p. 8087, 2021. Available: 10.3390/s21238087.

[74] "The Future of Innovative Smart Grid Technologies (download report)", Valuer.ai, 2022. [Online]. Available: https://www.valuer.ai/blog/innovative-smart-grid-technologies-for-the-future. [Accessed: 09- Jul- 2022].

[75] X. Pan, R. Khezri, A. Mahmoudi, A. Yazdani and G. Shafiullah, "Energy Management Systems for Grid-Connected Houses with Solar PV and Battery by Considering Flat and Time-of-Use Electricity Rates", Energies, vol. 14, no. 16, p. 5028, 2021. Available: 10.3390/en14165028.

[76] B. Mahapatra and A. Nayyar, "Home energy management system (HEMS): concept, architecture, infrastructure, challenges and energy management schemes", Energy Systems, vol. 13, no. 3, pp. 643-669, 2019. Available: 10.1007/s12667-019-00364-w.

[77] M. Weil, S. Ziemann and J. Peters, "The Issue of Metal Resources in Li-Ion Batteries for Electric Vehicles", 2022.

[78] J. Fossati, A. Galarza, A. Martín-Villate and L. Fontán, "A method for optimal sizing energy storage systems for microgrids", Renewable Energy, vol. 77, pp. 539-549, 2015. Available: 10.1016/j.renene.2014.12.039.

[79] C. Xu, Q. Dai, L. Gaines, M. Hu, A. Tukker and B. Steubing, "Future material demand for automotive lithium-based batteries", Communications Materials, vol. 1, no. 1, 2020. Available: 10.1038/s43246-020-00095-x.

[80] A. AL Shaqsi, K. Sopian and A. Al-Hinai, "Review of energy storage services, applications, limitations, and benefits", Energy Reports, vol. 6, pp. 288-306, 2020. Available: 10.1016/j.egyr.2020.07.028.

[81] "Design, Analysis, and Applications of Renewable Energy Systems | ScienceDirect", Sciencedirect.com, 2022. [Online]. Available: https://www.sciencedirect.com/book/9780128245552/design-analysis-and-applications-of-renewable-energy-systems. [Accessed: 10- Jun- 2022].

[82] "Housing conditions by dwelling type in the UK 2018 | Statista", Statista, 2022. [Online]. Available: https://www.statista.com/statistics/503705/distribution-of-the-population-in-the-uk-by-dwelling-type/. [Accessed: 15- Jun- 2022].

[83] Tesla.com, 2022. [Online]. Available: https://www.tesla.com/sites/default/files/pdfs/powerwall/Powerwall2ACDatasheet_EN_UK_feb2020.pdf. [Accessed: 10- Aug- 2022].

[84] M. Basyoni, M. Basyoni and K. Al-Dhlan, "Design, Sizing and Implementation of a PV System for Powering a Living Room", International Journal of Engineering Research

and Science, vol. 3, no. 5, pp. 64-68, 2017. Available: 10.25125/engineering-journal-ijoer-may-2017-23.

[85] "UK: monthly average sun hours 2022 | Statista", Statista, 2022. [Online]. Available: https://www.statista.com/statistics/322602/monthly-average-daily-sun-hours-in-the-united-kingdom-uk/. [Accessed: 10- Aug- 2022].

[86] 2022. [Online]. Available: https://www.researchgate.net/publication/322515372_Design_and_simulation_of_an_independent_solar_home_system_with_battery_backup. [Accessed: 10- Aug- 2022].

[87] "News Release: NREL Six-Junction Solar Cell Sets Two World Records for Efficiency", Nrel.gov, 2022. [Online]. Available: https://www.nrel.gov/news/press/2020/nrel-six-junction-solar-cell-sets-two-world-records-for-efficiency.html. [Accessed: 10- Jun-2022].

[88] M. Moghimi, D. Leskarac, C. Bennett, J. Lu and S. Stegen, "Rule-based Energy Management System in an Experimental Microgrid with the Presence of Time of Use Tariffs", MATEC Web of Conferences, vol. 70, p. 10011, 2016. Available: 10.1051/matecconf/20167010011.

[89] M. Hossain, H. Pota and C. Moreno, "Real-time Battery Energy Management for Residential Solar Power System", IFAC-PapersOnLine, vol. 52, no. 4, pp. 407-412, 2019. Available: 10.1016/j.ifacol.2019.08.244.

[90] F. Lambert, "Tesla battery research group unveils paper on new high-energy-density battery that could last 100 years", Electrek, 2022. [Online]. Available: https://electrek.co/2022/05/24/tesla-battery-research-paper-high-energy-density-battery-last-100-years/. [Accessed: 07- Jul- 2022].

[91] "Projected electricity prices 2020-2050 Statistic | Statista", Statista, 2022. [Online]. Available: https://www.statista.com/statistics/720679/projected-electricity-price-united-kingdom/. [Accessed: 11- Jul- 2022].

[92] 2022. [Online]. Available: https://publications.parliament.uk/pa/cm5803/cmselect/cmbeis/208/report.html. [Accessed: 11- Jul- 2022].

8.0 Appendices

Appendices I

Table 9 X-axis of graphs, days and corresponding time (half-hour=0.02)

day	Time	day	Time	day	Time	day	Time	day	Time	day	time	day	Time	day	Time
0.02	00:30:00	0.27	06:30:00	0.52	12:30:00	0.77	18:30:00	1.02	00:30:00	1.27	06:30:00	1.52	12:30:00	1.77	18:30:00
0.06	01:30:00	0.31	07:30:00	0.56	13:30:00	0.81	19:30:00	1.06	01:30:00	1.31	07:30:00	1.56	13:30:00	1.81	19:30:00
0.10	02:30:00	0.35	08:30:00	0.60	14:30:00	0.85	20:30:00	1.10	02:30:00	1.35	08:30:00	1.60	14:30:00	1.85	20:30:00
0.15	03:30:00	0.40	09:30:00	0.65	15:30:00	0.90	21:30:00	1.15	03:30:00	1.40	09:30:00	1.65	15:30:00	1.90	21:30:00
0.19	04:30:00	0.44	10:30:00	0.69	16:30:00	0.94	22:30:00	1.19	04:30:00	1.44	10:30:00	1.69	16:30:00	1.94	22:30:00
0.23	05:30:00	0.48	11:30:00	0.73	17:30:00	0.98	23:30:00	1.23	05:30:00	1.48	11:30:00	1.73	17:30:00	1.98	23:30:00
0.25	06:00:00	0.50	12:00:00	0.75	18:00:00	1.00	00:00:00	1.25	06:00:00	1.50	12:00:00	1.75	18:00:00	2.00	00:00:00

Appendices II

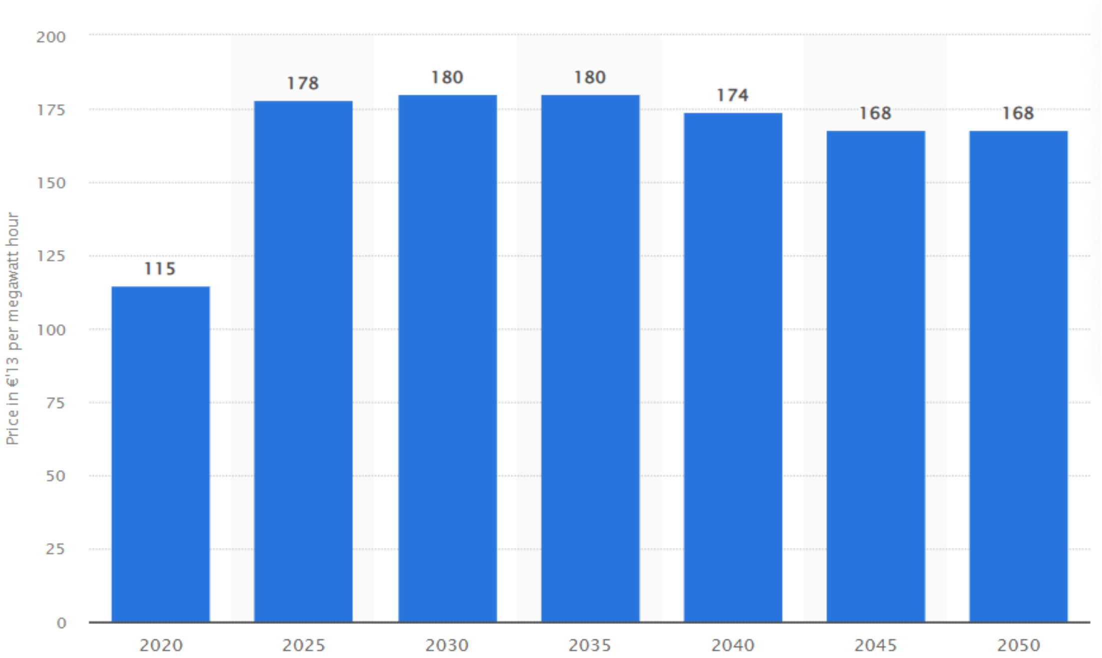


Figure 42 Predicted electric price in UK developed by Statista [91]

Appendices III

Table 10 simulink model