Can Energy Storage Add Value to Future Urban Planning and Operation?

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Abstract

Residential electricity demand is expected to rise in the next few decades due to the electrification of heating and transportation. Both European and UK national policies suggest that efforts should be made to reduce carbon emissions and increase the share of renewable energy, an important element of which is encouraging generation, typically photovoltaic (PV), in partnership with energy storage systems in the residential sector. The scale of the energy storage system is important, with community energy storage (CES) and household energy storage (HES) being the two principal systems used in the residential sector. Many advantages of CES over HES have been identified, but the performance and impact on individual households within CES require further analysis. In this study an agent-based model is proposed to investigate and analyse CES based on a range of criteria. Results indicate that both HES and CES can significantly reduce the grid peak power import grid and export to the grid, improve the community self-consumption rate (SCR) and self-sufficiency rate (SSR), and contribute to much higher energy saving. Time-of-Use (TOU) tariffs can effectively shave peak demand and lower energy bills of households, but do not improve SCR and SSR. The economic feasibility of storage can be improved by 1) combining different services and tariffs to obtain more revenues for households; 2) more legislative and financial support to reduce system costs; and 3) more innovative business models and policies to optimise revenues with existing resource. Lastly, in order to encourage adoption of PV and storage, it is important to compare the UK to a country with successful applications and comprehensive policy support. The study therefore compares and contrasts CES in the UK and Germany. Results indicate that the primary impacting factor on SCR is solar generation. The results highlight the importance of using a location-specific approach for system planning. Households in Germany should aim to improve the utilisation of on-site generation by installing a larger storage system, whilst UK households should improve total renewable generation output, for example by using a hybrid PV plus wind turbine system. In addition, more financial and legislative support is needed in the UK to improve feasibility of HES and CES.

Table of Content

Nomenclature and Abbreviation

A_{PV}	*Area of a PV Solar Panel (m^2)*
C_0	*Nominal Battery Capacity (kWh)*
C_e	*Effective Battery Capacity (kWh)*
CES	*Community Energy Storage*
CES-Flat	*Community Energy Storage Self-Consumption Mode under Flat Tariff*
CES-GC	*Community Energy Storage Grid-Charging Mode under Time-of-Use Tariff*
CESM	*Community Energy Storage Management*
CES-SC	*Community Energy Storage Self-Consumption Mode under Time-of-Use Tariff*
DER	*Distributed Energy Resource*
DNO	*Distribution Network Operator*
DOD	*Depth of Discharge (%)*
DSM	*Demand Side Management*
E_{ah}	*Total Energy Throughput (ah)*
E_{demand}	*Total Household Energy Demand (kWh)*
$E_{discharge}$	*Total Energy Discharged from Battery (kWh)*
E_{export}	*Total Exported Energy (kWh)*
EFC	*Equivalent Full Cycle*
$E_{fromCES}$	*Energy Import from CES Network (kWh)*
E_{import}	*Energy Imported Energy from Gird (kWh)*
$EM_{battery}$	*Total Carbon Emissions from Battery Manufacture (kg)*
EM_{PV}	*Total Carbon Emissions from PV Manufacture (kq)*
EM_{total}	*Total System Carbon Emissions (kg)*
E_{PV}	*Energy Generated by PV (kWh)*
E_{toCES}	*Energy Export to CES Network (kWh)*
FIT	*Feed-In Tariff*

HES	*Household Energy Storage*
HES-Flat	*Household Energy Storage Self-Consumption Mode under Flat Tariff*
HES-GC	*Household Energy Storage Grid-Charging Mode under Time-of-Use Tariff*
HESM	*Household Energy Storage Management*
HES-SC	*Household Energy Storage Self-Consumption Mode under Time-of-Use Tariff*
I_b	*Direct Normal Solar Radiations* ($kWh.m^{-2}$)
I_d	*Diffused Solar Radiations* ($kWh.m^{-2}$)
I_r	*Received Solar Radiation by an inclined surface of a PV Panel* ($kWh.m^{-2}$)
I_t	*Investment Expenditures in Year t (£)*
KPI	*Key Performance Indicator*
LCOE	*Levelised Cost of Energy* ($£.kWh^{-1}$)
LCOS	*Levelised Cost of Storage* ($£.kWh^{-1}$)
M_t	*Maintenance Expenditures in year t (£)*
NOCT	*Nominal Operating Cell Temperature*
PBT_{CO2}	*Carbon Payback Time of System (years)*
PV	*Photovoltaics*
p_{CES}	*Inter-House Trading Tariff within CES* ($£.kWh^{-1}$)
p_{export}	*Feed-In Tariff for Export* ($£.kWh^{-1}$)
p_{gen}	*Feed-In Tariff for Generation* ($£.kWh^{-1}$)
p_{grid}	*Energy Supplier Tariff* ($£.kWh^{-1}$)
$p_{standing}$	*Standing Charge* ($£.day^{-1}$)
q_{grid}	*Grid Carbon Intensity* ($kg.kWh^{-1}$)
Q_{loss}	*Battery Capacity Loss (%)*
R_b	*Tilt Factor for Direct Solar Radiation*
R_d	*Tilt Factor for Diffused Solar Radiation*
R_r	*Tilt Factor for Reflected Solar Radiation*
SCR	*Self-Consumption Rate*

SOC	*State of Charge (%)*
SPBT	*Simple Payback Time of System (years)*
SSR	*Self-Sufficiency Rate*
T_a	*Instantaneous Ambient Temperature (˚C)*
T_c	*Monthly Average Cell Temperature (˚C)*
TDCV	*Typical Domestic Consumption Values*
TOU	*Time-of-Use*

List of Publications

The work carried out during the PhD has led to the following publications:

Chapter 3 and 4:

- **Dong, S.**, Kremers, E., Brucoli, M., Brown, S. and Rothman, R., 2018. Residential PV-BES systems: economic and grid impact analysis. *Energy Procedia*, *151*, pp.199-208.
- **Dong, S.,** Kremers, E., Brucoli, M., Rothman, R. and Brown, S., 2020. Techno-enviro-economic assessment of household and community energy storage in the UK. *Energy Conversion and Management*, *205*, p.112330.
- **Dong, S**., Kremers, E., Brucoli, M., Brown, S. and Rothman, R., 2020. Impact of Household Heterogeneity on Community Energy Storage in the UK. *Energy Reports*, *6*, pp.117-123.

Chapter 5:

- **Dong, S**., Kremers, E., Brucoli, M., Rothman, R. and Brown, S., 2020. Improving the feasibility of household and community energy storage: A techno-enviro-economic study for the UK. *Renewable and Sustainable Energy Reviews*, *131*, p.110009.

Chapter 6:

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CRediT authorship contribution statement

Siyuan Dong: Data curation, Writing - original draft, Methodology, Investigation. **Enrique Kremers**: Writing - review & editing, Software. **Maria Brucoli**: Writing - review & editing. **Rachael Rothman**: Writing - review & editing, Supervision. **Solomon Brown**: Writing - review & editing, Supervision, Resources.

List of Figures

List of Tables

Declaration

I, the author, confirm that the Thesis is my own work. I am aware of the University's Guidance on the Use of Unfair Means (www.sheffield.ac.uk/ssid/unfair-means). This work has not previously been presented for an award at this, or any other, university.

Chapter 1 Introduction

1.1. Background

World energy demand is expected to increase at a rate of 2.2% per year from 2012 to 2035, with demand in buildings and industrial sectors accounting for 90% of this growth [1]. Due to the environmental benefits, government incentives and cost reduction of renewable technologies, both European and UK national policies suggest that efforts to reduce carbon emissions are essential and pursuing sustainable alternatives is vital to ensure our acquired wealth and future growth [2]. Many countries have focused their efforts to drive transition towards a low-carbon energy system (see Figure 1-1), but many issues still remain, mainly in three aspects: affordability, reliability and sustainability [3].

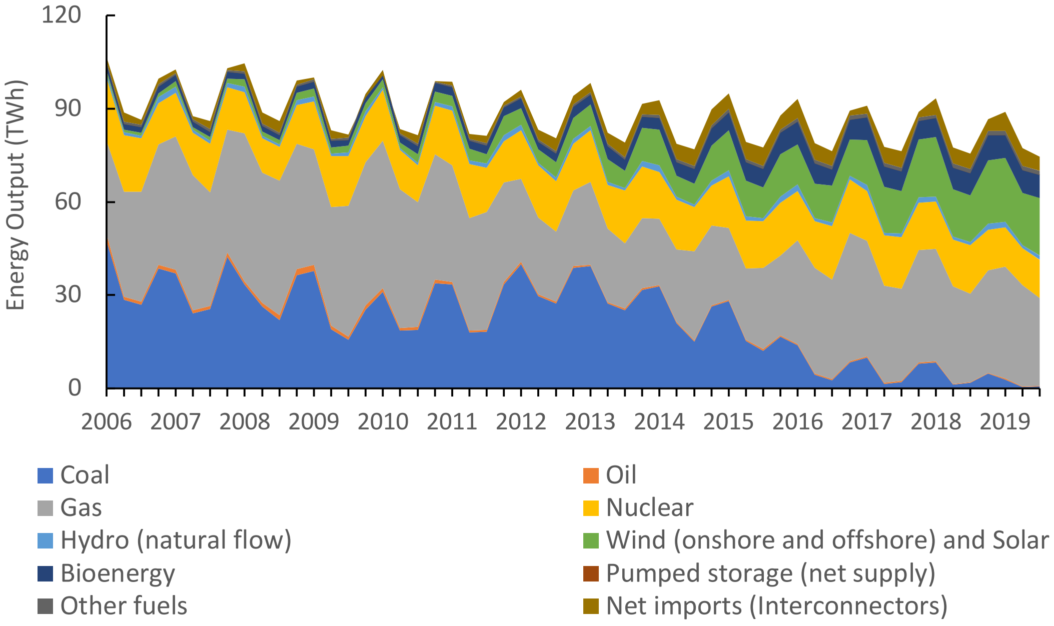


Figure 1-1 Electricity generation mix by quarter and fuel source of the UK [4]

Renewable energy is defined as energy obtained from natural and persistent flows of energy occurring in the immediate environment [5] i.e. renewable energy technologies make use of sustainable natural resources to produce the energy we need. Renewable energy is an important pathway to decarbonise our energy system and some of renewable technologies have been widely adopted in the world, including wind energy, solar energy, hydropower, geothermal and biomass. Amongst all the renewable energy sources, some are inherently more exploitable than the others. Hydropower [6] and wind energy [7] can be easily accessible to drive generators. Solar energy is more widely adopted by end-users due to its flexible installation and improved lifespan. Geothermal can be a stable and sustainable energy resource for heat supply in some countries. All of these are extremely important to reduce the CO_2 emissions related to processes reliant upon the combustion of traditional fossil fuels.

The energy system in the UK is undergoing a period of significant shift, from a large-scale traditional fossil fuel dominated mix towards an intermittent renewable generation dominated generation mix, as shown in Figure 1-1. There has been a significant increase in power output from wind and solar farms in the past decade due to the rapid cost reduction in low-carbon technologies [8]. In the UK, offshore wind projects provide the cheapest source of low-carbon power generation. The decreasing price of renewable technologies and growing awareness of climate change will contribute to a rapid adoption of renewable energy generation technologies, especially at residential level. A recent study suggests that in the future there might be around 11 million households participating in distributed generation, which is a significant growth compared to 1 million today [9]. The government predicts that there will be approximately 30 GW of renewables and storage commissioned by 2030 [10]. Although the centralised power system is undergoing a huge decarbonisation by integrating more renewable technologies, residential renewables are also becoming popular, facilitating a transition from the traditional centralised power system towards a co-existing central and decentralised power system.

Decentralised power systems have significant potential to optimise the use of energy, by transforming more energy consumers into energy prosumers that can both produce and consume energy, and therefore changing the relationship between demand consumption and power provision. The mismatch between demand and supply, makes it difficult to maintain grid stability [11] and flexibility [12]. Instead of transmitting power via long distance transmission lines to the end users with a considerable energy loss, local energy generation and electrical networks would potentially be more flexible and responsive to meet demand locally, which can effectively localise the energy supply and avoid or defer expensive network reinforcement and expansion. It is expected to be more critical in the future with the growth in renewable energy sources, especially at a residential user level. This problem requires several specific adaptations of the energy systems, including new type of balancing and energy storage services.

Energy storage is considered an essential compensation tool to improve dispatchability [13]. Electrical [14] and thermal storage [15] are the two main forms of storage, and are expected to play an important role in the future to make residential and commercial buildings more self-sufficient [16]. The selection of storage technology still needs to consider several factors, such as energy/power density, efficiencies, costs and technological maturity [17]. It is widely recognised that batteries can contribute to balancing an energy system dominated by intermittent renewables. In particular, Lithium-ion batteries are becoming increasingly affordable and popular due to the rapid development and mass production of electric vehicles. Battery cell cost is expected continue to further reduce in the future along with wide roll-out of renewable generation technologies, especially at domestic level.

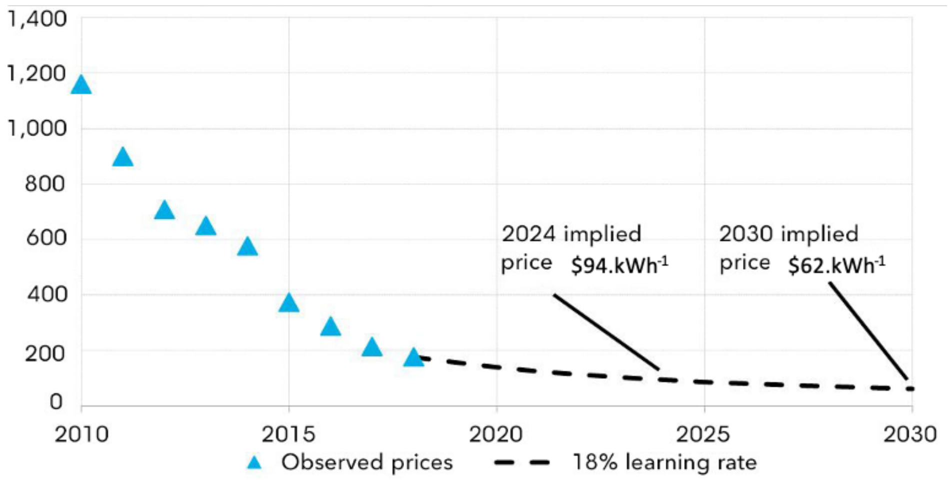


Figure 1-2 Lithium-ion battery pack price [18]

The UK government has been incentivising the adoption of domestic solar since 2000, mainly through a Feed-In Tariff (FIT). However, domestic users have largely stopped installation [19] as the relevant subsidies were recently removed [20]. Together with increasing electricity tariffs, the reduced financial benefits therefore shifted consumers' focus from primarily exporting PV generation to reducing PV generation export and supplying energy demand locally instead. Energy storage, especially via Li-ion batteries, has become an increasingly popular supplement to PV as it can further enhance household self-consumption [14], due to the high energy density, power density and conversion efficiency [21]. Coupling PV with energy storage has been widely adopted and investigated in many countries, such as the UK [22], Germany [23], and Switzerland [24].

The increasing deployment of renewable energy generation at residential level is shifting the development of energy systems towards a more decentralised structure and the community is expected to play a more important role, especially though CES. CES can act as an energy management system in the energy community and may be co-owned by the participants in that community [25]. Compared to household energy storage (HES), a CES system has significant technical and economic advantages [26] including: 1) better performance of the battery system due to smoother aggregated demand compared to single home demand; 2) lower requirements for the power rating of batteries; and 3) potential cost reduction of components.

In order to encourage more CES deployments, it is important to investigate and identify its significance compared to other systems. Although previous studies suggesting CES is good for the community and distribution networks, there are still some key issues that need to be addressed, how the households inside can benefit from the CES and what other potential services the CES can provide. Due to the growing awareness of environmental protection and demand for clean energy supply, it is important to evaluate the CES system not only based on traditional technological and economic perspectives, but also on the potential environmental aspect, so that we can establish how the CES can facilitate future urban planning.

1.2. Significance of Research

In the thesis, a multi-discipline assessment is used to evaluate HES and CES systems, with the aim of identifying the value of CES in the UK. The feasibility of current operational frameworks and other potential possibilities are investigated so that the project profitability can be enhanced and maximised. The research is significant to the scope of knowledge in community energy storage especially for the utility companies, end-users, potential investors and regulators, because it provides a performance analysis from technical, economic and environmental aspects. The results have been published in three peer-reviewed journal papers and a conference proceeding, which helps understand the value and potential of the CES compared to HES. The research may also encourage more deployment of renewable energy especially community energy system based on proposed frameworks.

1.3. Thesis Aims and Objectives

The aim of the research is to investigate how a CES network can contribute to a residential distribution network, such as peak import/export shaving, and inherent residential households with rooftop PV, such as improving localisation of energy supply and financial benefits. In order to achieve this aim, the work has the following specific objectives:

- Reviewing the state-of-art of residential solar plus storage applications and previous research to identify the potential research gap between existing technologies and CES applications;

- To develop a model to simulate different communities with HES and CES, and also to identify the advantages of CES over HES for the network and households respectively in the UK context;

- To assess the households' applicability of increasing the project profitability by demand-side management and inter-house energy trading for community and individual households;

- To compare and analyse the performances of the HES and CES in the UK and Germany so that the key impacting factors can be identified and hence improve the future applications in the UK.

1.4. Original Contribution

Most literature focuses on either the techno-economic assessment of energy storage or using mathematical programming to explore the optimal configuration of a CES system for community-level demand side management. There has been a limited number of studies that explore the behaviour of individual households within a network connecting to CES, especially in the UK context. In contrast to the optimisation-based approaches, agent-based modelling provides the opportunity to focus on the individual components of the system and their interaction with the wider environment, where the agents and their behaviour can be uniquely defined. The following results can be considered an original contribution to knowledge:

- Modifying definitions of self-consumption and self-sufficiency to assess system performances, which take into account inter-household sharing and ignore any discrepancy in battery state of charge between the start and end of the simulation;

- Proposing a novel agent-based model to simulate different system setups and inherent components and their interaction with each other, including PV, battery storage, households, and different communities;

- Through the proposed agent-based model, CES was demonstrated to be able to better at shaving peak PV power export and power input from the grid. With regard to individual households, intensive users were found to benefit more from CES, whilst HES was found to be more suitable for light energy users;

- Multiple the alternative options to improve the community energy storage, including inter-house electricity trading, and operation under TOU tariffs. The Flat Tariff was found more helpful to improve the usage of on-site generated PV electricity, while the TOU tariff was helpful to shave peak demand. The CES was found to be the better option, as the inter-house trading could contribute to additional considerable revenues for households and significant reduction in peak demand. The CES was proven to be the better alternative for both household and DNOs. However, the economic feasibility still remained as the biggest issue, which required further changes and improvements in several aspects, such as revenue stream combination.

- Potential applicable measures for improvements were examined in both countries. Although the overall performances of CES were found to be the most desirable in both the UK and Germany, the lack of sufficient PV generation and insufficient financial and regulatory support for PV and storage were the main hinders for the applications in the UK. Different planning approaches were therefore required. For the UK, it is necessary to adopt hybrid generation system, such as PV and wind turbines, while installing larger battery storage is more suitable for applications in Germany.

1.5. Thesis Structure

Following this chapter, the rest of the thesis is organised as follows:

- Chapter 2 provides an overview of distributed energy resources for residential sector. This chapter also introduces how the solar energy is implemented at the residential with household energy storage and community energy storage. Furthermore, previous works on residential PV plus storage are thoroughly reviewed and discussed.

- Chapter 3 develops the methodology for this research, including simulation paradigms, cases considered, components of the model. It also shows the details regarding battery storage model and its management strategies. Finally, several key performances indicators are introduced to the research for technical, economic and environmental assessments respectively.

- Chapter 4 uses the agent-based model to investigate the CES via the multi-discipline criteria proposed in Chapter 3. The HES and CES are assumed to operate to primarily meet local demand. The performances of household and community connecting to the CES compares with the HES and PV-only cases respectively. The recommendation for the selection of energy storage technologies is provided and the key issues hindering the feasibility are also discussed.
- Chapter 5 explores the potential alternatives to improve the feasibility of the CES, including demand side management under time-of-use tariff and inter-house trading. Different operational strategies of HES and CES, and the impact of sharing tariff rates on the household profitability are investigated

respectively. The existing challenges are analysed and potential solutions to enhance the economic feasibility are also suggested.

- Chapter 6 compares the household and community energy storage in the UK and Germany. Different types of household demands are chosen to represent the typical users in the UK and Germany. Three operational strategies and different system configurations are simulated to investigate the optimum performances. The key issues between the project feasibility for both countries are identified and different suggestions are analysed and provided accordingly.

- Chapter 7 concludes with a summary of the research in the thesis and also presents the contribution and recommendation for future research.

Chapter 2 Literature Review

2.1. Review of Distributed Energy Resources

The energy system is undergoing a significant transition from traditional centralised and carbon intensive systems towards decentralised and increasingly renewable systems. There are abundant wind resources and considerable solar resources in the UK. The UK government has devoted a clean development plan by increasing in both residential and industrial renewable energy. If this huge renewable potential is going to play a remarkable role in the future in the UK, many technical challenges will have to be fully addressed and solved. Every type of renewable energy resource has its own problems. Biomass is useful and sustainable for CO_2 emissions removal, but growth of biomass needs a considerable land use and its transportation also remains a big issue [27]. Hydropower and geothermal power have very strict geographical requirements, and most of the applicable sites are either geographically remote or already occupied for other purposes [27]. For resources like solar, wind and tidal, the intermittency has been the biggest issue and the unpredictability has imposed many challenges on the network. Alongside these challenges, the transitions also provide a wide range of opportunities due to the increasing distributed energy resources (DERs).

DERs are electricity-producing resources or controllable loads that are connected to a local distribution system or connected to a host facility within the local distribution system [28]. It is also defined as ‘‘behind-the-metre’’ power generation and storage resource, typically located on customer’s premises and operated for the purpose of supplying all or portion of the consumers’ electric load [29]. Emerging technologies, such as microgrids, can diversify the grid and also add new sources of energy generation and two-way power flows. DERs provide a number of opportunities for customers to self-supply energy, manage demand profiles, enhance power quality and resiliency, helping achieve clean energy goals. At the same time, there is also potential for DERs to complement the grid. Some key motivations for both grid operators and customers to adopt DERs have been identified and can be generalised as follows [28]:

- ***Economic benefits***: Avoiding costs associated with energy bills for customers by more efficient use of energy.

- ***Deferred or avoided network investments***: Avoiding expansion of generation, transmission, or distribution infrastructures, which benefits all participants in the energy system.

- ***Resiliency and power quality***: Contributing to a more resilient power system that can ensure a stable and secure energy supply in the event of short-term interruption and loss of grid service.

- ***Clean energy***: The integration of clean DERs can help decarbonise the energy system and also achieve the clean energy goals.

DERs consist of a variety of technologies. Some of them have been widely adopted and have more market experience and penetration while some are undergoing rapid development with a small share of the market. Common DER technologies include small-scale renewable energy technologies, such as solar PV panels; and also include other technologies, such as energy storage.

2.1.1. Solar PV Panels

Solar energy is energy produced from the sun in the form of electric or thermal energy and is becoming increasingly popular in some countries with abundant solar resources. There are several ways of capturing solar energy and the most widely adopted of these is with PV solar panels that convert solar energy into electricity via the photoelectric effect. There was 94 GW solar photovoltaics capacity installed globally by 2018, which accounts for 55% of total newly deployed renewable power generation capacity [30]. With the increasing capacity of PV, the global weighted-average total installed cost of utility-scale solar PV projects was around \$1210 kWp^{-1} compared to \$1389 kWp^{-1} in 2017 [30]. The reduced PV module price and large installation capacity also contribute to lower levelised cost of energy (LCOE) of utility-scale PV panel, around \$0.085 kWp^{-1}. However, the residential solar panel is still relatively expensive, around \$0.16 - 0.267 kWh^{-1} according to Lazard [31].

Figure 2-1 Rooftop Photovoltaic Panel

The solar panels can be installed at residential, commercial and utility scales. Residential solar energy applications are typically installed on the rooftop of residential buildings or ground-mounted where space allows. In general, there are two types of residential solar installations [32]. The first and most common approach is to install the solar PV system and connect it to the power grid. In this way, users are able to feed surplus electricity to the grid and obtain financial reward. The second is often known as the Stand-Alone system, which is usually installed for homes located in remote areas without an accessible grid connection. The stand-alone system is usually coupled with a storage system to charge surplus electricity for later use. For commercial solar, the capacity is usually much bigger than residential, and there is also a higher requirement on land.

According to Shubbak [33], the development of PV technologies has undergone three generations. The first generation is crystallin silicon based on silicon wafers; the second generation refers to the thin film technology and third generation PV technologies include organic cells, advanced inorganic thin films and multi-junction cells. Fraunhofer ISE [34] suggests that the silicon-based wafer technology accounted for approximately 95% of the total PV production in 2017 and only around 5% was thin film PV. The silicon cells can achieve high conversion efficiency, ranging from 22% for multi-crystalline cells to 28% for single crystal cell [34]. Thin cells are found to be able to absorb the same amount of sunlight with lower costs and required materials [35]. Thin film PV panels are also very easy and flexible to install with a more satisfactory lifetime around 25 years [35].

Although the current storage management strategy has not considered other factors, such as varying electricity price, the design of a system is highly location-specific, and the system may contribute to extra benefits by combining different strategies and services. The increasing scale of storage, either HES or CES, makes it possible to participate in more complicated interaction with the electricity market so that more financial profits can be generated. However, it is also important to take other factors into consideration during system planning, such as non-economic interests at household, community and society levels [36].

2.1.2. Battery Energy Storage

Energy storage comprises a variety of technologies that can store and release energy via mechanical, thermal or electrochemical processes. In the past decades, many battery chemistries have emerged and provided a range of performance capabilities and costs. Battery storage are very mature energy storage devices and are considered as a good complement for the integration of renewable energy sources, which can improve grid stability, flexibility, reliability and resilience [37]. Amongst all the storage technologies, the pumped hydro storage is by far the most common technology with installed capacity around 9000 GWh globally [38]. In recent years, the interest in energy storage has increased dramatically because of the technology advances, reduced costs, and the increasing awareness of climate change. Battery [14] is one of the main forms of energy storage, which will be reviewed in more details in this section.

2.1.2.1. Types of Battery Energy Storage

There are many types of battery storage available nowadays, such as lithium-ion (Li-ion), lead acid, and sodium-sulphur. For residential users, battery storage is one of the most popular energy storage solutions for the domestic market to cope with domestic electricity generation assets. Batteries are a set of several cells connected in series, in parallel, or both, which can generate a desired voltage and capacity from the electrochemical energy stored inside. A battery cell is a special and sealed container filled with two conductor electrodes and an electrolyte. The battery is connected to an external source or load that is driven by electrons flowing through circuits generated by the exchange of ions between two electrodes. Battery energy storage systems can obtain a reasonable electrical characteristic by connecting many low-voltage power battery modules in series or in parallel. In general, a battery storage system consists of batteries, the control and power conditioning system and the rest of the plant. This very structure can protect the entire system and ensure normal operation [39]. Batteries have been widely researched for a long time and currently many types of them are mature technologies. In spite of this, a range of battery technologies have been advanced [40] and become relatively cost-effective options [41]. At a commercial level, currently the mostly used rechargeable batteries are lead-acid and lithium-ion batteries, which will be briefly reviewed in this section.

- Lead-acid

The Lead-Acid battery is the most mature type of battery technology. The battery is made up of several cells immersed in an electrolyte that is a dilute solution of sulfuric acid. Lead dioxide is the main constituent of the positive electrode while the negative electrode is made of sponge lead. When the battery discharges, both positive and negative plates become lead sulphate and the electrolyte loses much of its dissolved sulphuric acid and becomes primarily water. During charging, both electrodes return to their initial state to supply energy in the next discharging process [42]. There are two main kinds of lead-acid batteries, namely flooded batteries and valve-regulated batteries. The former type is very common and widely used and the latter still requires further research.

The battery's charging/discharging performance deteriorates with the number of reversible redox reactions. Generally, the cycle life of a battery is between 1200 and 1800 cycles with an overall efficiency around 80%, which is significantly determined by the depth of discharge and operation temperature [43]. High operating temperatures can contribute to better performance by improving its capacity, but at the cost of reduced systems lifetime. Its characteristic of low daily self-discharge makes lead-acid battery a reasonable option for long term energy storage. The batteries have poor performance and short lifetime when they operate outside the ideal operational temperature range, 15 – 40 ˚C [43]. Lead-Acid batteries have lower specific energy and power compared to Lithium-ion batteries, and cannot provide frequent power cycling, which make it usually at a partial state of charge and the sulphating can further cause premature failure. The advantages and disadvantages of lead-acid batteries are generalised in Table 2-1.

Table 2-1 The Advantages and Disadvantages of Lead-acid Batteries [40]

Advantages	**Disadvantages**
Low initial costs	Modest specific energy and power
Mature technology	Short cycle life
Widely manufactured	High O&M requirements
Cheap raw materials	Temperature sensitive
Good round-trip efficiency	Limited reliability
No memory effect	Slow charge speed
Low self-discharge rate	Hazardous raw materials

- Lithium-ion (Li-ion)

The mass production of Li-ion batteries has enable it to be widely used in most appliances nowadays [10]. Li-ion batteries have been remarkably attractive to other industries, aiming to develop high power devices for applications, such as electric vehicles and stationary energy storage. The Li-ion are active to react with materials on both anode and cathode. Aluminium and copper usually serve as collectors at the electrodes because of their desired stability and oxidation potentials. The cells of Li-ion batteries are made of positive and negative plates and filled with liquid electrolyte material. A porous separator is used as the boundary of electrode areas, which enable positive lithium ions to pass through. Graphite is usually chosen as negative electrode material while $LiMeO_2$ is for anode. A non-aqueous organic liquid is usually selected as the electrolyte, containing dissolved lithium salts [44]. During the charging cycle, positive lithium ions flow from anode to the graphite sheets. The operation of discharge undergoes reversely. As the interface of organic electrolytes with electrode materials is thermodynamically unstable, a solid electrolyte interphase layer is formed on the graphite anode side during charge-discharge cycles. This layer protects the anode from a direct electrolyte exposure due to its lack of conductivity. However, it may grow slowly during future operation resulting in a loss of active lithium, which relates to the battery capacity loss and increased resistance.

Li-ion batteries have high energy density and specific energy [23], and also can fully charge and discharge power within a short period of time. According to Zubi et al. [40], the time to reach 90% of the rated power the battery is roughly about 200 ms with a considerable overall efficiency of 78% within

3500 cycles. With increasing number of electronic devices and applications, the great power and energy density would be substantially helpful to the roll-out. Li-ion batteries are generally seen as a good option for those applications with strict requirements on weight and response time. However, they are mainly used for short time scale applications due to their high daily self-discharge, approximately from 1% to 5% [45], but they do not require active maintenance to ensure their performance. Another advantage of Li-ion batteries is the variety of types available. There are several types of Li-ion battery cell, which means that they can be used for a wide range of applications based on their characteristics.

However, the Li-ion batteries also have several shortcomings. Although they have really good energy and power density, they require protection from being over charged and discharged with additional control on the current to ensure their safe operation [40]. Another issue is thermal runaway that can lead to fire and explosion of a battery cell. The increasing use of Li-ion batteries pose a significant safety risk and hazard [46]. In this way, Li-ion batteries require safety mechanism to limit voltage and internal pressures, which can increase weight and limit performance in some cases [44]. In addition, the Li-ion batteries suffer from aging issues that take place with the time and increasing number of use cycles [45]. The advanced technologies manage to enhance the lifespan of Li-ion batteries, but batteries may need to be replaced with expensive new ones after a while, which may lead to some issues if the batteries are embedded in the equipment.

There are many types of Li-ion batteries, and the selection of the specific type is usually based on their purposes. Lithium Cobalt Oxide (LCO) batteries are widely used for mobile phones, laptops, and similar portable devices due to its high specific energy. However, LCO also has a relatively short life span, low thermal stability and limited specific power, which means that they must be charged and discharged at a current within its C-rating to avoid overheating and undue stress [40]. In the recent years, LCO is losing favour to Lithium Manganese Oxide (LMO) that has lower internal resistance and better current handling due to its three-dimensional spinel structure [47]. LMO therefore can be charged and discharged at a very high rate with moderate heat build-up. For this reason, LMO batteries are commonly adopted for devices with high power demand. However, LMO has a small capacity, roughly one 30% lower than LCO batteries [47]. Nowadays, most LMO blend with lithium nickel manganese cobalt oxide (NMC) to improve the specific energy and prolong the lifespan. Many electric vehicles integrate with combined LMO and NMC in their design, which ensure enough current boost on acceleration and long drive range at the same time.

NMC has good overall performance, desired specific energy, and the lowest self-heating rate. The main reason for the enhanced performance benefits from the combination of nickel (high specific energy with poor stability) and manganese (low internal resistance with poor specific energy) [48]. In 1996, Lithium Iron Phosphate (LFP) emerged as a satisfied battery technology with high current rating, long cycle life, good thermal stability, and enhanced safety and tolerance if abused [48]. However, LFP batteries have lower nominal voltage, higher self-discharge amongst all Li-ion batteries. In 1980s, Lithium

Titanate Oxide (LTO) batteries were invented and became popular due to its zero-strain property, no SEI film formation and no lithium plating during fast charging and discharging at low temperature. It has better safety, low-temperature performance and long lifespan, but the expensive cost and low specific energy still yet to be improved [47].

Table 2-2 The Advantages and Disadvantages of Lithium-ion Batteries [40]

Advantages	**Disadvantages**
Extraordinary specific energy and power	High upfront cost
Long calendar and cycle lives	Advanced management system required
High round-trip efficiency	Safety concerns
Low O&M requirements	Thermal runaway
Good operating temperature ranges	Material bottleneck concerns
High reliability	Currently poor recovery and recycling
Extensive global R&D research	
Good self-discharge rate	
Relatively fast recharge	

2.1.2.2. *Key Parameters of Battery Energy Storage and Simulation Method*

For the better representation of the performances of different battery storage, there are several important terms to describe the operational characteristics, which are critical to the model development in this thesis and underpin elements of the simulation:

- ***Battery Capacity*** represents the maximum amount of electricity that can be stored within a certain period of time, which usually uses kWh or MWh as units. The capacity can also be illustrated as ampere hours (Ah), which is the number of hours that a given current can be supplied. The maximum power output that a battery can produce at a certain time is measured in kW or MW.

- ***Depth of discharge*** (DOD) represents the amount of charge a battery holds and is represented as a percentage of the battery total available capacity. For instance, if a battery has used 80% of its capacity with 20% remaining, then its DOD is 80%. The DOD can also achieve up to 100%, but this is likely to damage the battery lifespan. It is therefore that battery producers usually recommend controlling the DOD within 80%.

- ***Battery lifetime*** usually refers to the total number of full cycles that can be achieved by a battery. It is also used to represent the length of battery warranty, which assumes the battery operation is under the operational specifications within a given period of time.

- ***Cycle life*** is the time length that a battery can operate at certain operational specifications before a material performance loss is experienced.

- ***Roundtrip efficiency*** refers to the amount of energy actually discharged relative to the total energy provided. The efficiency losses usually occur during the battery charge/discharge process.

Operating the battery within the recommended system parameters can substantially prolong the lifetime with a desired performance. The terms explained above are suitable for majority of the battery technologies, which can also be used to compare the strengths and weaknesses of different battery types. This is important because different battery technologies and their use can vary according to the chemistry, design, application and particular efficiencies and lifetime characteristics.

Battery capacity plays an important role in the battery’s performance across its lifetime, which is significantly influenced by battery aging during use, including calendar and cycling aging. The former is the loss from the passage of time while the battery is left at a set state of charge (SOC). Cycling aging is caused by charging and discharging the battery, which is also reliant upon the SOC, the depth of discharge (DOD) and the operation temperature. The common aging phenomena includes loss of cyclable lithium via side reactions, loss of electrode active materials, and resistance increase through interfacial layer growth [49]. Battery aging should be considered during operational planning because of the operating costs. It is therefore important and crucial to have an accurate model to simulate the battery capacity degradation to optimise the cost-effectiveness of a battery.

There are several ways of simulating losses of different types of batteries in existing literature, which effectively calculate the aging effects by mathematically simulating the electrochemical reactions inside the batteries [50,51] or correlate the experimental data into an empirical [52] or a semi-empirical model [45,53]. The former mathematical simulation approaches usually start with theoretical assumptions that explain explicitly the degradation mechanisms and how they can be influenced by the use of battery. This type of approach focuses on simulating the loss of active material on electrodes, which requires many details regarding degradation at molecular levels and it is therefore difficult to further directly corelate the charging/discharging patterns with battery status [54]. Empirical and semi-empirical models are usually adopted in the battery planning and operation research [45,52,53]. These types of models can be used to simulate a particular battery application that has a certain battery operation range and a considerable amount of experimental data can be measured and then correlate with an equation. In general, empirical models can produce results with decent accuracy but with limited applicability [50], because they require measured data from specific applications. This type of model is usually more difficult to generate due to time-consuming experiments. Additionally, empirical battery degradation models are not suitable to simulate the batteries deployed for frequency regulation [50], which further limits their applicability.

2.1.3. Comments on DERs

With the growing penetration and reduced costs of renewable energy technologies, the decentralised energy system is becoming increasingly important, especially at residential level. A substantial number of domestic users have adopted distributed generation technologies using renewable energy reviewed previously such as rooftop solar panel. Distributed generation has recently started to be coupled with energy storage in domestic households. Installation of electrical and thermal storage systems in households can significantly enhance the self-consumption of on-site generation and provide certain level of energy independence from the grid. Two widely used batteries have been reviewed in this section, and the increasing deployment of batteries is mainly Li-ion batteries because of the extraordinary characteristics, such as high specific power and energy, fast charge/discharge rate and high efficiency. These attributes together with various incentives by the industry and government enable residential users to have more choices when they decide to integrate DERs in their homes. Amongst the applications, PV plus battery storage has become the predominant option within the residential sector due to the increasing electricity tariffs and reduced subsidies.

2.2. Review on Solar PV Plus Storage and Residential Applications

In recent years, reduced government subsidies for renewable energy generation [12,13], expensive energy prices [55] and the growing awareness of environmental protection [2] have contributed to an increasing number of end users starting on-site energy production, especially via PV. There have been many studies suggesting that the transition of energy consumers towards energy prosumers via PV and battery storage will lead to a significant disruption to the centralised energy system [56]. This is because the energy consumers with DERs are likely to decrease imports and hence reduce the reliance upon the utility companies, which will inevitably change the way the energy consumers interact with the existing centralised energy supply system [57].

2.2.1. The Disruption and Opportunity of PV Plus Storage

In a traditional energy system, electricity is generated by centralised power plants, such as thermal power plants, hydroelectric plants, or nuclear power plants. The generated electricity is transmitted through the transmission and distribution network and finally reaches the end-user side. The network operators are only responsible for the transmission and distribution of electricity without participating in electricity trading. The electricity generation from power plants and consumption on the end-user side is an instantaneous process that is managed by an electricity market ensuring the balance between supply and demand.

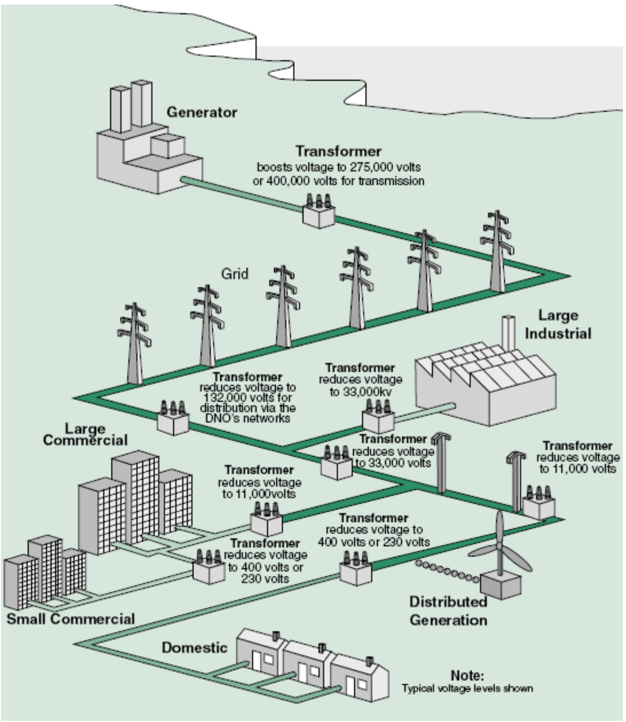


Figure 2-2 A Schematic of Traditional Centralised System [58]

Figure 2-2 is a schematic of the traditional centralised energy system in the UK. The well-existing centralised electricity supply model has facilitated rapid development in the past decades. With increasing household demand, the power plants have to expand the generation capacity and the network also needs to undertake relevant reinforcement or expansion to ensure security of supply [59]. The existing energy system has to encounter many more challenging situations due to the emergence of new technologies, climate change policies [60,61], the increasing energy price [62], and more actively engaging consumers [63]. All of these factors affect the system management and introduce new levels of complexity. However, the traditional centralised system has to respond to specific development of any component of the system [58] to increase the reliability in a more effective and environmental-friendly manner [64]. Design of the centralised system allows companies to offset their risk and provide enough financial capability to ensure they can operate cheaply, such as acquiring new low-carbon generation assets at high costs, and also to survive occasional exposure to extreme circumstances in energy markets.

The emergence of PV is a good instance of one such change challenging the system. The intermittency of PV generation leads to many issues, such as voltage fluctuations and harmonic distortion [11]. To solve this issue, reliability was usually improved by connecting the residential PV to the grid, but this caused issues for the energy system because of the one-way power delivery from generators to consumers [65]. Additionally, the PV electricity production increases with time through the day until reaching its highest, in the afternoon and then falls to the lowest in the evening. As the wholesale market electricity price is based on the supply and demand, the price goes up with the increasing demand and decreasing supply. The peak PV production happens during the day, usually at noon, and will inevitably inject enormous amounts of surplus electricity to the grid and hence drive down the wholesale price down, potentially becoming negative. For this case, it heavily diminishes the profitability and competitiveness of traditional centralised generators, potentially resulting in huge problems for the industry in the long term [66]. This may become even worse with overgeneration in the future, also known as the ‘‘duck curve’’ [66] shown in Figure 2-3, which was predicted in California that the significant net demand drop during midday caused by the large power input from solar resources. Although the solar generation in the UK unlikely to be comparable to California, the increasing PV installation capacity will possibly lead to similar demand reduction during the day, but less significant.

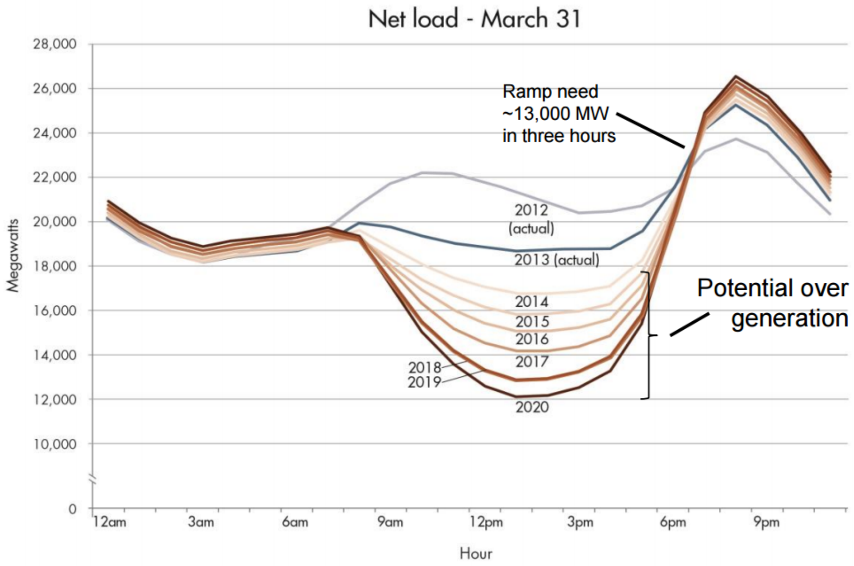


Figure 2-3 Illustration of the "Duck Curve" [66]

Apart from the technical issues, the growth of PV also makes the revenue recovery challenging, also known as a death spiral [67]. It refers to the falling residential demand resulting in revenue recovery of the traditional utility companies. As the electricity price is based on the demand and supply, the electricity price should decrease with the increasing supply. However, the costs of infrastructure are charged regardless of utilisation, which accounts for a considerable proportion of the retail electricity price. This further encourages the consumers transitioning towards being prosumers, inevitably leading to financial disparity to the households without PV. In return, the lowered revenues cannot incentivise the large generators that may gradually decommission their assets and end up with negative social-economic outcomes [67].

The issues mentioned above have drawn considerable attention from academia to research and develop potential solutions, such as microgrid [68,69] and coupling with energy storage [70]. Many other efforts from industry and government also have put efforts to respond to the challenges in a cost-effective manner, such as providing relevant financial [71] and legislative supports [72,73]. Amongst various applicable solutions, residential storage is considered as an important element and emerges in the market. Many benefits of battery energy storage have been identified and a key capability is to store surplus generation for later use [74], which can effectively reduce the surplus power injection to the grid. Additionally, the stored electricity can be used during the peak demand period that usually comes with more expensive electricity price. Battery storage can also be used to shave the peak demand [75], reducing the congestion on transmission and distribution networks, and ultimately contribute to defer or avoid network reinforcement or expansion [73]. Most importantly, storage complements the PV production significantly by improving the power quality and voltage fluctuations, which enhances the overall system reliability and security of supply [76].

With the various types of support and the falling costs, residential PV has been increasingly popular. As mentioned earlier, the unpredictability of the intermittent solar production makes it important to measure the matching between the production and consumption. Two metrics are frequently adopted to quantify the matching between supply and demand for the residential PV systems [14], self-consumption rate and self-sufficiency rate. The traditional self-consumption rate represents how much PV electricity is consumed locally within the house. In contrast, the self-sufficiency rate measures the share of household load demand supplied by the PV system, indicating how independent the household is from the external power grid or how reliant the household is upon the power grid. In general, researchers quantify the self-consumption and self-sufficiency through two main approaches [14], load-matching and grid-injection. The former focuses on the overlaps between demand and production, while the latter aims to quantify the net power generation and demand. Load-matching is a very important indicator for the building designers to determine the system size for the long-term profits. In contrast, the grid-injection approach focuses on the short-term system performance, which is more useful for network operators.

In the past, many installations of PV for electricity production resulted in the injection of the majority of generated electricity into the grid and being remunerated with FITs that was higher than electricity tariffs. For households, it was economically inefficient to use on-site generation to meet their own demand and hence reduce electricity injection. However, with reduced subsidies, there was no longer financial attractiveness of injecting PV electricity to grid [77]. With an increasing price gap between the FIT and electricity tariff, people started to move their strategy towards self-consumption. However, direct self-consumption is heavily reliant upon the weather that usually means a self-consumption rate between 20% and 35% [78], which cannot guarantee a stable electricity supply to reduce energy demand. In this way, people started to realise the importance of introducing other strategies to enhance self-consumption.

As shown in Figure 2-4, there are two common ways to enhance PV self-consumption in residential homes, energy storage [23] and demand side management [79]. The value of an energy storage system is to reduce the electricity bill by storing the surplus PV generation for later consumption. In contrast, demand side management (DSM) aims to improve the energy consumers' behaviour [79]. For example, load shifting is a means of DSM, which aims to move demand consumption from a time period requiring huge amount of energy to another period that has sufficient PV production. Both methods are found able to effectively improve the use of PV electricity [80], reduce the energy bill [22] and also ease the burden of distribution network operators and energy suppliers [81]. More details of these two methods will be presented in the following sections.

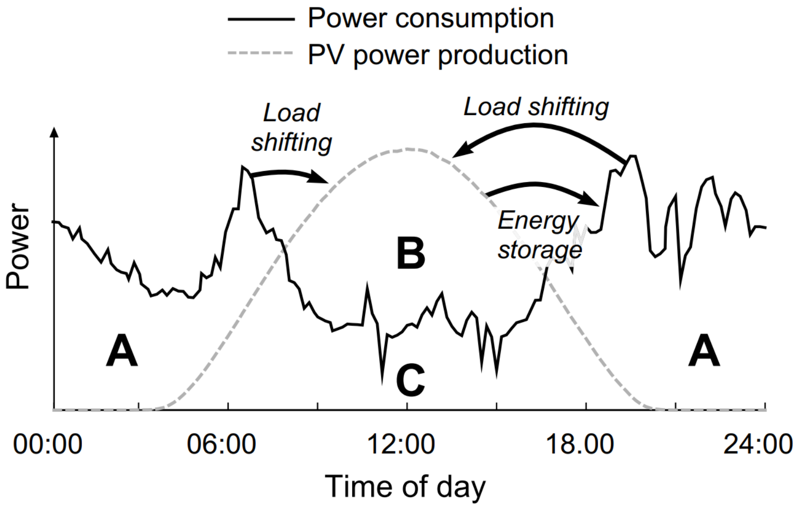


Figure 2-4 Two Methods of Enhancing the Utilisation of Domestic Solar Production [14]

2.2.2. Improving Self-Consumption of Residential PV

The addition of energy storage to the PV is an effective way of improving self-consumption, especially battery storage. As reviewed previously, battery storage has emerged as the most popular option contributed by its high efficiency and rapid charge/discharge characteristics. Amongst all the battery technologies, lead-acid battery is the most mature with a desired cost-effectiveness, but Li-ion batteries are expected to have a great potential in future development. However, the expensive upfront cost still remains beyond most customers' affordability, but may be significantly improved by future roll-out of electric vehicle [10].

In most cases, HES refers to a stationary battery system connecting to the PV system. There are two common layouts for residential PV plus storage systems [82], AC and DC coupled systems. Figure 2-5 a) shows a schematic of a typical AC coupled system, where the HES connects by an inverter and charge regulator to the PV system, which represents the majority of applications currently. This type of system is easy to install and retrofit existing rooftop PV system, but the downside is the electricity from PV may be inverted many times and hence causes a reduction in overall efficiency. Figure 2-5 b) is the DC coupled system, where the battery can be charged directly from the solar panel and also power the home via the built-in battery inverter. As a result, DC coupled systems are slightly more efficient than AC coupled systems, as the power supply is inverted fewer times. However, DC coupled battery systems can be difficult to retrofit to existing PV, and reconfiguration is often needed. Therefore, DC coupled system is often seen in newly built commercial or residential buildings.

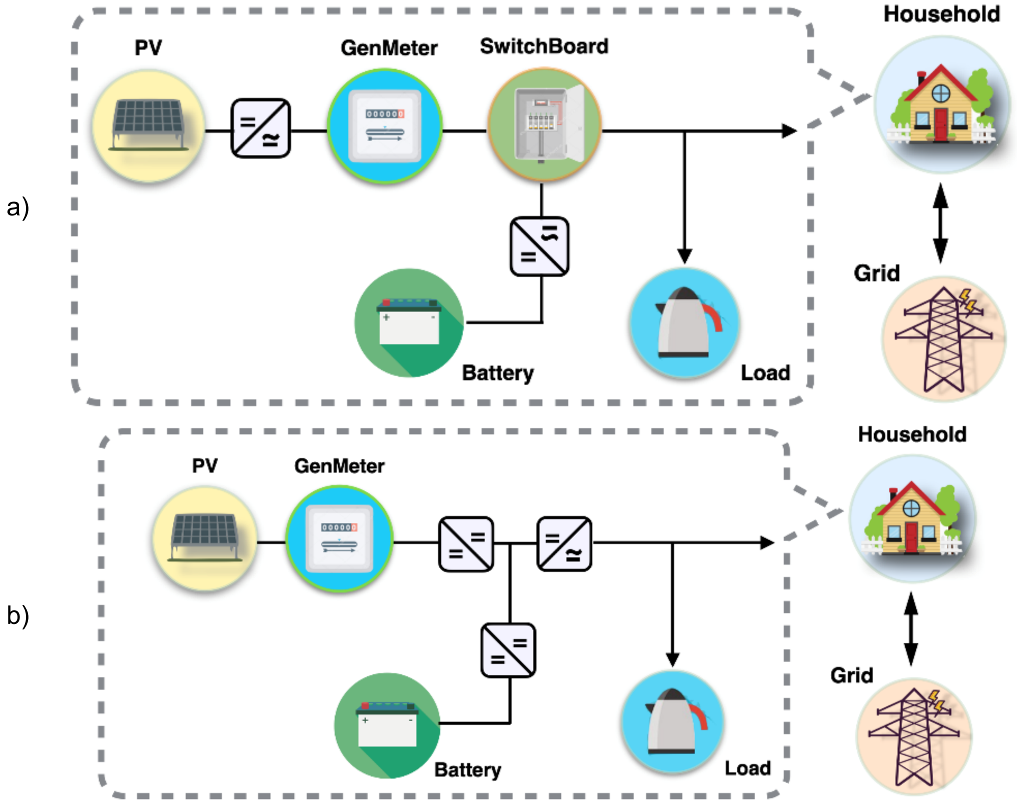


Figure 2-5 a) AC and b) DC Coupled HES System

Another way of improving self-consumption is to use DES to encourage consumers to optimise their energy use and a common method is via financial incentives [83]. DSM is of great potential for controllable and shiftable load that can operate at flexible time schedules during a day, such as plugin hybrid electric vehicle, washing machines, and heating. The main objectives of DSM can be classified into six different categories, including peak shaving, valley filling, load shifting, strategic conservation, strategic load-growth and flexible load shape [84]. For example, load shifting can shift the power demand of those shiftable loads to the time period that has surplus PV generation. The power injection to the grid therefore can be effectively reduced. This technique can be undertaken manually by turning on those demand during sunny days. It can also be achieved automatically, assisted by numbers of devices and control algorithms together with comprehensive weather forecast [85].

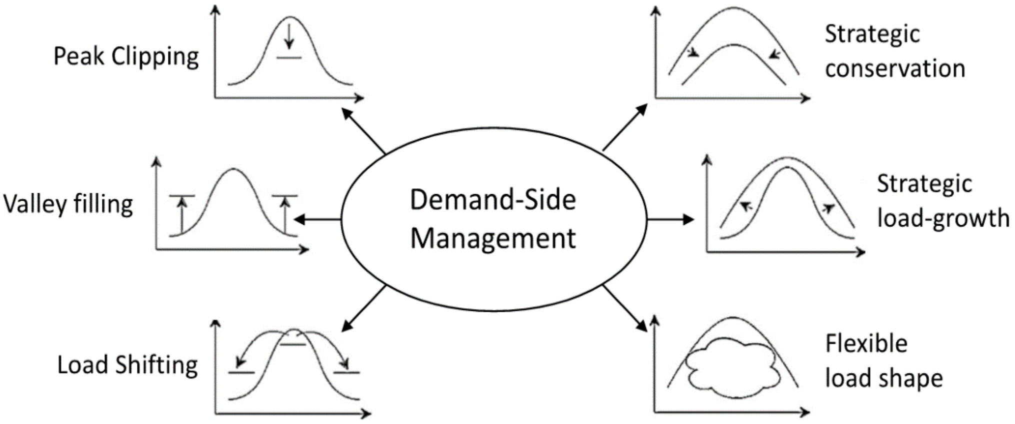


Figure 2-6 Six Main Objectives of Demand Side Management [84]

There are a number of other DSM technologies applicable to the majority of homes [84], such as direct load control, load limiters and smart appliances. However, not all household demands are suitable for DSM because either the operation of some appliances is bound to a particular time, or the power required by the shiftable appliances is not significant enough to contribute to any impacts. DSM together with HES is therefore emerging as an increasingly popular option to increase the self-consumption. The economic benefits can be even further enhanced by introducing price signals [24]. In the UK, the plan to upgrade to a smart energy system [86] along with the regulator's desire to mandate half-hourly settlement of all electricity users [87], have contributed to the installation of smart meters and development of time of use (TOU) tariffs. A TOU tariff is a pricing plan that uses time-dependent electricity prices to encourage consumers to use cheaper electricity at times when more energy is available [88]. The introduction of TOU tariff aims to enhance the flexibility and sustainability of the electricity system, and also benefits the consumers by lowering energy prices [88]. The benefits of this type of tariff are significant. It can contribute to a better balance between supply and demand for the network operators, which helps to avoid expensive network reinforcement and to increase the penetration of intermittent renewable sourced generation. Additionally, the consumers are able to effectively lower their energy costs by combining behaviour change in consumption and tariff incentives. There are a few types of tariffs in the current market [88]:

- ***Static TOU***: Two or more rates for given periods of times are applied to consumers for their electricity consumption.

- ***Dynamic TOU***: Different tariff rates are applied based on the time of day. The times and rates vary on daily basis.

- ***Direct Load Control***: Customers give demand-side management operators limited control over certain technologies in their homes.

Many studies have been carried out across the world to investigate the added value of energy storage and DSM to enhance the self-consumption of PV generation, which are reviewed in the following section.

2.2.3. Previous Research on Residential Solar Plus HES

Initially, much research investigated whether the HES could improve PV self-consumption. Bruch and Müller [89] investigated a 6 kWp residential PV plus lead-acid battery in Southern Germany. Their results suggested the annual SCR of the household can achieve 29% without storage, but SCR was improved to 37% with 2 kWh storage and 51% with 4 kWh. Schreiber and Hochloff [90] found the addition of 7.4 kWh battery could improve SCR from 31% to 72%, compared to a 4.1 kWp PV-only system. Weniger et al. [82] ran a full year simulation on a residential home with 3.2 kWp PV coupled with 4.4 kWh battery storage. Their results showed that the battery storage could enhance the SCR to 65% compared to SCR of a PV-only system, 35%, which are in line with the previous studies. Researchers have also explored the value of DSM. For example, Widen [91] examined 200 single-family households in Sweden with PV peak capacity varying from 3 – 12 kW. Multiple appliances were programmed into a load-shifting algorithm, which managed to increase the overall PV-self-consumption by around 200 kWh on average and a maximum €20 annual energy costs savings. Castillo-Cagigal et al. [92] analysed the effects of storage and active DSM in a house equipped with PV generation and grid connection. The SCR could be increased considerably via storage and DSM by up to 20%. They also suggested that the DSM could possibly reduce the storage size and increase the scalability.

With the increasing studies confirming the benefits of HES and DSM, the research focus has shifted towards evaluating and improving the cost-effectiveness on the PV plus HES system. A study in Germany [93] tested several combinations of PV system and storage sizes to determine the most cost-effective system configuration. They suggested that the economic feasibility of PV plus HES were already profitable, but the assumed cost of battery storage at €171 kwh^{-1} was unrealistically low. Truong et al. [94] assessed a particular HES model in the Germany context and conclude that the profitability of the system requires substantial subsidies and increasing electricity tariffs, which was also emphasised by Quoilin et al. [95]. Uddin et al.[22] even argue that the addition of HES cannot provide any economic benefits, and the financial loss can be higher when degradation effect is included. Linssen et al. [23] conducted a techno-economic analysis of residential PV plus HES in Germany and the improvement in SCR could achieved up to 58%. They emphasised the sensitiveness of cost optimisation to regulation frameworks and support schemes because the difference in break-even prices of battery with and without supporting schemes could vary by up to €300 kWh^{-1}. They also suggested that realistic load and production profiles should be used in research to avoid any overestimation and incorrect calculation outcome. The optimisation of the system configuration and operations has therefore become one of the main focuses of recent research.

Quoilin et al. [95] focus on improving the feasibility by optimising the system design, but the uptake is still found too expensive and requires further cost reduction. Although the cost of battery storage has fallen considerably since 2010 from £1000 kWh^{-1} to £140 kWh^{-1} 2019, the price of battery storage units still remains very high [18]. Talent and Du [96] investigated the optimal sizing and energy scheduling of a PV-battery system under a TOU and a demand tariff in Australia. The optimal system set-up was found to be 5 kWp and 7 kWh with a net present value at AUS $4260. Gitzadeh and Fakharzadegan [75] used a mixed integer programming model to investigate the optimal storage sizing on pre-existing PV installations and the impacts of different tariffs. The optimal battery capacity was found to be 30 kWh, which reduced the annual energy costs from $884.7 to $632.7. However, the economic profitability was questionable if battery degradation was considered. Pimm et al. [97] investigated the performance of a 100-houehold community with various levels of PV penetration, battery storage and heat pump usage. The DSM under TOU tariff could effectively lower the peak energy demand by 60%. Pena-Bello et al. [98] used a linear programming to determine the best-suited battery technology in Austin and Geneva. Their results suggested that the system profitability could be significantly improved by combining other applications with self-consumption and load shifting, such as avoiding PV curtailment and demand peak shaving. They also pointed out the four key factors that influence the economic profitability of a PV-coupled battery system, including household demand, geographical characteristics, and battery technologies.

Nowadays, the growth of residential solar coupled with HES systems is widely recognised as a helpful solution to keep a household self-sufficient. Many previous studies have proven the PV self-consumption can be enhanced by adding battery storage with/without DSM. However, the increasing penetration of solar also poses new challenges to local network operators with substantial power injection during the day or significant power import surge because of the arbitrage performed by the battery storage [97]. In addition, the promising electrical performance of Li-ion batteries will dominate the future applications, but the expensive costs still hinder accessibility to the domestic market, especially for those countries or region without related supporting schemes. It is therefore important to explore other potential alternative to enhance the benefits on both perspectives of residential homes and network operators. A few measures of incentivising the deployment of energy storage were recommended to shave peak demand at low voltage level [97], such as capacity charges based on the maximum import and export capacity, and storage rental or sharing between the households and aggregators. Some also argue that scaling up of storage capacity to a community energy storage may be helpful to increase the accessibility of battery storage to the users [26]. The research reviewed in previous paragraphs suggest that the addition of HES can significantly improve the utilisation of PV generation and also provide more flexible operation options for both users and network operators based on different objectives. However, the expensive cost of battery storage is still considered as the main hinderance of its wide adoption. There are some ways proposed to improve the accessibility of storage, such as combining different revenues, and scaling up the storage capacity. Therefore, the community energy storage has the potential to benefit both households and network operators at a lower cost. The next section is to present a state-of-art review on community energy storage.

2.3. Review on Community Energy Storage (CES)

The built environment accounts for a significant proportion of total annual energy consumption in the UK [99]. Electrification of heat [100] and transport [101] will inevitably lead to increasing peak demand which probably also will cause congestion in the network. With the rapid development of DERs, the network will have to tackle all the challenges imposed by the increased demand and generation to ensure the security of supply. The simplest solution is to reinforce or expand the network, which tends to be expensive. In recent years, communities are identified as a key scale for future energy system and are expected to play a more significant role along with the wider energy system, especially for energy storage. CES can potentially benefit the network operator from a cheaper and mobile infrastructure [102]. However, most energy storage is either distribution-grid connected or installed in a single household in the UK.

As an emerging concept, CES has several definitions. According to Parra et al. [103], CES is defined as an '*Energy storage system located at the consumption level with the ability to perform multiple applications with a positive impact for both the consumer and the Distribution System Operators*'. Koirala et al. [36] defined CES as '*an energy storage system with community ownership and governance for generating collective socio-economic benefits such as higher penetration and self-consumption of renewables, reduced dependence on fossil fuels, reduced energy bills, revenue generation through multiple energy services as well as higher social cohesion and local economy*'. The California Public Utilities Commission also provide a similar definition on CES [104]. From the concepts given above, there are many similarities that outlines the basic functions and characteristics of CES. Firstly, CES can also be installed for high or medium voltage substations to provide grid service [103], such as grid support and ancillary services, and also contribute to network reinforcement deferral. Secondly, CES can also be used for the end-user and DERs to serve different objectives [105], including enhancement of self-consumption and integration of DERs, peak shaving, economic incentives, seasonal storage and emergency services.

A typical CES system includes a battery, a four-quadrant inverter, and a management system that monitors and controls the battery and inverter separately. Compared to other options, CES can add extraordinary capacity to the grid compared to HES, and also can be installed near end-users, effectively reducing the construction and expansion of transmission networks. The comparison of advantages and disadvantages is shown in Table 2-3.

Table 2-3 Advantages and Disadvantages Between HES and CES [106]

	HES	CES
Advantages		Reduced levelised cost of storage;
	Ability to participate in energy market;	Can be shared between users and applications;
		Cheaper costs due to scaling effects;
	Less affected by grid regulations;	Connection point can be chosen individually to increase voltage quality of local grid
Disadvantages	Doubts of consumers about battery technology;	Restrained by complex grid regulations;
	Expensive costs of storage system;	Difficulty in system planning and construction;

As mentioned previously, electrification will lead to increasing peak demand and further worsen energy congestion. The grid operators will deal with simultaneous generation and demand that potentially will lead to temporary problems in the grid. Currently, many cases end up with very costly solutions, such as grid enforcement and expansion, due to the limitation in the use of innovative and flexible solutions, such as localised balancing mechanisms provided by aggregators or prosumers. The costly investment is eventually shared by all consumers connecting to the grid. According to [107], CES can potentially contribute to the grid operator, obtaining cheaper and mobile infrastructure with a wide range provision of grid services. CES can also maintain the operation of low voltage networks during outages or maintenance. The other benefit of CES is owners of solar panels can further improve the self-consumption by storing surplus solar generation in the CES. There is a promising potential of CES deployment, which can avoid unnecessary grid upgrading, lower grid costs and enhance grid management. Moreover, CES can provide more flexibility and space for green generation in local distribution grids and increase reliability of power supply and provision of emergency power. There are a variety of perspectives on how CES should be used by either the network operators or the end-users. Similar to other new technologies, the deployment of CES in the existing grid and its integration with DERs will encounter several technical and economic challenges, which will be reviewed in next section.

2.3.1. Prospect and Challenges of CES Deployment

At the moment, there has not been a clear agreement on how CES can be utilised. Therefore, CES may be part of a utility-owned or operated community solar project to improve the power quality. It can also be a part of a self-sufficient energy community to enhance the self-consumption of the on-site generation. Many obstacles have been identified which may hinder the deployment of CESs, which can be generalised as [108–110]:

- Technical and operational standards: Currently, there are not any official standards, which imposes a significant uncertainty on CES deployment and further questions the safety and quality of relevant applications.

- Ownership and unbundling: In the UK, only energy suppliers are allowed to own an energy storage system. A more beneficial strategy is to allow network operators to have the permit to possess storage systems. In this case, considering the flexibility that CES may provide, CES can be potentially owned by either domestic users or low-voltage network operators. However, it will require more guidelines on the operation and how the revenue stream is distributed. Parra et al. [9] suggested that the CES can be purchased either by the end-users connecting to their renewable generations, or by utility companies, aggregators or building service companies to integrate with renewable generation plants of end-users. The former is helpful for the community to achieve autarky, while the latter can contribute to more attractive financial revenues. In this way, it is necessary to develop new policies and business models including different services that can be potentially provided by CES.

- Market access: In many cases, the energy storage is very disadvantageous due to the limited market access. In real operations, energy storage facilities have to produce sufficient turnover to maintain market access. The installation of CES can provide extra system flexibility to stakeholders, whereby success will be dependent upon ensuring users are offered the best value and are remunerated. It is therefore essential for policymakers to improve the existing market ensuring participants have market accessibility and optimise the revenue streams.

- Business model: As mentioned previously, CES can be used for enhancing self-consumption of households and also grid services to acquire considerable financial benefits, which is essentially reliant upon who owns the facilities and how to run the operation. According to UK Power Networks [111], a variety of business models have been investigated, such as ‘Merchant Services’ where the network operator may build and directly operate the CES facility. Alternatively, a third-party entity may be contracted and run the assets, which is also known as ‘Contract Services.’ The configuration and operation of CES needs to carefully assess the advantages and disadvantages, while more efforts from legislators are required to ensure a clear roadmap for CES.

Lombardi and Schwabe [112] propose a sharing economy business model to obtain more profits if the CES can have more operational freedom, thus, achieving a better profitability if with further reductions in battery costs.

2.3.2. Previous Research on CES

CES is of great importance in creating a more efficient energy system. Parra et al. [113] proposed a CES model to investigate the improvements in demand load shifting by CES and also to optimise the best CES configurations for different communities. A 100-household community was chosen as a study object connecting to CES that could perform demand load shifting under an Economy 7 tariff and a real-time-pricing tariff. The results showed that CES managed to shift the fraction of the daily peak demand from 97% for a single home to 85% for a 100-home community at a levelised cost of storage (LCOS) between 0.14 and 0.32 £.kWh^{-1}. They also suggested that the aggregation of household demand was able to smooth the total peak power during peak time, and the benefits would be enhanced with the increasing CES capacity.

Barbour et al. [25] carried out a comparison between HES and CES in a community. The results indicated that CES generally provided better return on investments compared to HES. The CES could also effectively reduce the imports and exports between the communities and the power grid compared to the communities with HES. For CES, every installed kWh capacity was able to reduce 5.6 kWh import and 6.2 kWh export, compared to 2.4 kWh import and 3.8 kWh for HES. Additionally, for a community with 3244 MWh total demand, an 8.5 MWh CES can achieve even better internal rate of return (9.3%) compared to that of 13 MWh HESs (8%). They concluded that CES was a more effective alternative compared to HES.

Marczinkowski and Ostergaard [114] used EnergyPLAN to conduct a case study of a smart island energy system focusing on the technical feasibility of PV plus HES/CES. The results show that both HES and CES can contribute to less electricity import and higher self-consumption, but the annual full capacity cycles of residential batteries are much higher than communal batteries (157 and 68 cycles respectively). However, although residential PV and batteries contribute to a high local use of PV power, more economic benefits and involvement for consumers, long storage period and ineffective use of residential batteries could lead to a greater constant loss of electricity, making residential batteries less favourable than communal batteries. For communal batteries, they result in only 36% of the household demand directly and less customer involvement and benefits, but it provides a good opportunity to integrate with other energy resources and to enhance grid stability. They concluded that CES is more favourable from a system perspective and HES is more suitable for consumers.

There are many other researchers working on the operation and management of CES. Arghandeh et al. [115] proposed a hierarchical control system to optimise energy cost savings over time for a 50 kWh CES. The algorithm used locational marginal prices and a 24-hour distribution network load forecast as the input to produce optimised battery operation schedules. The results showed that the addition of 20 CES units manged to shave the peak demand, and the schedule also could help the CES operators to make profit according to the locational marginal price. Additionally, the CES showed great benefits for the distribution networks, including load support during outages, improved reliability and service availability.

AlSkaif et al. [105] proposed a reputation-based framework to manage the power flow in a CES. In the framework, the system tracked and calculated the reputation factors for each household based on the historical behaviour within the CES. The reputation factor refers to the ratio between the total amount of renewable power shared by households during the set of previous days and the total renewable power shared by all households in the microgrid. The amount of energy from CES was mainly determined by the reputation factor and the available energy in the CES battery. Simulation results assessed the performance framework and show that a cost saving of up to 68% can be achieved by sharing only their surplus renewable energy. The proposed framework suggested that the fairness in energy allocation could be obtained by the reputation-based policy and the CES also was beneficial to decrease households' reliance on the power grid.

Chathurika et al. [116] developed a novel energy trading system based on game theory with a CES device for demand side management within a network at a neighbourhood scale. Households were allowed to trade power freely within the community. Combining with a TOU tariff, the CES could manage power flows through from and to the customers and the grid in a dynamic non-cooperative repeated game strategy. The results showed the system was able to provide peak load levelling for the grid and reduce the daily average energy costs of participating users by 26%. The benefits would be further enhanced with the increasing participants and higher round-trip efficiency of the battery.

However, some authors have pointed out that the CES systems still struggle to achieve feasibility. Van Der Stelt et al. [117] adopted optimisation and dynamic pricing to compare the techno-economic performance of HES and CES for residential prosumers in Netherlands. The results showed that both HES and CES could significantly improve the use of on-site generation by at least 22% compared to the baseline households without a storage system. Both systems could effectively reduce household energy cost, ranging from 22 to 30%. However, neither type of storage system was found profitable under the current system, but the payback time of CES (26 years) was found shorter than that of HES (43 years).

Sardi et al. [118] conducted a study aiming to optimise the allocation of CES in a distribution system with PV generation. The proposed strategy considered all possible options to gain benefits, including energy arbitrage, peak power generation, energy loss reduction, emission reduction etc. The results suggested the CES deployment was helpful for the distribution networks on both technical and economic perspectives. The biggest significance of CES was to effectively defer network upgrade, which saved around almost 80% of total benefits.

Muller and Welpe [106] investigated the possibility of sharing electricity storage at community level. They proposed two potential technical frameworks for CES, connecting through a public network or a private network. The authors claimed there was a lack a suitable regulatory framework for the integration of CES within public networks, and also a lack of experience with microgrid setup and operations. They pointed out the expensive net levelised cost of an energy storage system was still a significant barrier for economic viability. In addition, there were no incentives or business models available to use, further worsening the profitability of the CES project. It was further suggested that the policymakers should evaluate options how distribution network operators could encourage such applications, for instance, enforcing more transparency in the network operation and providing more financial incentives.

DVN GL [107] investigated the feasibility and scalability of CES for grid service in the Netherlands. Results suggested that CES is feasible at certain locations suffering from congestion problems or needing network expansion. It required an intelligent algorithm to combine different grid services so that the revenue streams could cover the upfront cost. However, the author also pointed out the main barriers to a CES including a lack of standardisation, compensation payments, ownership, and market accessibility, which were in line with [106] and [9].

2.3.3. Comments on Previous Research on CES

As reviewed in the Section 2.3.2, although many studies have been carried out throughout the years to investigate CES and existing energy systems and also to identify the challenges, most literature focuses on either the techno-economic assessment of energy storage (e.g. [15,30]) or using mathematical programming to explore the optimal configuration of a CES system for community-level demand side management (e.g. [23,31]). It is certain that CES has great potential to benefit the local network by shaving peak demand, and also to facilitate higher PV self-consumption of residential homes. However, most studies focus on how CES can impact on network and community total demand, but there has been a limited number of studies that explore the behaviour and performance of individual households within a network connecting to CES.

With increasing retail electricity prices in countries which have a greater renewable energy uptake, energy poverty is likely to become a more critical issue. Meanwhile, there are still many households less likely to install PV or other renewable generation technologies because of the expensive costs, available area for the installation, the lack of relevant financial and regulatory incentives etc. Improving the feasibility of CES can potentially be helpful to solve such issues and the improve the decarbonisation of the energy sector. There is a lack of understanding in how the behaviour and performance of households or end-users is influenced by CES, so that CES can be built to facilitate households' energy consumption. Additionally, it is important to investigate other potential alternatives to solve the current hinderances identified previously, such as profitability and regulatory frameworks. More research is therefore needed to find innovative solutions to create business models, add revenue sources and remove legal barriers.

2.4. Summary

This chapter provided an overview of existing renewable energy technologies available for residential households. The energy system is evolving towards a less carbon-intensive direction and also becoming more decentralised. It is anticipated that more residential households will start to adopt renewable energy generation. The growing retail electricity tariffs and reduced government subsidies have shifted households' operation towards self-consumption. Amongst all the options, energy storage and demand side management are expected to be vital and further enhance self-consumption. Although residential PV plus battery storage at a household level has been extensively studied, the expensive costs of energy storage systems still hinder the uptake, and therefore a more cost-effective alternative is needed.

A number of previous studies have confirmed the potential advantages of CES for residential users and distribution network operators, which makes CES a satisfactory alternative for HES systems. However, most studies focused on the performance of the community or the network, while the behaviour and impacts on households have received limited attention. Additionally, the wide deployment of CES is still questionable because of the lack of experience, regulatory framework, implementation knowledge and financial incentives. It is therefore important to have a better understanding how CES systems and its users behave so that the challenges can be well addressed and hence provide corresponding solutions.

Chapter 3 Research Methodology

3.1. Introduction

There are several approaches applicable for energy systems modelling. It is important to note that there is no optimal approach, and the selection of the approach is dependent upon the problem. Agent-based modelling has been used to study problems involving high-levels of human behaviours, but is also suitable for engineering problems, such as energy network modelling [120–123]. The entire system aims to control a complex community energy system where parts are represented as autonomous agents that can communicate with each other. Since the agent-based approach facilitates self-organisation, the pre-set logic will interface itself to other existing agents once the agents join the system [124].

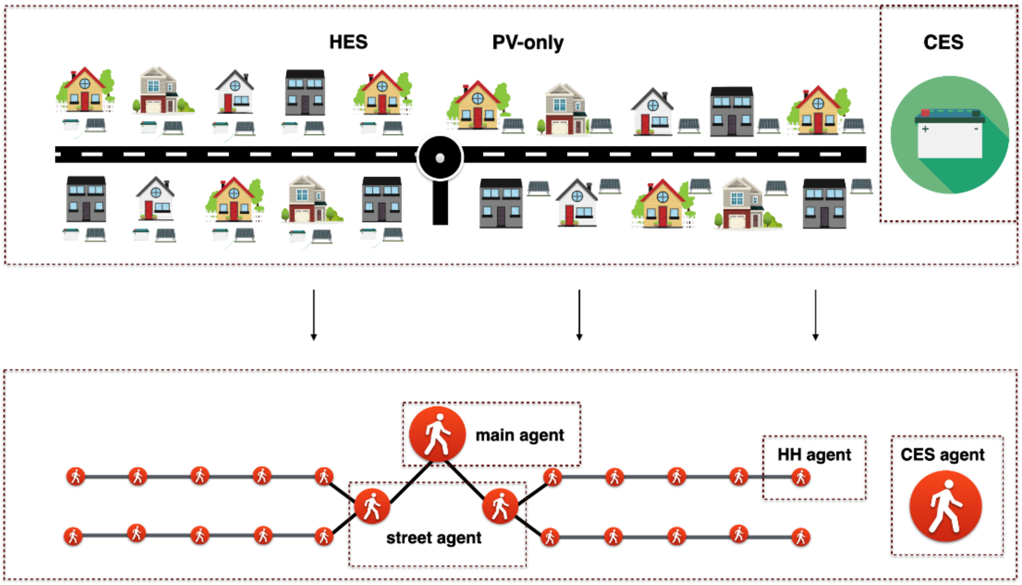


Figure 3-1 The Structure of the Agent-based Model for this Study

Figure 3-1 shows the agent-based framework developed in this work. It builds upon a description of a microgrid system including a supply/demand model that consists of multiple agents, representing households, presenting supply and demand to the network based on their needs and capacities respectively, and engineering models representing the physical energy technologies that each contain. To develop an agent-based framework, it is important to define the detailed functions of each agent based upon the characteristics of the individual energy resource:

- **Energy Source Unit**: the energy unit provides electricity to the system. In this study, it refers to a PV unit.

- **Energy Storage Unit**: the battery is considered as the energy storage unit that stores energy when energy supply within the network is sufficient and supplies energy back when excess energy is needed.

- **Energy Demand**: the energy demand represents the electricity or heat demand of a particular household.

- **Energy Source Agent**: it manages the represented energy source based on the local measured information and the communications with other agents. The agents will determine how much energy will be supplied and direct corresponding energy source to do so.

- **Energy Storage Agent**: the energy storage agent manages the presented energy storage unit according to local measured information and load agents, which determine the amount of energy to be charged or discharged.

3.2. Cases Considered

To determine the potential savings from the deployment of PV with a storage system, an agent-based model is proposed in this study. In this model, each household agent is designed to be a house where energy demand is met by a grid connection, a rooftop PV system and/or a storage system based on the needs and capacities for that household. The agents are able to interact with each other according to the rules to determine the overall system behaviour, which is mainly attributed to this type of household and its installation of DERs. More details of the cases considered in the study are described in the following sub-sections.

3.2.1. Case 1: PV-Only

PV-only is an initial exemplary application when households started to install PV. In this case, each household is installed with a PV system that produces electricity to localise household consumption. The PV is connected to a DC/AC converter. The surplus energy is then exported to the power grid. No storage system is included. If load demand is higher than PV power, the residual power will be met by grid import. A typical household in the UK usually install a PV system with a capacity at 3 kWp [97]. For households in Southern Germany, a solar panel with higher capacity is preferable [94] due to the high government subsidies and abundant solar radiance. In the case study presented in this thesis, households in Germany and the UK are assumed to install the same PV capacity at 3 kWp and the system arrangement of Case 1 is shown in Figure 3-2.

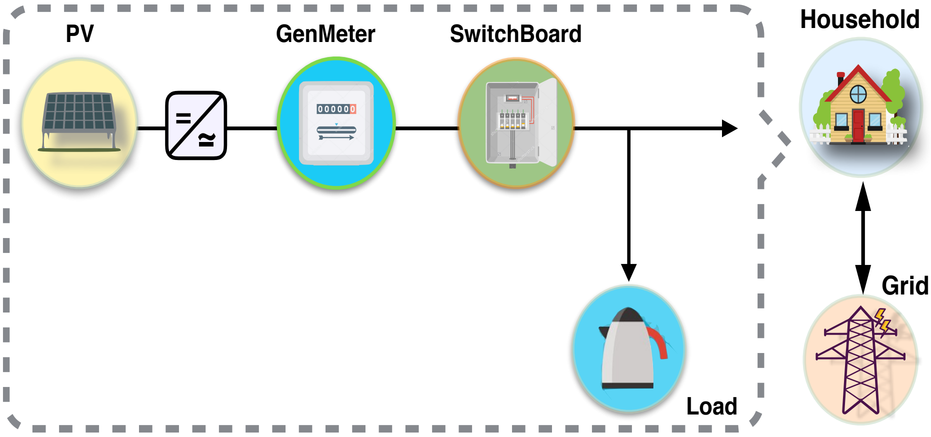


Figure 3-2 System Arrangement of Case 1 PV-Only

3.2.2. Case 2: HES

For Case 2, the system configuration is based on Case 1 with the addition of a HES and a HES management system (HESM). The battery is connected to a bidirectional DC/AC converter. Once there is surplus power, it will be used to charge the battery, within the State of Charge (SOC) range. The HESM monitors and manages the energy flux to/from a household, based on the availability of on-site generated PV power, the SOC of the HES, and the household energy demand. The HES is installed within a household and its autonomous operation aims to minimise the electricity bill cost. The system architecture of Case 2 is shown in Figure 3-3.

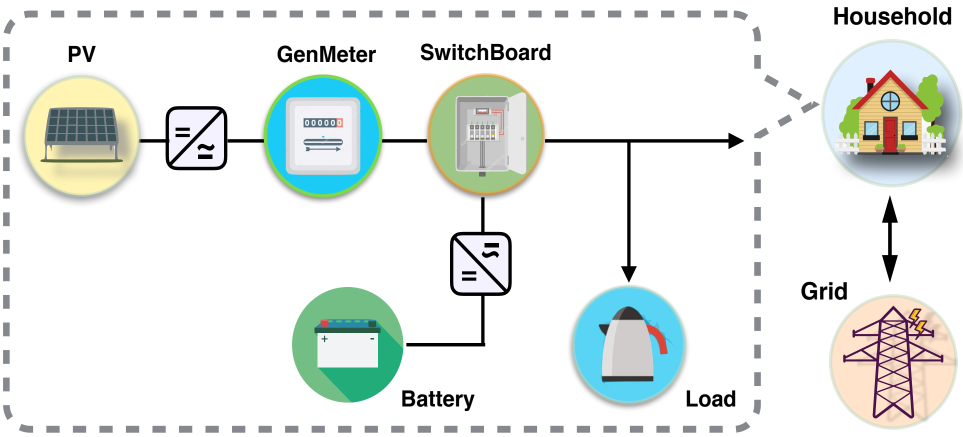


Figure 3-3 System Arrangement of Case 2 HES

3.2.3. Case 3: CES

In Case 3, the CES consists of a large battery and a CES management system (CESM). The CES is connected to several households via a private network, storing their surplus PV system power after households have shared electricity with their neighbours. The CES is assumed to be collectively owned by the households within the community, where households are allowed to import and store electricity via CES as much as possible, instead of being allocated a certain share of CES. At a certain time period, a household can either be a supplier that shares a proportion of renewable energy, or an energy consumer that requests a specified quantity of energy from neighbours, CES and/or the power grid. Both the battery and household are connected to the grid by AC power cables. The CESM is able to communicate with each household in order to collect and analyse the data to ensure the CES operate within its capacity and rated power. The system architecture of Case 3 is illustrated in Figure 3-4.

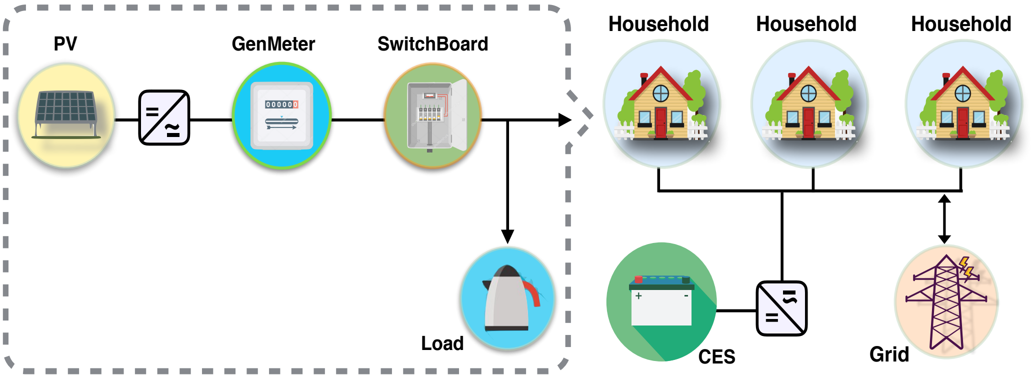


Figure 3-4 System Arrangement of Case 3 CES

3.3. Household Demand

Part of this work focuses on the analysis of different load profiles and their multidisciplinary assessment. In order to understand the effect of introducing PV plus storage within households, it is important to acquire data on the electricity demand profiles of domestic households. Due to the lack of real measurement of demand, synthetic load profiles are generated and adopted in this research. The household types and corresponding annual energy consumption are shown in The load profiles of Germany are obtained in a similar method. The profile generator developed at the Technical University Chemnitz [127] can simulate the behaviour of the residents based on a demand model, and includes operation patterns for electrical devices. The complexity and detailed consumption patterns are extremely useful for the ABM used in this study. The load profile is calculated by adding up the energy use of each device of a chosen predefined household. Five different types of households in Germany are chosen to represent the household diversity.

Table 3-1. The CREST demand model is used to generate demand profiles to represent the energy demand in UK households [125]. The model is based on the UK Time Use Survey to stochastically produce a synthetic load profile for a household according to several parameters, including number of residents, time of year, etc. The model has been proven to be able to produce the desired demand profiles of different households, mirroring the demand of real households in the UK [125]. Five different households are chosen in the model and their consumption profile data are in 1-minute intervals of 34 typical household appliances. Their demands range from Electricity Profile Class 1 Low to High band according to Ofgem [126]. The characteristics of each household type vary from each other, in terms of relation between peak and base load and load fluctuations.

The load profiles of Germany are obtained in a similar method. The profile generator developed at the Technical University Chemnitz [127] can simulate the behaviour of the residents based on a demand model, and includes operation patterns for electrical devices. The complexity and detailed consumption patterns are extremely useful for the ABM used in this study. The load profile is calculated by adding up the energy use of each device of a chosen predefined household. Five different types of households in Germany are chosen to represent the household diversity.

Table 3-1 Annual Energy Demand of Households in the UK and Germany

UK [125]			**Germany** [127]		
Household Type	**Description**	**Demand (kWh)**	**Household Type**	**Description**	**Demand (kWh)**
HH0	*Adult-Single*	*1850*	*CHR19*	*Couple, 30-64, both at work, with home help*	*4225*
HH1	*Adult-Couple*	*2562*	*CHR02*	*Couple, 30 - 64 age, with work*	*1857*
HH2	*Adult-Couple with a Child*	*3910*	*CHR29*	*Single adult under 30 years with work*	*1468*
HH3	*Adult Couple and two Children*	*3507*	*CHR45*	*Family with 1 child, 1 at work, 1 at home*	*3563*
HH4	*Retired Couple*	*4752*	*CHR54*	*Retired Couple, no work*	*2736*

3.4. Photovoltaic System Simulation

The output of the PV system is the AC power produced by the PV system. It consists of the PV modules as well as their inverters. The PV system generation is determined by the installation location and the amount of solar radiation captured by the inclined PV surface, which accounts for the tilt angle of the PV panel towards the sun and energy transfer efficiency described by Deshmukh and Deshmukh [128]. The solar radiation received by an inclined surface of a PV panel can be obtained by:

$$I_r = I_b R_b + I_d R_d + (I_b + I_d) R_r \tag{1}$$

Where I_b and I_d are the direct normal and diffuse solar radiations, R_d and R_r represent the tilt factors for the diffuse and reflected part of the solar radiations. Due to the natural characteristics of the sun, the solar radiation estimation is therefore reliant upon the position of the sun that varies monthly. Thus, hourly power output from a PV panel with an area A_{pv} (m^2) on an average day of the *i* th month, when total solar radiation of I_T ($kW.m^{-2}$) is incident on PV surface, can be obtained by:

$$P_{si} = I_{Ti} \eta A_{PV} \tag{2}$$

Where system efficiency is given by:

$$\eta = \eta_m \eta_{pc} P_f \tag{3}$$

And the module efficiency η_m is given by:

$$\eta_m = \eta_r [1 - \beta (T_c - T_r)] \tag{4}$$

Where η_r is the module reference efficiency, η_{pc} is the power conditioning efficiency, P_f is the packing factor, β is the array efficiency temperature coefficient, T_r is the reference temperature for the cell efficiency and T_c is the monthly average cell temperature and can be obtained by:

$$T_c = T_a + \alpha\tau / U_L \tag{5}$$

Where T_a is the instantaneous ambient temperature, U_L / $\alpha\tau$ = $I_{T,NOCT}$ / (NOCT – $T_{a,NOCT}$), and NOCT is normal operating cell temperature, $T_{a,NOCT}$ = 20 °C and $I_{T,NOCT}$ = 800 W.m^{-2}. The specification of PV used in the study is shown in Table 3-2. The Solar radiance data is obtained from the Microgen Database developed by Sheffield Solar [129]. The PV data is based on a measured time series in Southern Germany in 15-minute time slots for the year 2013 [130]. Each household owns a PV system with the same specification to eliminate the discrepancies of electricity production from PV and the PV agent in the model shown in Figure 3-5:

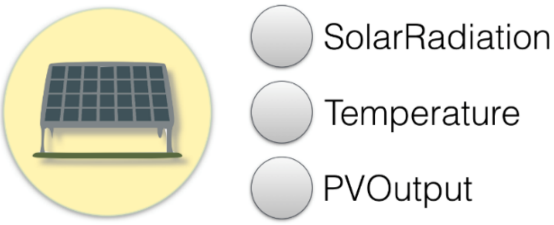


Figure 3-5 PV Agent in the model

Table 3-2 Summary of PV Parameters Assumed for This Study [63]

Parameter	**Value**	**Unit**
Area Per Panel	1.63	m^2
Nominal Power Per Model	300	W
Number of Modules	10	
Open Circuit Voltage Under Standard Test Condition	61.2	V
Short Circuit Current Under STC	5.22	A
Normal Operating Cell Temperature (NOCT)	45	°C
Air Temperature Required for NOCT	20	°C

3.5. Battery Storage Model

Lead acid and Li-ion batteries are widely used in real-life application of PV-battery systems. A Li-ion battery model is used in this study, as this technology is already predominantly utilised for both residential and utility applications, given its good charging/discharging capability, no memory effect, slow calendar losses and low maintenance costs [131]. The capacity of battery storage is selected to meet the required load demand as much as possible during periods where renewable generation is unavailable. The sizing is also dependent upon several other factors including maximum depth of discharge, temperature correction, rated battery capacity and battery life. As such, the required battery capacity can be expressed as [128]:

$$B_{rc} = E_{c(Ah)} D_s / DOD_{max} \eta_t \tag{6}$$

Where $E_{c(Ah)}$ is the load in Ah, D_s is the battery autonomy or storage days, DOD_{max} is the maximum battery depth of discharge, η_t is the temperature correction factor. The charging or discharging state of the battery is determined by the difference between power generated and load. In this way, the charge quantity of a battery bank at time t can be obtained by:

$$E_B(t) = E_B(t-1)(1-\Delta) + (E_{GA}(t) - E_L(t)/\eta_{inv})\eta_{battery} \tag{7}$$

Where $E_B(t)$ and $E_B(t-1)$ are the charge quantities of battery bank at the time t and t-1, Δ is the hourly self-discharge rate, $E_{GA}(t)$ is the total energy generated by the renewable resource after loss in the controller, $E_L(t)$ is load demand at the time t, η_{inv} and $\eta_{battery}$ stand for the efficiency of inverter and battery charging efficiency. The charge of the battery bank is also subject to the following constrains:

$$E_{Bmin} \leq E_B(t) \leq E_{Bmax} \tag{8}$$

Where E_{Bmax} and E_{Bmin} are the maximum and minimum charge of the battery bank. In this work, the parameters assumed for the lithium-ion battery storage are shown in Table 3-3.

Table 3-3 Parameters for the Li-ion battery [132]

Parameter	**Value**	**Unit**
Maximum Battery SOC	100	%
Minimum Battery SOC	20	%
Roundtrip Efficiency	92	%
Cycle Lifetime	3000	Cycles
Battery Degradation	0.4	%.year^{-1}

The capacity plays an important role in the battery's performance across its lifetime and hence it is meaningful to simulate the storage capacity degradation. There are two types of capacity losses, including calendar losses and cycling losses. The former is the loss from the passage of time while the battery is left at a set SOC. Cycling loss is caused by charging and discharging the battery, which is also reliant upon the SOC, the DOD and the operation temperature. There are several ways of simulating losses of different types of batteries in existing literature, which effectively calculate the aging effects by mathematically simulating the electrochemical reactions inside the batteries [50,51] or correlates the experimental data into an empirical [52] or a semi-empirical model [45,53].

The degradation model is adapted from an empirical degradation model developed by Wang et al. [53]. For the purposes of this study, both storage systems are assumed to operate in an environment at 25 ◦C. The loss of capacity has a dependence on Ah-throughput-dependent ageing expression that includes operation DOD and equivalent full cycles (EFCs) mathematically expressed as:

$$E_{ah} = EFC \times DOD \times C_0 \tag{9}$$

Where the E_{ah} is the total energy throughput in Ah, C_0 is the nominal capacity of storage. The number of EFCs is calculated by dividing the total amount of battery output energy by effective battery capacity:

$$EFC = E_{dischage}/C_e \tag{10}$$

Where the $E_{discharge}$ is the total energy discharged from battery and C_e is the effective battery capacity after every cycle. Then the capacity loss, Q_{loss}, for a Li-ion battery with a maximum charging/discharging rate at 0.5 C can be calculated by:

$$Q_{loss} = 30330 * \exp\left(\frac{-31500}{RT}\right) * {E_{ah}}^{0.552} \tag{11}$$

The battery agent in the model is shown in Figure 3-6.

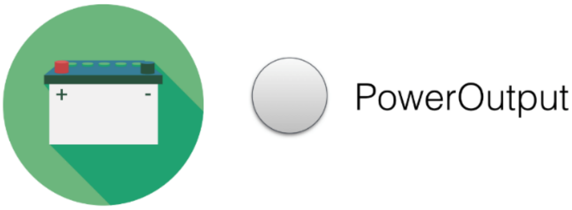


Figure 3-6 Battery Agent in The Model

3.6. Management Strategy for HES and CES

The addition of a storage system is designed to reduce energy imports from the power grid in order to lower energy bills by improving self-consumption. The model enables households to operate under the three cases described previously. In this study, four management strategies are introduced to operate under different tariff structures and to meet different goals as outlined in the subsequent sections.

3.6.1. Operations Under Flat Tariff

When HES and CES operate under flat tariffs, a Self-Consumption Mode is introduced mainly to maximise the use of PV generation and minimise the export or curtailment of surplus PV power (PV_{gen}), as households have limited financial incentives to adjust power dispatching. The Self-Consumption Mode under the flat tariff has been investigated and it is widely adopted in HES case studies. The proposed HES management strategy aims to minimise electricity imports from the power grid by optimising the use of on-site generated PV energy. The power is simultaneously supplying the household demand first and then charge the HES with surplus PV power for the later use when PV generation is not enough. Therefore, several limits on SOC are set to regulate the battery operation and the HESM flowchart is shown in Figure 3-7.

- $SOC_{Min} < SOC < SOC_{Max}$: The HES supplies the demand of the house and any remaining energy required is drawn from the power grid.
- $SOC = SOC_{Max}$: The energy demand of the household is satisfied and the surplus energy is exported to the network.
- $SOC <= SOC_{Min}$: The HES stops working and the load demand is met the grid import.

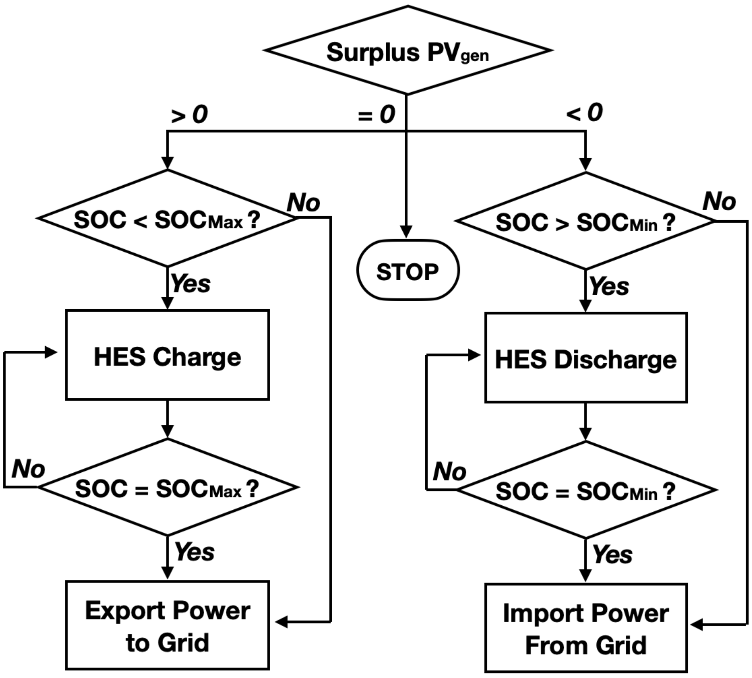


Figure 3-7 Self-Consumption Mode of HES

For CES, a different management strategy is proposed. As the CES is connected to households via a private network, it is assumed that the solar electricity is primarily used to supply the simultaneous household demand and surplus PV power is then shared with neighbours within the same CES network. The distribution of surplus power is determined by a central aggregator that calculates the total surplus power and total needed power at each time step (1 min). Figure 3-8 presents a flowchart for the CESM algorithm applied. If the total power needed can be covered by other households' surplus power, the households with higher demand than the on-site PV generation, are supplied with shared power from those households with surplus power according to a proportion accounting for the total amount of surplus power. Once the excess power is no longer needed by households, it is used to charge the CES and any surplus power is exported to the power grid.

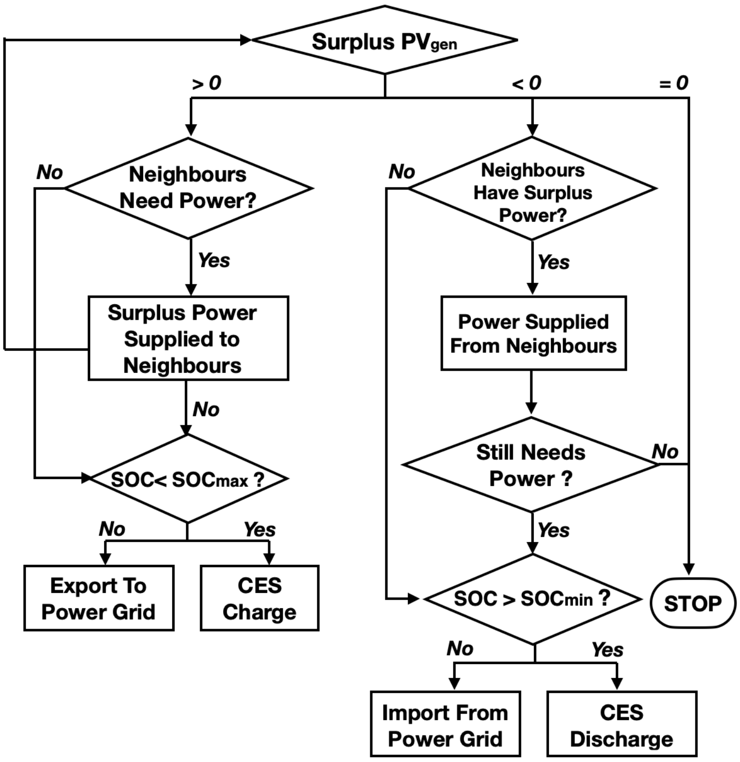


Figure 3-8 Self-Consumption Mode of CES

3.6.2. Forecast Function Under Time-Dependent Tariffs

When the system operates under the TOU tariff, a forecast function is triggered before the next day begins and Figure 3-9 shows how the forecast function works. When there is surplus PV generation, it will only charge the battery continuously without any energy output. The forecasted net energy demand is calculated on hourly basis and combines with the electricity price at given time to determine how much savings can be achieved if the battery discharges the available energy to meet the demand. As a result, the forecast function can produce two important outputs: (1) the potential daily maximum amount of energy to be stored and (2) at what time the discharge of battery electricity can contribute to the greatest cost savings. The two outputs are represented as $SOC_{reserve}$ and ES Discharging Point. The former one can be used in Grid-Charing mode, while the ES Discharging Point can be used for both Grid-Charging and Self-Consumption Modes.

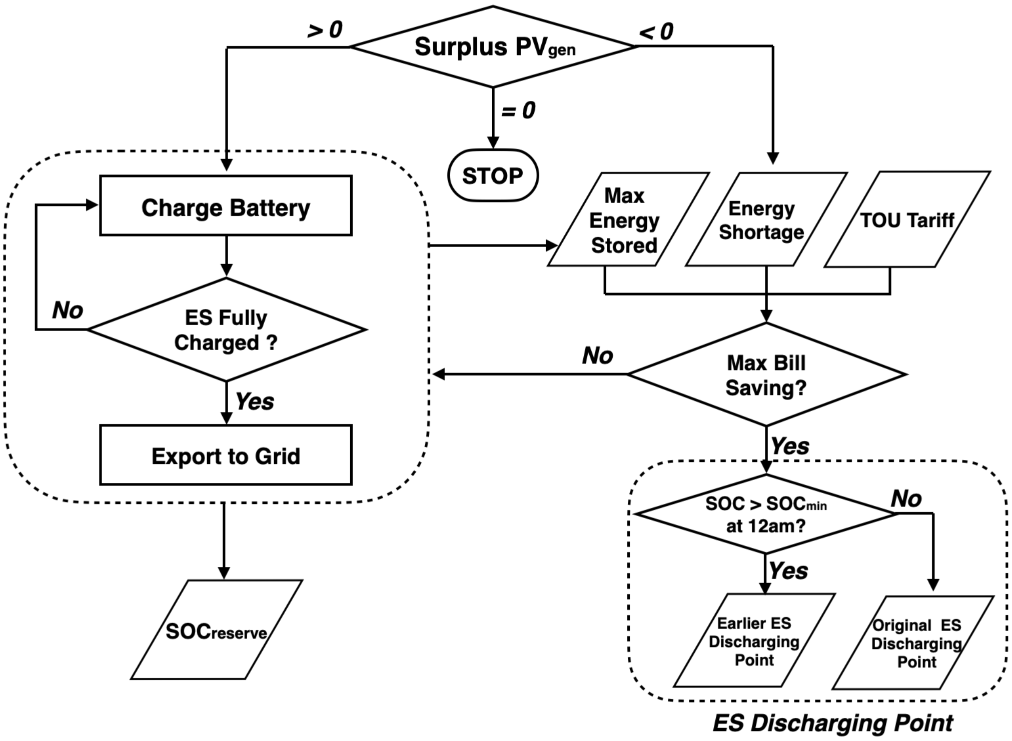


Figure 3-9 Forecast Function of Control Unit

3.6.3. Self-Consumption Mode Under TOU Tariff (HES-SC and CES-SC)

The Self-Consumption Mode for HES and CES under TOU tariff is adapted from the basic Self-Consumption Mode, also known as Greedy mode, described in Section 3.6.1. The only difference is that the Self-Consumption mode under TOU tariff uses the ES Discharging Point to control the discharging process of the battery. It does not influence the original charging process, where the battery starts to charge when there is surplus PV power. However, when the PV production is not enough to meet the local demand, the battery will only start to discharge and supply power to households if the time reaches ES Discharging Point until fully discharged and the flowchart of HES-SC is shown in Figure 3-10. For the CES, the Self-Consumption Mode under TOU still works similarly, as the control unit prioritises the PV power to meet the households' demand and then charges the battery. The forecast function output is only used to limit the battery discharge in order to obtain the maximum energy saving without any other incentives. The flowchart of CES-SC Mode is shown in Figure 3-11.

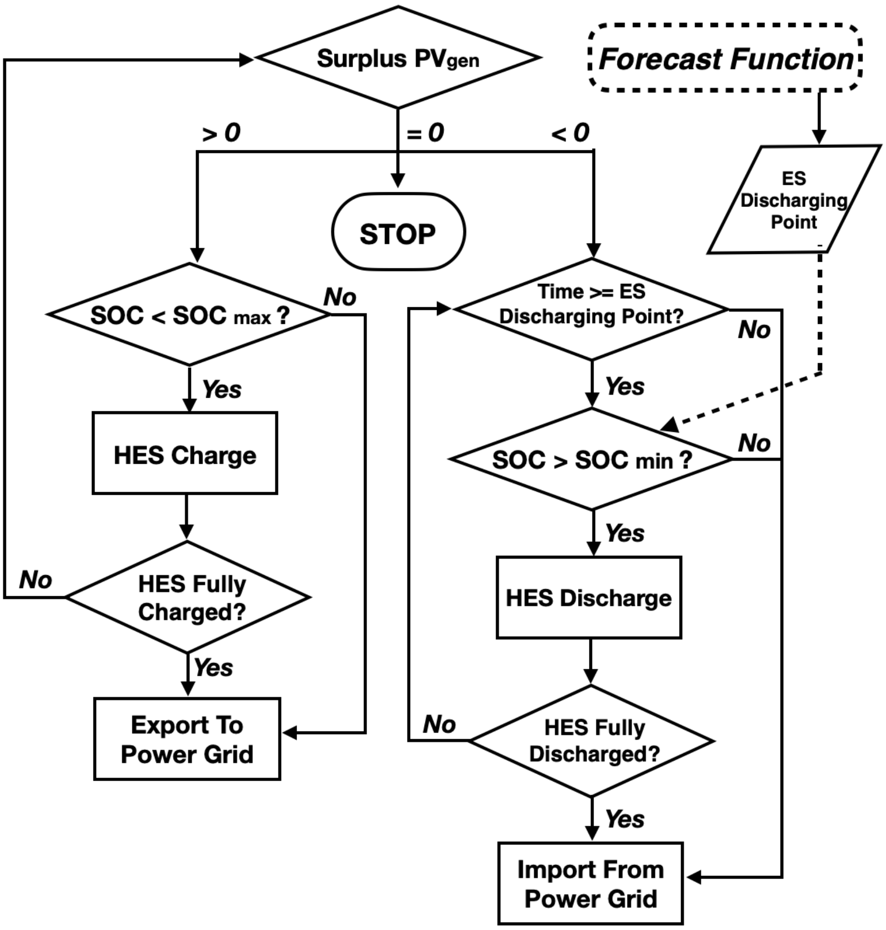


Figure 3-10 Flowchart of HES-SC Mode

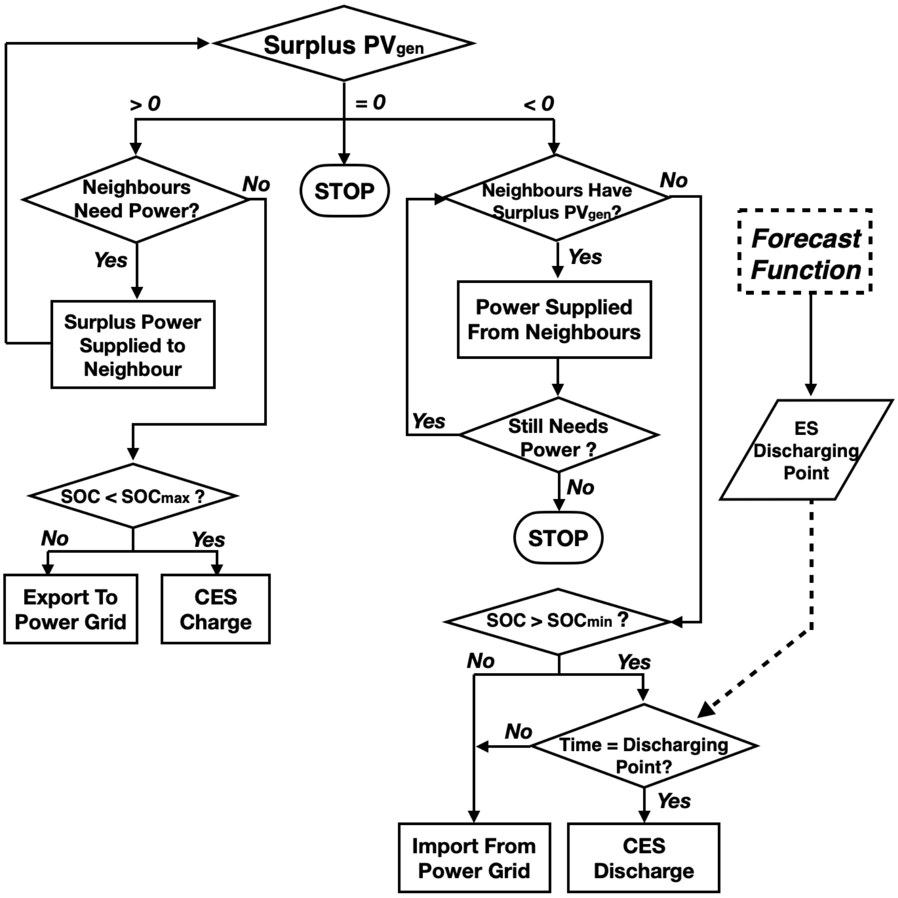


Figure 3-11 Flowchart of CES-SC Mode

3.6.4. Grid-Charging Mode for HES and CES (HES-GC and CES GC)

The development of Grid-Charging Mode under TOU tariff aims to improve storage system use, especially for those days without sufficient on-site PV production. Two outputs from the Forecast Function are used as parameters to control the storage system. The Grid-Charging Mode is based on the Self-Consumption Mode under the TOU tariff presented previously with an additional function that enables the battery to charge from the power grid. The $SOC_{reserve}$ is the SOC after battery charging from the power grid during the off-peak time and the battery is then expected to be fully charged with the addition of electricity from PV. The battery will discharge when it comes to the discharging point as predicted, and the remaining operation works the same as the HES-SC and CES-SC Modes. The operation flowcharts of HES_GC and CES-GC Modes are presented in Figure 3-12 and Figure 3-13, respectively.

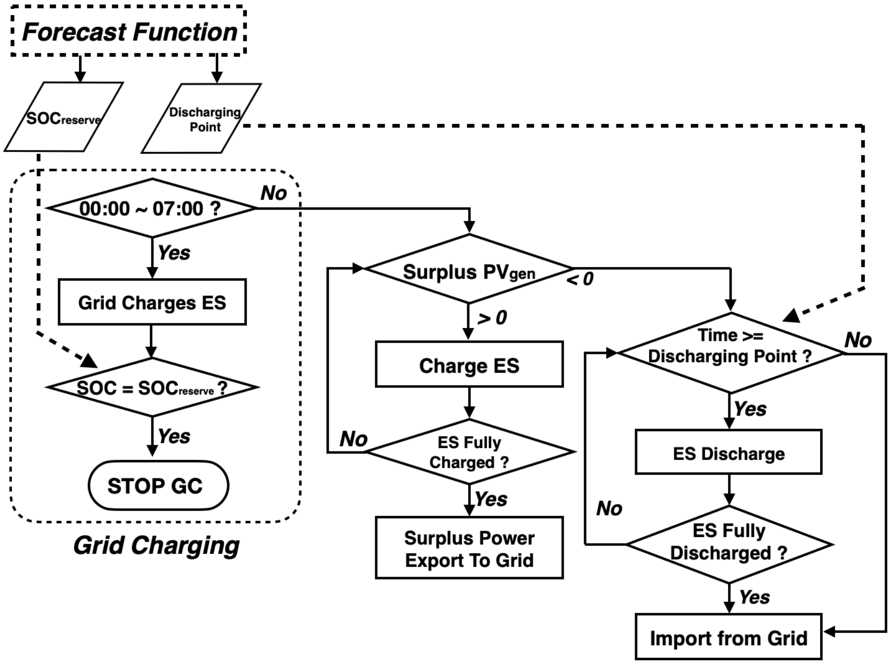


Figure 3-12 Flowchart of HES-GC Mode

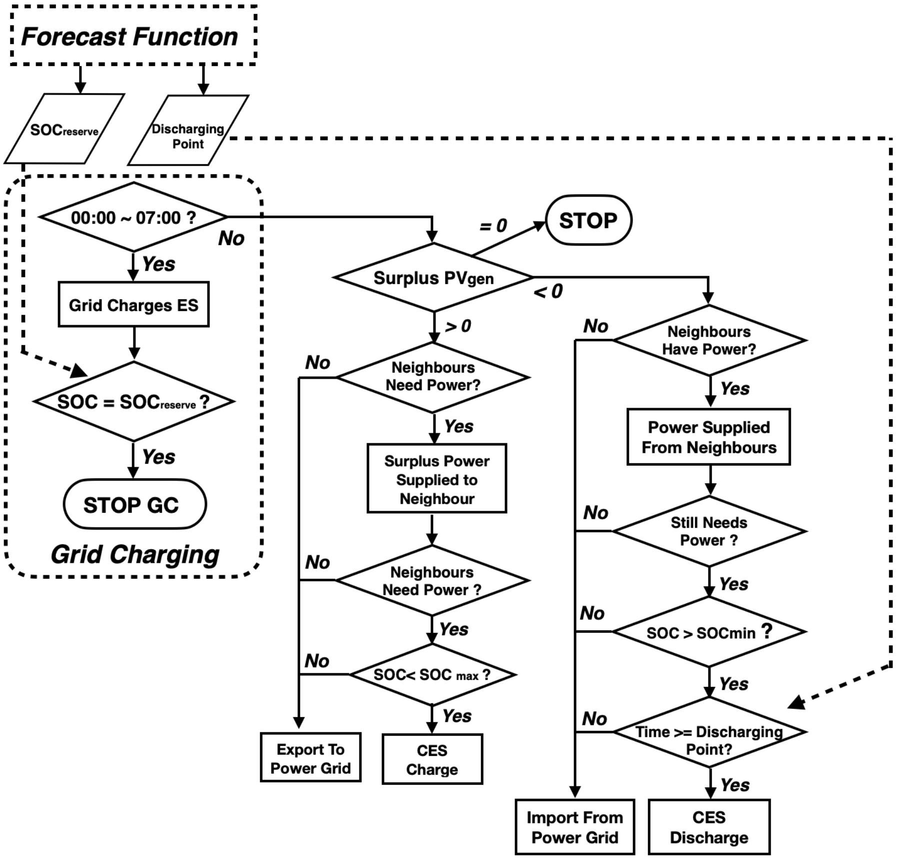


Figure 3-13 Flowchart of CES-GC Mode

3.7. Evaluation Criteria

To quantify and evaluate the performance of Cases 1-3, this section provides several evaluation criteria for the proposed framework. Several key performance indicators (KPIs) are introduced to the study. First, the use of energy in each case is investigated, along with the proportion of demand that can be locally satisfied by on-site PV generation and storage. The economic impact of the proposed system on the households, in terms of financial system payback time and energy bill reduction, is then measured. Finally, the carbon avoidance and payback time of CO_2 emissions from manufacture in the three Cases are used as KPIs to represent the environmental influence.

3.7.1. Technical Analysis

For the three cases, the following values are analysed by integrating the calculated power flow during the simulation:

- The amount of electricity generated from the PV system;
- The amount of PV electricity instantaneously consumed by the household;
- The amount of electricity supplied from HES and CES;
- The amount of electricity shared with neighbours;
- The amount of electricity imported from neighbours;
- The amount of electricity exported to the grid;
- The amount of electricity imported from the power grid.

With these values, the relevant KPIs can be calculated, i.e. the SCR and SSR. In this study, SCR and SSR are modified and different from the traditional definitions for single households in literature [14]. The traditional definitions only consider direct self-consumed energy and the output and input energy from/to the battery and are no longer suitable for our study on households within a CES community. Therefore, the new definitions consider inter-household sharing and ignore any discrepancy in battery state of charge between the start and end of the simulation. The new definitions of SCR and SSR proposed in this study are as follows:

The SCR is defined as self-consumed PV electricity excluding imported electricity over the total amount of PV generated electricity i.e. it is the proportion of PV that is self-consumed:

$$SCR = (E_{PV} - E_{export})/E_{PV} \tag{12}$$

where E_{PV} is the total amount of energy generated by PV and E_{export} represents the amount of PV energy exported to the power grid. The SSR is the proportion of demand that is met from either PV, neighbours or storage.

$$SSR = (E_{demand} - E_{import})/E_{demand} \tag{13}$$

where E_{demand} is the energy demand of a household and E_{import} represents the amount of electricity imported from the power grid.

3.7.2. Economic Analysis

The economic performance of Cases 1-3 is investigated and the energy bill, FIT generation, FIT export payment and payment from shared energy via CES are calculated for each household.

$$Energy\ Bill = E_{import}p_{grid} + dp_{standing} - E_{PV}p_{generation} - E_{export}p_{export} \tag{14}$$

where p_{grid} is the electricity unit cost charged by energy suppliers in £.kWh^{-1}, d is the number of days, $p_{standing}$ is the standing charge (£.day^{-1}), $p_{generation}$ is the FIT generation rate in £.kWh^{-1}and p_{export} is FIT export rate in £.kWh^{-1}. Different sets of tariffs available from the market are adopted to obtain the minimum result of Equation (11). This function is specifically proposed as the predominant interest for domestic consumers to install batteries is to reduce energy costs [133]; similarly, it is also the primary reason in the adoption of renewable energy communities [134]. In this study, a simple payback time (SPBT) is adopted as a metric to indicate economic feasibility. Payback time is the number of years an investment takes to pay for itself, and is typically defined as the net cost divided by the yearly savings [135].

$$SPBT_{system} = Total\ Net\ Cost/Annual\ Energy\ Bill\ Savings \qquad (15)$$

Regarding the investment payback time, for a household, the upfront cost of PV, battery and relevant equipment may be recovered via FIT and savings from electricity import. The energy bill savings focus on the reduction in energy usage charges compared to the fully grid-supplied households. The CES is considered as an asset collectively owned by households within the same CES network. For Case 3, an extra DNO system modification fee [72] is also included and the cost of a CES system and its related components is split for each household. The value of shared electricity between neighbours is excluded in this study for simplicity. Different economic parameters used for each chapter will be presented later. Separate energy tariffs and system capacities are used to conduct a sensitivity analysis on system payback time and the results are presented in the following section. Three exemplary energy tariffs are chosen for the studies, which represent the three price classes of tariffs currently available from the retail electricity market in order to investigate the sensitivity of financial interest and identify the suitable energy storage installation objectives.

Another economic parameter adopted is the Levelised Costs of Energy (LCOE), which is widely used throughout the literature to determine the economic feasibility of various power generation alternatives. It is the net present value of the unit-cost of electrical energy over the lifetime of a generating asset. The LCOE approach considers all the costs occurring during the project's lifespan and associated energy production. The LCOE of PV is calculated as:

$$LCOE = \sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t} \Bigg/ \sum_{t=1}^{n} \frac{E_t}{(1+r)^t} \tag{16}$$

where it is investment expenditures in the year t; Mt is the operation and maintenance expenditures in the year t; E_t is the amount of electricity generated by PV in year t; r is the discount rate and n is the expected lifespan of the PV. The Levelised Cost of Storage (LCOS) is calculated as formulated in Eq (17), which is converted from LCOE in Eq (16) but uses the total amount of energy discharged from storage and also with the addition of charging cost.

$$LCOS = \sum_{t=1}^{n} \frac{I_t + M_t + C_t}{(1+r)^t} \Bigg/ \sum_{t=1}^{n} \frac{E_{discharge}}{(1+r)^t} \tag{17}$$

Where C_t is the energy cost for the amount of electricity charged in the battery in year t and $E_{discharge}$ is the amount of electricity discharged by the battery in year t.

3.7.3. Environmental Analysis

The environmental benefits attributable to renewable systems, in terms of low carbon emissions during electricity generation, are the main reason for their integration into the grid and replacement of traditional carbon-intensive technologies. However, manufacturing renewable technologies is an energy-intensive process. It is therefore of great importance to quantify the environmental benefits of renewable technologies.

Life Cycle Analysis and carbon footprints are two common methods to investigate the environmental impacts of an application, where energy payback time and carbon emission savings are often used as indicators. In this study, the environmental analysis is to calculate the CO_2 avoidance by using PV and a storage system and the payback time of total carbon emission. The total carbon emissions (EM_{total}) in the study only includes the CO_2 emissions produced during the PV and battery manufacture process, and electricity generation. Emissions generated from other processes, such as system operation and maintenance, are excluded due to the complexity of data collection. The EM_{total} is determined as:

$$EM_{total} = Q_{PV} + Q_{battery} + E_{import}q_{grid} \tag{18}$$

here the Q_{PV} and $Q_{battery}$ are the total amount of CO_2 produced during PV and battery production respectively (kg), and q_{grid} is the grid CO_2 intensity ($g.kWh^{-1}$). The carbon emissions used in the study represents the cradle-to-use values from literature [136–138]. The avoided CO_2 is from the local PV generation and the reduction of energy imports from the grid:

$$EM_{avoidance} = ((E_{demand} - E_{import}) + E_{PV}) \times q_{grid} \tag{19}$$

The export of surplus PV to the grid can only lead to a marginal reduction in grid carbon factor, and therefore the carbon avoidance here only focuses on household and community level. The Payback Time of the system's CO_2 (PBT_{CO2}) is converted from energy payback time in years that represents the total energy input during the manufacturing process. The PBT_{CO2} is calculated via:

$$PBT_{CO2} = EM_{total}/EM_{avoidance} \tag{20}$$

Chapter 4 Identifying the Value of CES

4.1. Introduction

At the moment, the most common PV plus storage applications are Case 2 PV plus HES described in Chapter 3. Many advantages of CES over HES have been identified, but the design and operation of CES has received significantly less attention. Most existing research has analysed CES at community level only, but the performance and impact on individual households has yet to be fully explored. There is some evidence to suggest that grid-scale and behind-the-meter storage may increase CO_2 emissions in historic power systems [139]. This study seeks to quantify the potential for CES to contribute to CO_2 avoidance and energy cost reduction, as well as the improvement in self-consumption. In this chapter, the agent-based model described in Chapter 3 is used to investigate a 10-house community based on a multi-criteria assessment. The aims of this chapter are to undertake technical, economic and basic environmental evaluations to quantify and compare three different cases. The key results from this chapter were published in:

- **Dong, S.**, Kremers, E., Brucoli, M., Brown, S. and Rothman, R., 2018. Residential PV-BES systems: economic and grid impact analysis. *Energy Procedia*, *151*, pp.199-208.

- **Dong, S.,** Kremers, E., Brucoli, M., Rothman, R. and Brown, S., 2020. Techno-enviro-economic assessment of household and community energy storage in the UK. *Energy Conversion and Management*, *205*, p.112330.

- **Dong, S**., Kremers, E., Brucoli, M., Brown, S. and Rothman, R., 2020. Impact of Household Heterogeneity on Community Energy Storage in the UK. *Energy Reports*, *6*, pp.117-123.

4.2. Data Input

The demand data adopted in this study is described in Section 3.3. Five different types of load profiles are used in this study. Household power demand is represented by a load profile generated from CREST demand model with 1-min resolutions and used as the model input. Five synthetic demands range from Electricity Profile Class 1 Low to High band according to Ofgem [126] as shown in The load profiles of Germany are obtained in a similar method. The profile generator developed at the Technical University Chemnitz [127] can simulate the behaviour of the residents based on a demand model, and includes operation patterns for electrical devices. The complexity and detailed consumption patterns are extremely useful for the ABM used in this study. The load profile is calculated by adding up the energy use of each device of a chosen predefined household. Five different types of households in Germany are chosen to represent the household diversity.

Table 3-1. The solar radiance data is obtained from the Microgen Database developed by Sheffield Solar [129]. Each household owns a 3kWp PV system with the same specification, in order to eliminate the discrepancies of electricity production from PV. The economic and environmental parameters adopted in this study are shown in Table 4-1.

Table 4-1 Economic and Environmental Parameters Adopted in This Chapter

Parameter	**Value**	**Unit**
3 kWp PV Cost [132]	*2700*	£
2.5 kWh Battery Unit Cost [132]	*1108*	£
Feed-In Generation Tariff [71]	*0.0381*	£.kWh^{-1}
Feed-In Export Tariff [71]	*0.0524*	£.kWh^{-1}
Electricity Retail Price [140]	0.*1323*; 0.*1504*; 0.*1801*	£.kWh^{-1}
Retail Standing Charge [140]	*0.2044*	£.day^{-1}
UK Grid Carbon Intensity [136]	*0.323*	kg.kWh^{-1}
CO_2 Emission During Inverter Manufacture [137]	*12.03*	kg.kW^{-1}
CO_2 Emission During PV Manufacture [138]	*865.44*	kg.kWp^{-1}
CO_2 Emission During Battery Manufacture [137]	*175*	kg.kWh^{-1}

4.3. Results and Discussion

4.3.1. Technical Assessment

In this section, the criteria proposed in the Section 3.7 are used to evaluate the installation of CES compared to HES and PV-only and also to quantify the impact of increasing CES capacity. The performance of the community and households in the three cases are evaluated by SCR, SSR and energy savings respectively. Energy demand varies dramatically throughout a year, therefore representative months are chosen for winter/spring (March), summer (May) and autumn (September), where the behaviour is typical of those seasons but substantially different from each other.

4.3.1.1. Value of Energy Storage to a Community

The impact of introducing CES to a 10-house community is first investigated. It is assumed that the total storage capacity of HES and CES in the community is 30 kWh. Therefore, for HES application, each household is installed with a 3 kWp PV and 3 kWh home battery storage system, while for Case 3 the households are connected to a 30kWh communal battery. Figure 4-1 and **Error! Reference source not found.** shows the monthly and annual energy import savings of the community throughout a year in the three cases considered. The addition of an energy storage system, either HES or CES, can contribute to extra energy savings though energy storage cannot make a significant difference during the colder months. Throughout the whole year, Case 3 is able to contribute to slightly more energy saving than Case 2, approximately 500 kWh.

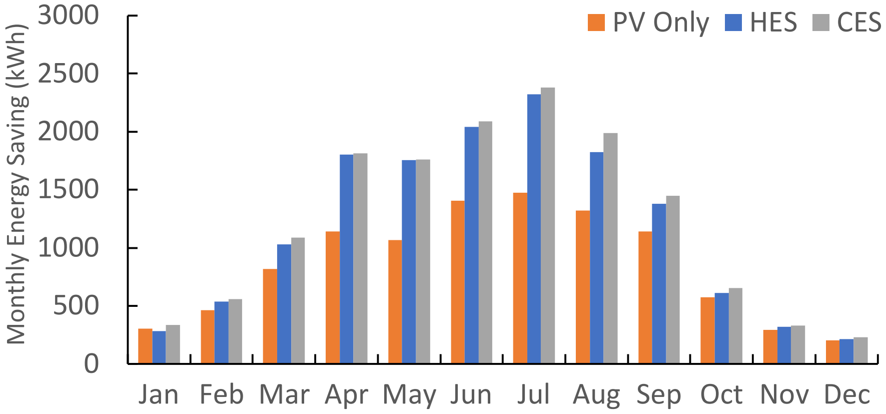


Figure 4-1 Monthly Energy Savings for A Community in Three Cases

Figure 4-2 illustrates the annual SCR and SSR of a community in the three cases. It is found that both HES and CES can significantly improve the community's SCR, by around 26%, compared to Case 1, in common with other studies (e.g. [14]). The similar SSR and SCR of Case 2 and 3 means that both systems have a similar capability of harvesting and utilising PV production. However, as the total storage capacity of Case 2 and 3 are the same, the amount of electricity they can store theoretically has a marginal difference that varies with the demand of households. The slight improvement in SSR of Case 3 can be understood as the role that shared electricity plays in the system, which is further analysed in Figure 4-3.

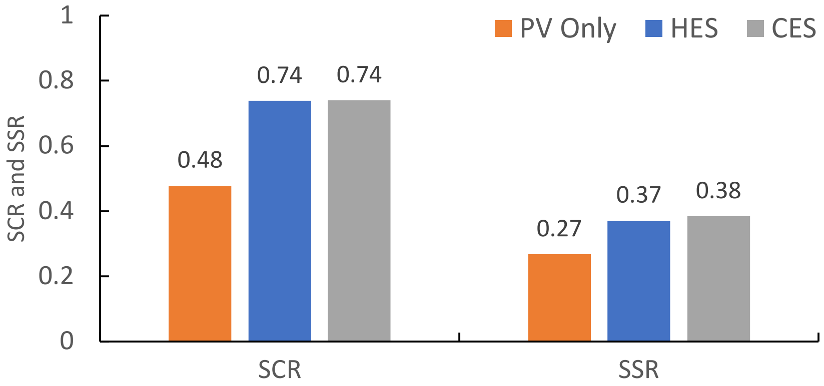


Figure 4-2 Annual SCR and SSR for A Community in Three Cases

Figure 4-3 illustrates the power flux going through and out of a community. The power export and import of a community from the power grid are shown by the negative and positive shapes respectively. For Case 1, when PV generation is appreciable, the majority of the community demand can be met by this. In comparison, when the PV cannot produce enough power, both HES and CES are able to supply part of the community demand by offsetting the surplus PV power that is injected to the grid in Case 1. In Figure 4-3 c), the CES prolongs the self-sufficient duration of the community for approximately 640 mins without any significant power exchange. Case 2 and 3 can significantly reduce power interaction range of the community by 33% and 50% respectively compared to Case 1. However, starting from the 900th minute, CES is able to fully supply its power to meet the total demand, while HES can only supply part of it but with longer duration. This is due to the CES's better power rating to supply the total community demand, while the HES can only provide energy to its owner.

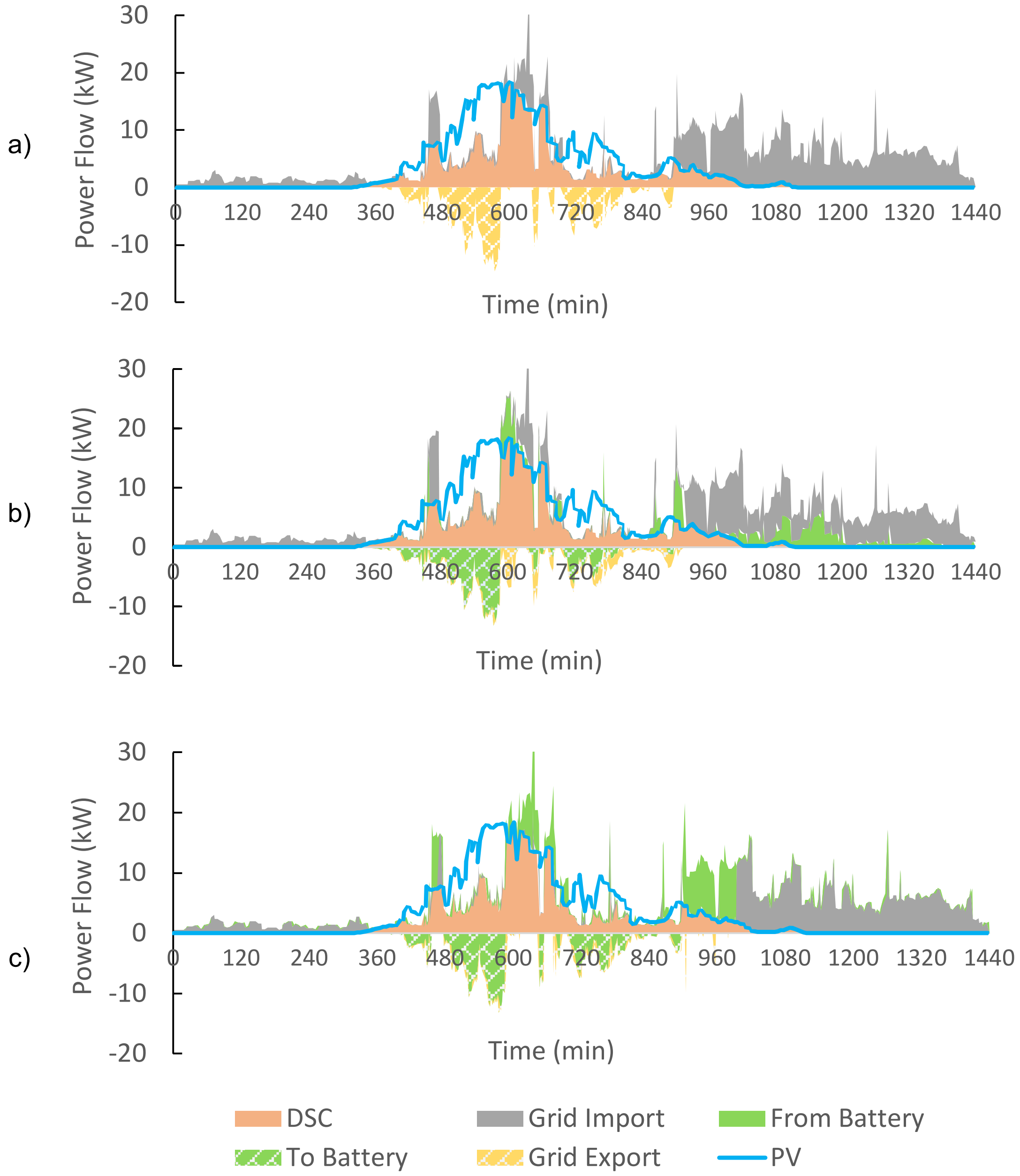


Figure 4-3 Community's Power Injection in September with a) PV-only b) HES and c) CES

4.3.1.2. Value of Energy Storage to Households

The results in the Section 4.3.1.1 suggest that the addition of HES and CES are beneficial for the community, in terms of peak power injection range and reducing the reliance on the power grid at a community level. The Cases 1 to 3 are now analysed from the households' perspective. Two types of households are chosen for the assessment. HH0 represent a household with low annual energy demand (1850 kWh), while HH2 presents a medium-high energy user that consumes 3910 kWh per year. Both households are assumed to have the same rooftop PV panels setup and same PV generation in all cases, and the only difference is their storage option, as described in Section 3.2. In Figure 4-4, it is clear that Case 1 shows the poorest annual performance, while both HES and CES have higher SCR and SSR. However, the results suggest that HES is more suitable for HH0. Although a better utilisation of PV production can be achieved via CES, the demand of HH0 cannot be effectively met as much as Case 2. In contrast, HH2 is able to save more energy via CES network and it is considered as the better option.

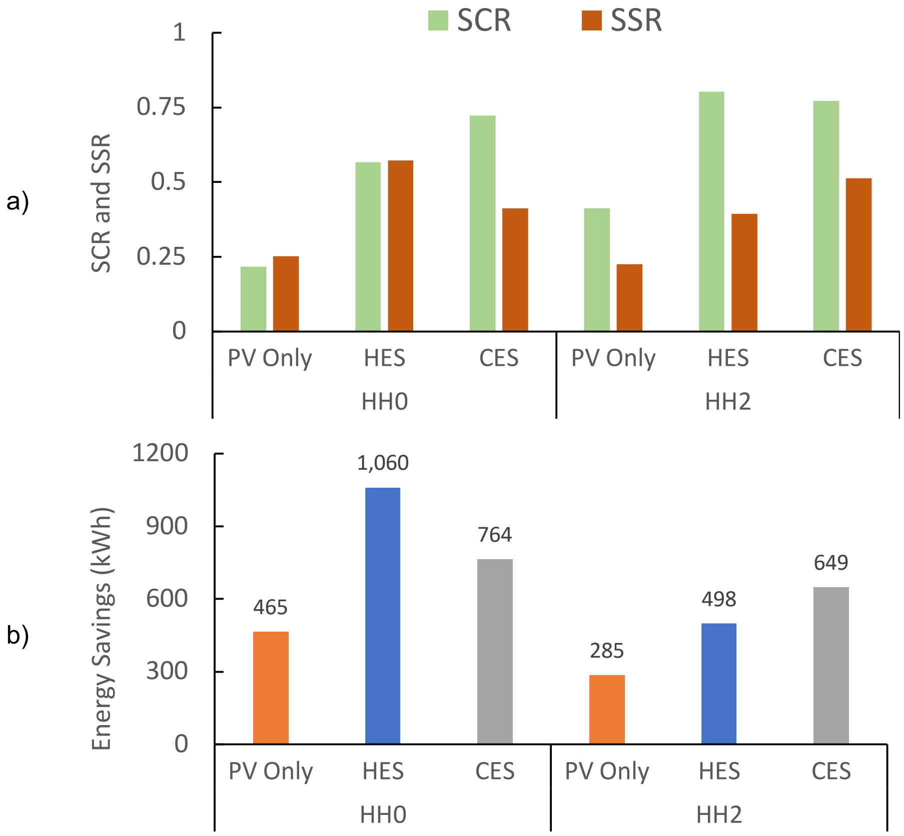


Figure 4-4 Annual a) SCR, SSR and b) Energy Savings of HH0 and HH2

Figure 4-5 shows the SCR, SSR and energy savings of HH0 and HH2 over a year, illustrating a similar trend to Figure 4-4. However, it occasionally appears to not follow the tendency of the annual results. For example, HH0's SSR of CES in May is higher than that of the HES in Case 2. This is due to the HH0 demand being much higher than the others at some points and it extracts significant amounts of surplus PV power from its neighbours. In some months, the monthly results might be against the tendency due to the fluctuation of the PV generation. However, the system performance still follows the season trend, and the fluctuation should not be significant enough to influence the overall annual results. However, it is of great importance to consider more historical PV generation profiles for system planning.

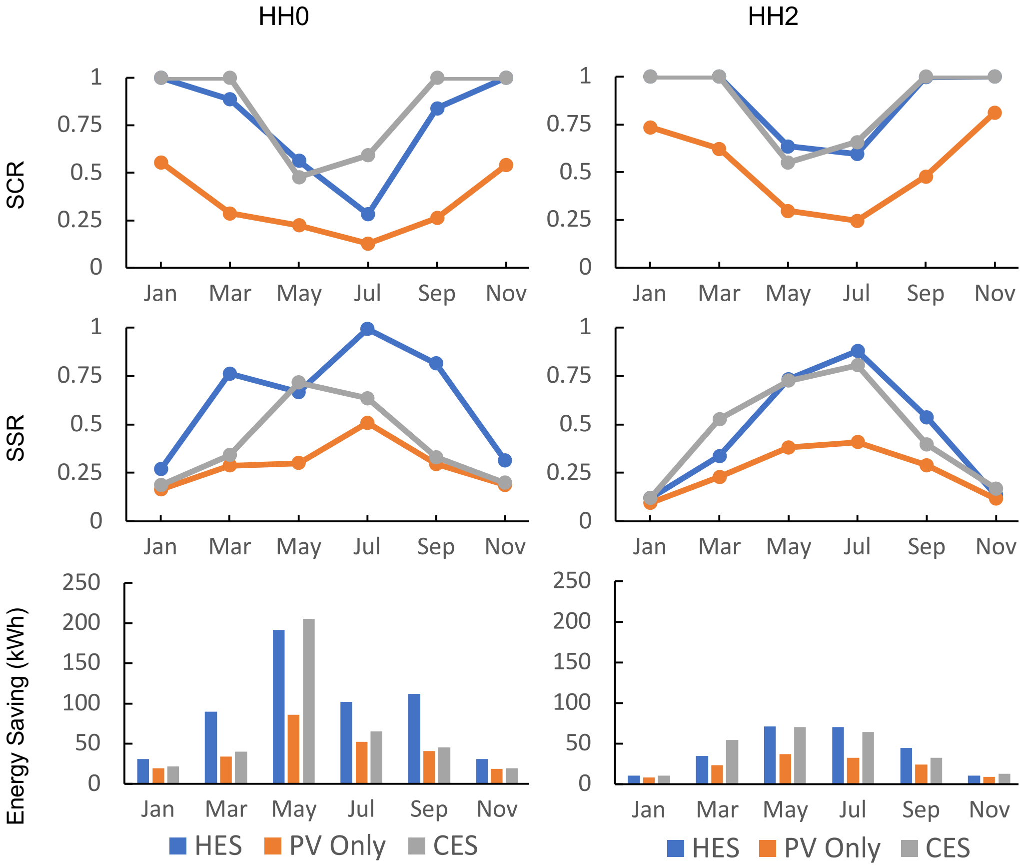


Figure 4-5 Monthly SCR, SSR and Energy Savings of HH0 (left) and HH2 (right)

Figure 4-6 illustrates a set of daily power interaction profiles of HH0 and HH2 in September, showing a similar trend in Figure 4-3. However, at household level, HES can contribute to longest self-sufficient duration among three cases, while CES can make the most effective use of PV production. Both HES and CES can significantly reduce the power interaction with the grid and localise more consumption. However, most PV power of HH0 is either shared with neighbours or charged to the CES, but it barely receives any power from the CES. For this case, installing a HES might be for the best benefit of a household, in terms of energy and cost savings, while a CES can contribute to the most energy saving for the community. This is due to the inherent characteristics of the current CESM in which the CES aims to supply the community demand as a priority, which might lead to issues of equity.

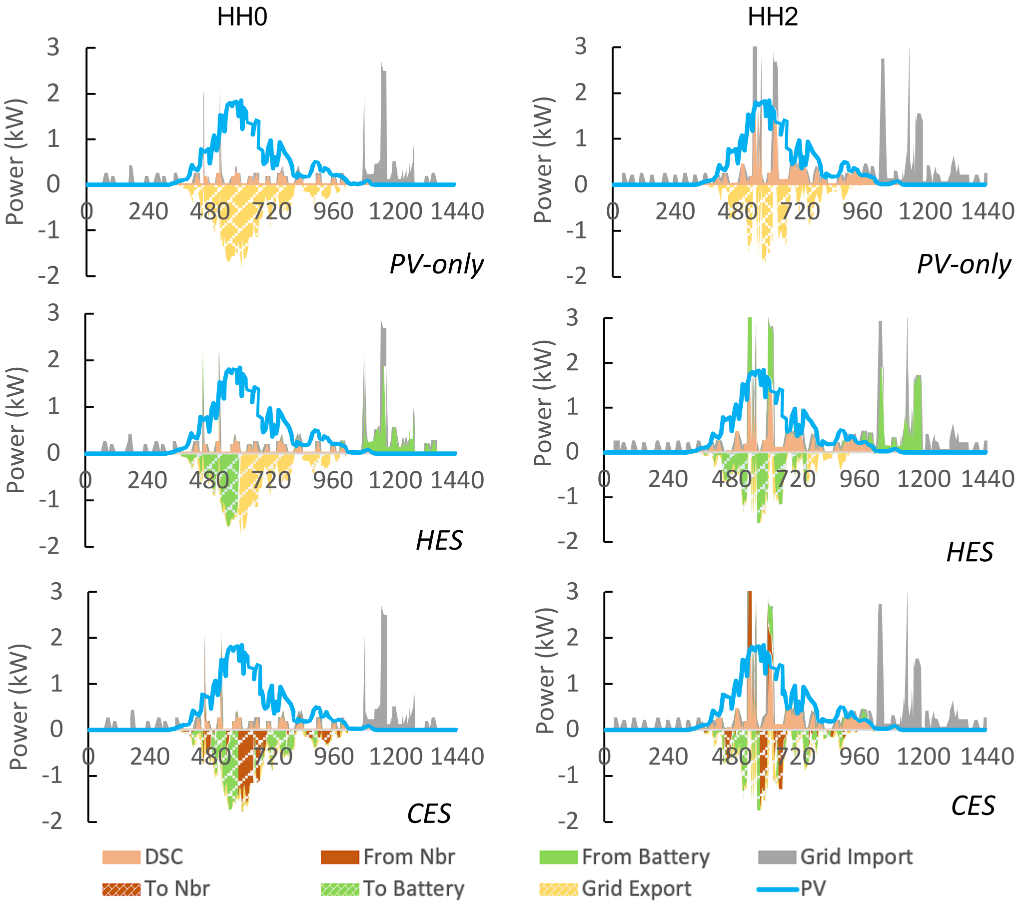


Figure 4-6 Daily Grid Interaction of HH0 (left) and HH2 (right) in September

4.3.1.3. CES Capacity Comparison

Section 4.3.1.1 has demonstrated that the installation of CES can potentially contribute to the community, in terms of better utilisation of PV production and reduction in peak electricity import from the grid. Therefore, to extend this, the value of CES and how the performance varies with the CES capacity are investigated. As before, the community is assumed to be connected to the same 30 kWp rooftop solar panel with a CES ranging from 20 kWh to 45 kWh. Figure 4-7 suggests that the system is able to reduce more energy import by adding more storage capacity. The CES can save 13872 kWh energy compared to Case 1 over a year, 10202 kWh. However, compared to 20 kWh CES, the capacity of 45 kWh is 2.25 times larger, but the increase in annual energy saving is only 1943 kWh, 15% more than annual saving of the 20 kWh CES. The results find that every 5 kWh of CES capacity can contribute to approximately 400 kwh energy savings per year.

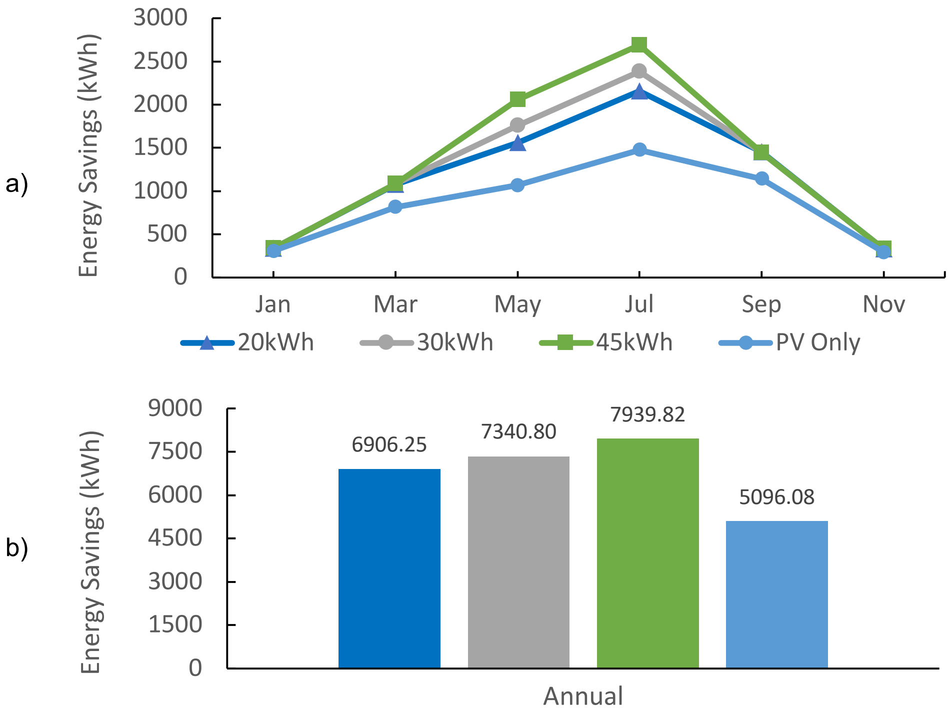


Figure 4-7 a) Monthly and b) annual Energy Saving of a Street with Different CES Capacities

Figure 4-8 shows how the monthly SCR and SSR vary with the capacity of CES, which reflects a similar tendency to that described previously. Through the whole year, Figure 4-9 suggests that an extra 25 kWh contributes to an 11% increase in SCR of a 20 kWh CES from 69% to 80%, and a 5% improvement in SSR from 36% to 41%. The increasing CES capacity can significantly improve the utilisation of PV power by keeping more of it within the community. However, the increase in PV power available from CES is still marginal compared to the total demand.

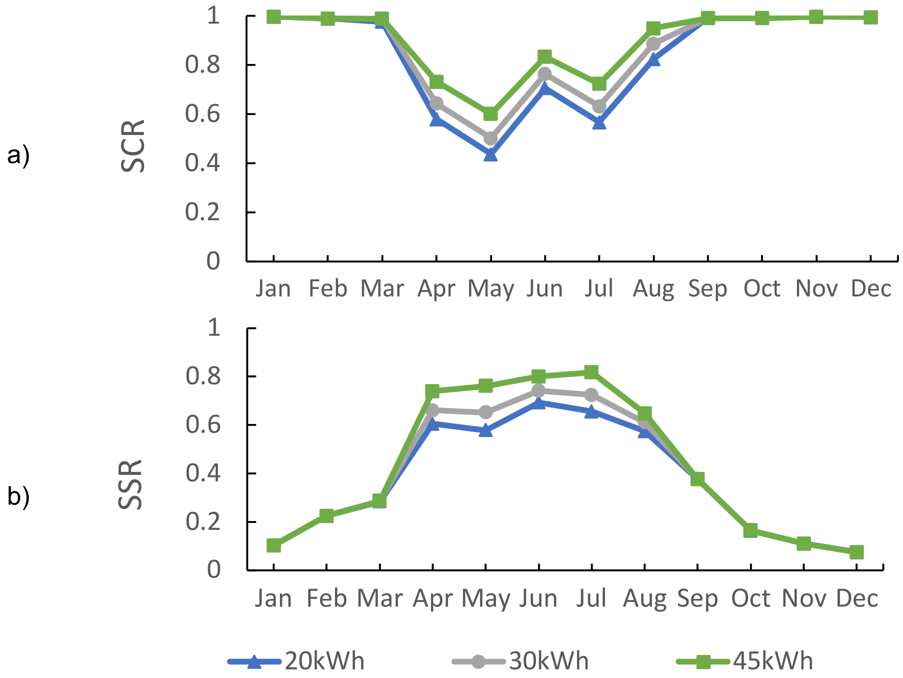


Figure 4-8 a) SCR and b) SSR of A Street with CES in Different Sizes

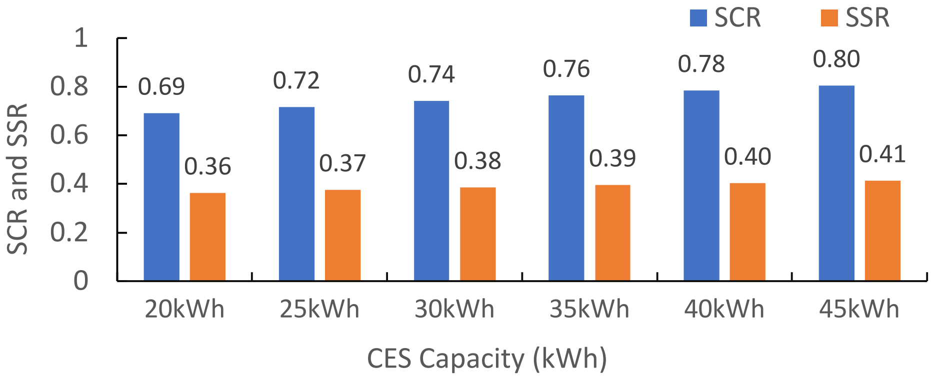


Figure 4-9 Annual SCR and SSR of A Community with CES

The daily SOC charts of CES with different capacities in four different months are shown in Figure 4-10. In March, the CES is not fully used and the SOC remains at a low level between 20% and 30%. In May, more electricity can be generated during the day and abundant surplus PV power enables CES to finish a full charge and discharge cycle. Additionally, the increasing CES capacity contributes to a longer power supply period of time, but still cannot meet the demand for the rest of the day. For this case, CES with smaller capacity is more efficient and economic compared to larger CES that has more idle capacity not being used. Therefore, it is possible to use a battery with lower capacity to achieve the same extent of localised consumption, especially for apartment buildings. However, the CES embedded in apartment buildings may be a different case, due to different total and individual demands [141,142] and different tariff structures.

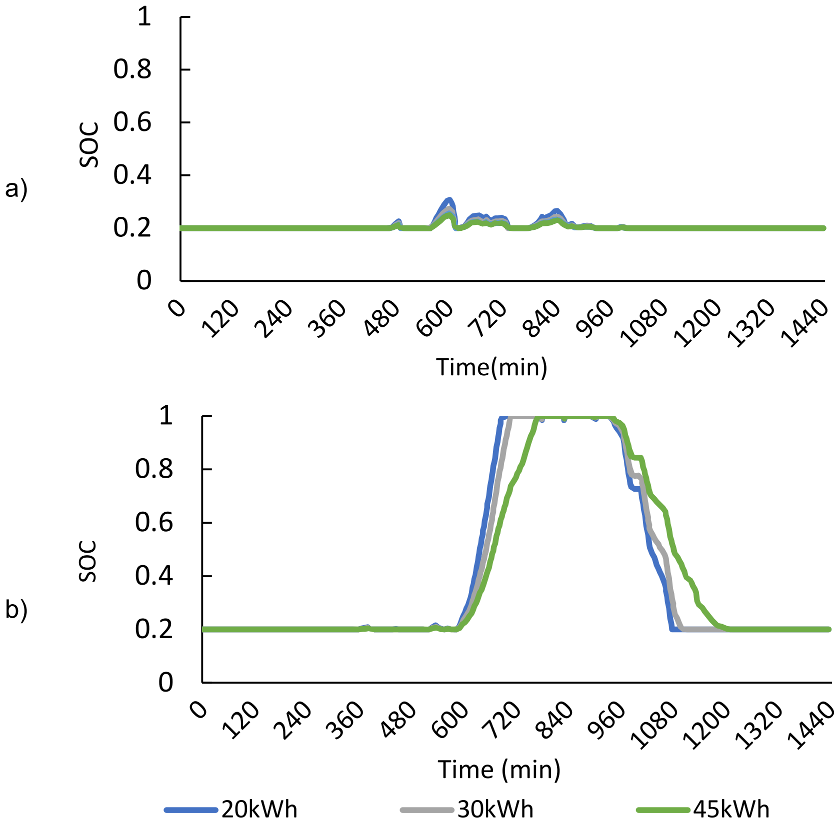


Figure 4-10 The SOC of CES with Varying Capacities in a) March and b) May

For applications in the UK, seasonal variation plays a vital role in the use of energy storage systems. It is important to address the issue that ineffective use of storage is very likely to happen during winter, which still requires more consistent generation sources or more advanced technologies to exploit the potential of the system. For example, the battery could store cheap off-peak electricity and use it during peak price hours if some time-based price signal is available. If the community size and battery capacity are big enough, HES and CES could participate in electricity market executed by a more advanced management strategy.

4.3.1.4. *Impact of Demand Heterogeneity on Community*

In order to investigate the impact of community demand heterogeneity, 12 communities are considered. Both the highest possible and lowest possible community demands are modelled (i.e. 10 houses each with the highest demand and 10 houses each with the lowest demand respectively). The remaining 10 communities modelled each have 10 houses with randomly allocated load profiles. The average monthly consumptions are shown in Figure 4-11, with the error bars representing the highest and lowest demand cases.

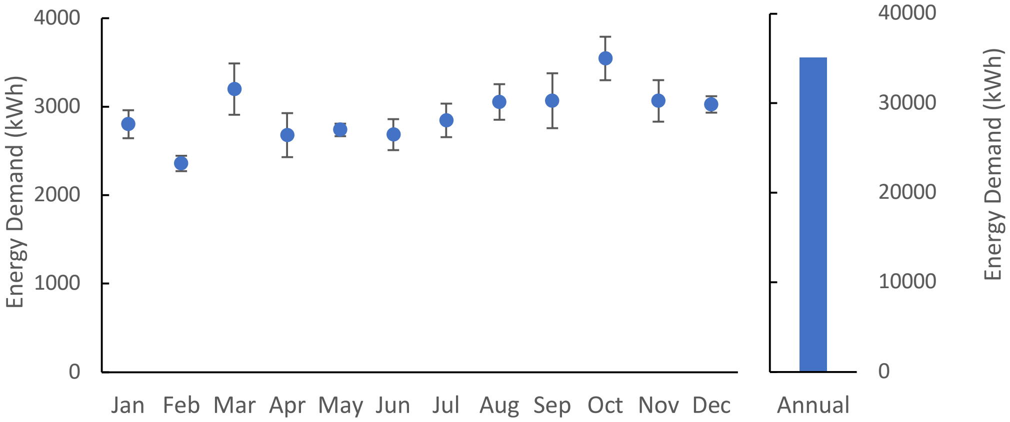


Figure 4-11 Monthly and Annual Energy Consumption of a Community

Figure 4-12 a) shows the average SCR of the 12 simulated communities. The SCR is significantly influenced by seasonal changes rather than demand heterogeneities, where warmer months contribute to lower SCR and colder months lead to a higher SCR. Although the community demand in some months in Figure 4-11 has significant variation due to heterogeneity, such as September, the average SCR of the community remains very high, around 97%. For the months where the demand is significantly smaller or larger than the PV production, community demand heterogeneity is found to be less influential to the community SCR. However, when the monthly demand is similar to PV production, such as June, a demand changes up to 350 kWh leads to a 6% SCR variation. Across the whole year, the demand heterogeneity leads to a decrease in annual average SCR ranging from 74% to 68%, which is not a significant change for a 10-house community with a 30 kWh CES, but it could be for a bigger community.

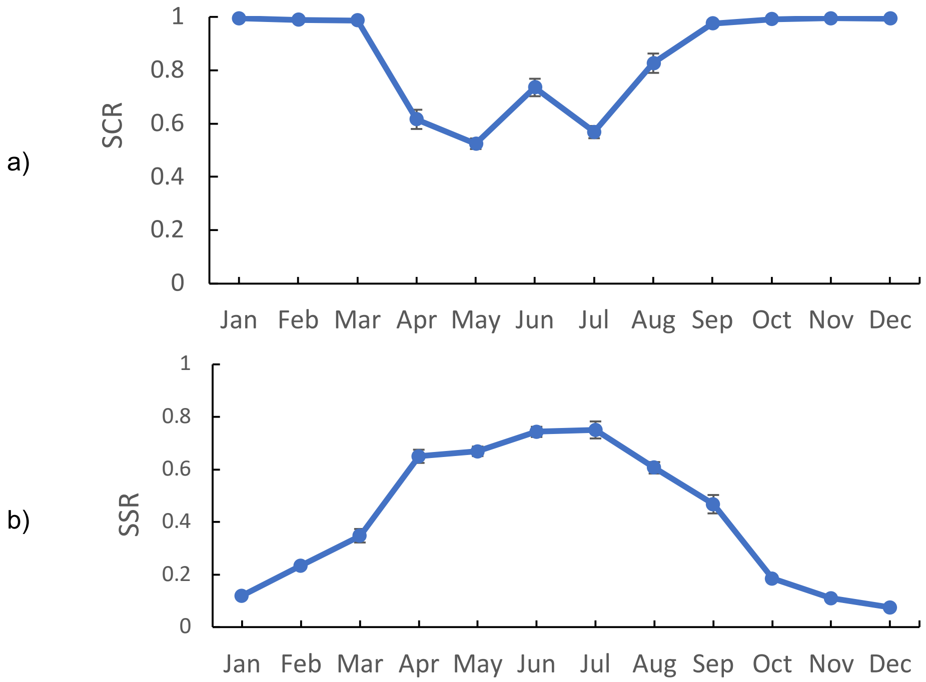


Figure 4-12 Community Demand Heterogeneity Impact on a) SCR and b) SSR

Figure 4-12 a) shows the average SCR of the communities with various demands. As with Figure 4-12 b), the variation of SSR through the year clearly shows that seasonal changes play a more important role. This mirrors the tendency of monthly PV production over a year, suggesting the increasing PV production contributes to more community demand met by PV energy. In winter the difference between demand and PV production is so large that the demand variation to contribute to any obvious change in SSR, while in summer the change in SSR is more obvious and a 6% variation can be achieved. Across the whole year, for a community with an average consumption at 35065 kWh and SSR at 40%, a demand variation ranging up to 3258 kWh can lead to a 7% variation in SSR. As mentioned previously, the SSR of a community is determined by the community demand, but the demand heterogeneity does not lead to any obvious variation.

In addition, a further investigation is carried out to validate our findings. 30 different metred residential consumption data are chosen from SmartMeter Energy Consumption Data in London Households provided by UK Power Networks [143]. Similarly, 30 PV generation data series for the validation are obtained from Renewable Ninja [144] based on [145,146]. The data are used to reproduce 30 different combinations of street demand and PV production and the annual community energy demand and PV production are shown in Figure 4-13. The annual demand and PV output chosen for validation are lower than the data input in our simulation, but the demand heterogeneity has more marked fluctuation than the synthetic consumption data generated by CREST demand model. During winter months, the household consumption data used for validation is significantly higher than that consumed during summer months. This can be because of the households measured by UKPN might adopt electric heating.

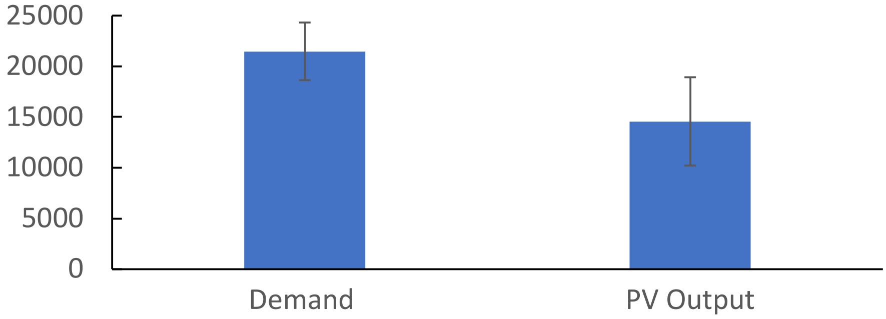


Figure 4-13 Annual Community Energy Demand and PV Output for Validation

The validation simulations were carried out to investigate the CES and HES community respectively. Figure 4-14 shows the validation results of annual SCR and SSR and the variation in SCR and SSR still remains due to the seasonal reason. However, the deviation in our findings in Figure 4-12 are insignificant, but within the range of validated results. The mean absolute error of monthly SCR of CES community is 0.181 and that of SSR is 0.218.

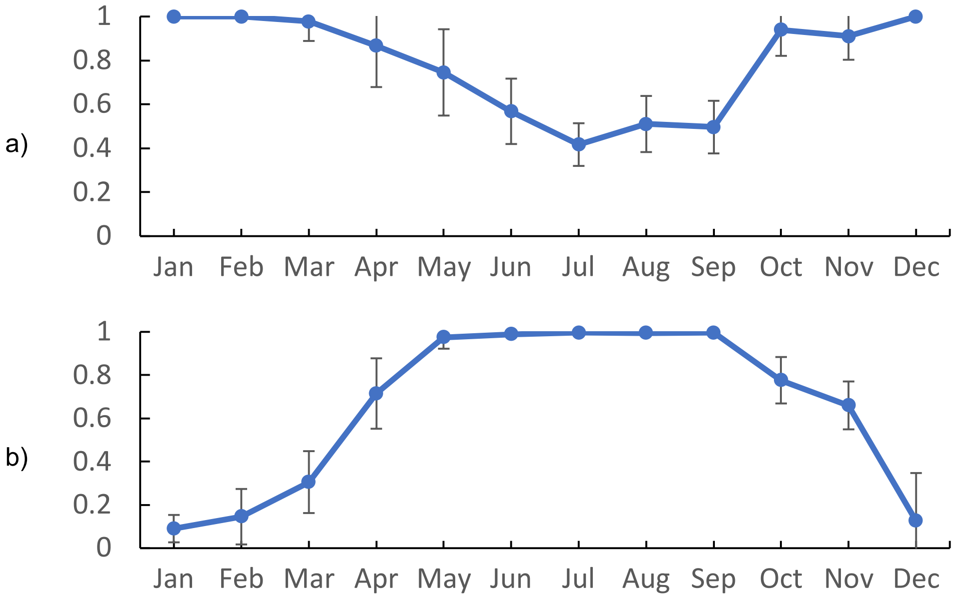


Figure 4-14 Monthly a) SCR and b) SSR of CES Community for Validation

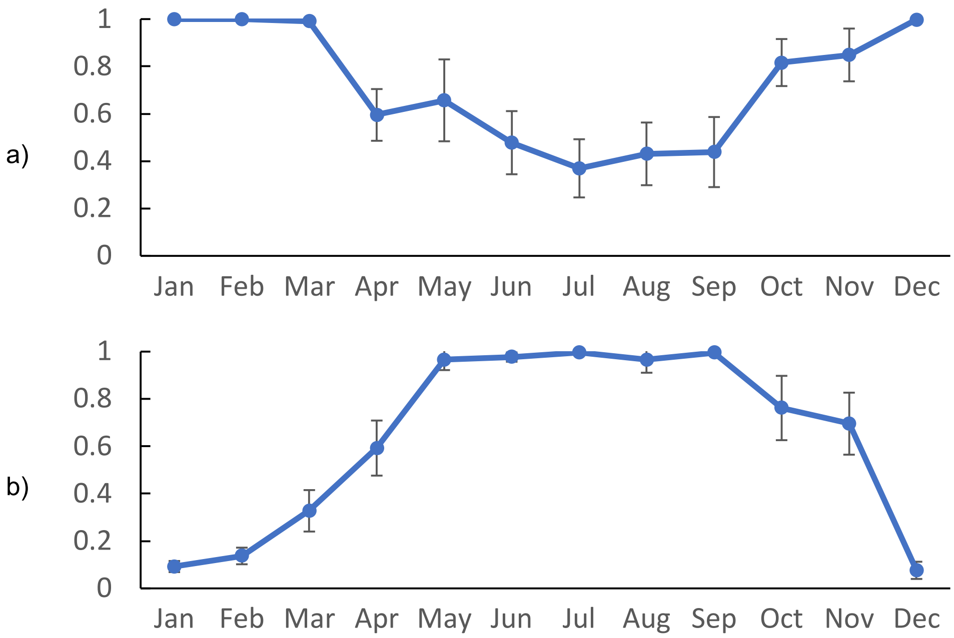


Figure 4-15 Monthly a) SCR and b) SSR of HES Community for Validation

The Figure 4-15 shows the monthly SCR and SSR of the HES community and similar trends shown in Figure 4-15 can be observed. High SCRs and low SSR suggest that the solar output from December to March are not sufficient and can only contribute to very limited proportion of community energy demand. In comparison, between May and September, high SSRs and low SCRs indicates that the community makes the best use of the solar output and can supply majority of electricity demand locally. The overall SCRs and SSRs of HES community are similar, but CES community is better (up to 10%), and both communities investigated in the validation are slightly higher comparing to Figure 4-13. Although some particular months in our study shows random peaks (such as June), the overall annual and monthly results show the same trend and within the validation result ranges. In our validation, the main variance of SCRs and SSRs of HES and CES communities happen in September, October and November. It could be due to the PV production for the validation markedly different from the one used in our research.

The results in Section 4.3.1.4 have shown that community demand heterogeneity can lead to some changes in energy localisation within the community and also CES performance, especially when demand and PV production are similar. In contrast, demand heterogeneity is found to be insignificant when the demand remarkably differs from PV production, as the variation cannot make any drastic improvement in the utilisation of the PV energy. Although the validation study suggests that there might be some surge or reduction in the SCRs and SSRs in some months, the data in our study are within the range of validation findings. Lastly, our results match the trend discovered by other researchers [28], as different types of demand profiles have little influence on CES system performance, but they are meaningful for system planning.

4.3.1.5. Impact of Demand Heterogeneity on Community Energy Storage

Figure 4-16 shows the average monthly CES duty cycle over a year, which follows the trend of community SSR demonstrated previously. Demand heterogeneity is found to have insignificant impact on the CES performance, which leads to a negligible change in the number of CES duty cycles. In contrast, the CES operation is heavily reliant upon season changes. As the CES is only used to charge surplus PV electricity, the duty cycles of the CES increase with the total PV surplus production. The CES can finish a full charging/discharging cycle per day from April to August, and during simulation sometimes two full cycles can be achieved within a day. However, in winter months the average number of cycles is below 10. Across the whole year, the average CES duty cycle is ca. 217 cycles with a range from 200 to 250, and correspondingly the capacity of a brand-new CES is found to have a degradation at around 3-4% per year based on the total energy output.

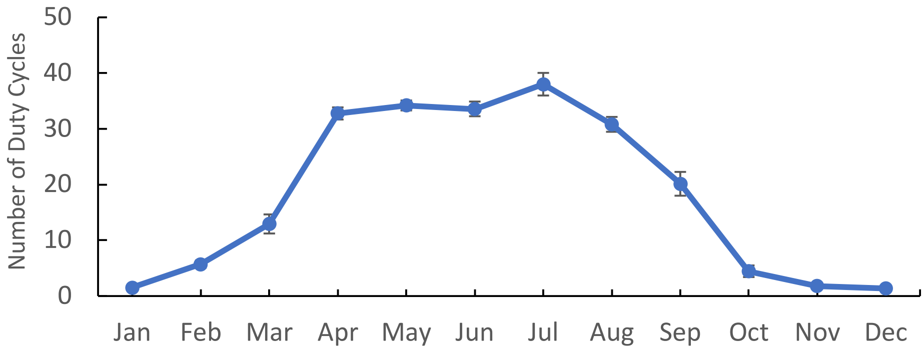


Figure 4-16 Impact of Community Demand on the CES

Although community demand variation can change the use of the battery, our results find that the change in the number of CES duty cycles looks unlikely to cause any significant capacity degradation of the CES, compared to an average at 4000 full cycles across a lithium-ion battery's lifespan [29]. However, most empirical battery degradation models are tailored for a specific battery application, where the battery operation region is narrow so that a satisfactory accuracy can be achieved. Our model is adapted from a battery cell model developed by [26], of which the battery operation pattern will be different from that of CES system. In this way, the battery degradation model still needs further validation by comparison with real data.

4.3.2. Economic Analysis

In this section, economic performances of the three cases are compared and analysed. Three tariffs are used in the study representing the tariffs from low to high classes. The energy savings in the previous section are used to calculate the economic benefit, in terms of energy cost reduction and payback time of total system investment. The payback time is evaluated at street and household level respectively. Here, both HES and CES are considered as private or collective private assets, so the system capital investment is only recovered by energy cost savings and subsidy via FIT. The ownership of CES and operation charges are therefore excluded from the study. Table 4-2 shows the payback time of three application with a total storage capacity ranging from 20 kWh to 45 kWh at various tariff levels. The capital investment can be paid back in a shorter period of time when the system adopts a higher tariff. Case 1 has the shortest payback time, suggesting that expensive storage system costs and low electricity price are the main barrier to system cost recovery. The results also show that higher battery capacities struggle to recover the investment costs under current frameworks, within the 10-year battery warranty.

Table 4-2 Payback Time (years) of a Street with Three Different Tariffs

Storage Capacity	**Low Tariff (£0.1323 kWh^{-1})**		**Medium Tariff (£0.1504 kWh^{-1})**		**High Tariff (£0.1801 kWh^{-1})**	
	HES	**CES**	**HES**	**CES**	**HES**	**CES**
0 kWh (PV-only)	*8.27*		*7.63*		*6.77*	
20 kWh	*10.55*	*10.31*	*9.67*	*9.43*	*8.50*	*8.28*
25 kWh	*11.16*	*11.01*	*10.21*	*10.06*	*8.97*	*8.81*
30 kWh	*10.77*	*11.59*	*9.84*	*10.58*	*8.63*	*9.27*
35 kWh	*12.38*	*12.16*	*11.31*	*11.10*	*9.92*	*9.71*
40 kWh	*13.20*	*12.84*	*12.07*	*11.71*	*10.58*	*10.23*
45 kWh	*14.02*	*13.39*	*12.81*	*12.20*	*11.23*	*10.66*

As the value of shared electricity within a CES community is not considered in this study, the adoption of energy tariffs by households is crucial to recover the investment. As is expected, the high energy tariff is found to result in better payback times of the CES system, while other tariffs seem unlikely to make the whole installation financially feasible. From the perspective of households, it also follows the similar trend that higher energy tariff can better incentivise self-consumption to maximise energy costs saving so that a shorter payback time can be obtained. Table

4-3 shows the payback time of households with low and high demand when they adopt high supplier tariff. As can be seen, light energy users pay back the HES system in a shorter time, while CES is more economically feasible to intensive energy users.

Table 4-3 CES Payback Time of HH0 and HH2 with High Supplier Tariff

Storage Capacity	**HH0**		**HH2**	
	HES	**CES**	**HES**	**CES**
0kWh (PV-only)	*10.56*		*7.35*	
2 kWh	*10.85*	*12.85*	*8.01*	*6.34*
2.5 kWh	*11.38*	*13.85*	*8.48*	*6.85*
3 kWh	*10.79*	*14.84*	*8.17*	*7.32*
3.5 kWh	*12.17*	*15.24*	*9.27*	*7.62*
4 kWh	*12.86*	*15.92*	*9.81*	*8.05*
4.5 kWh	*13.74*	*16.77*	*10.46*	*8.43*

From an economic perspective, HES and CES can contribute to significant energy savings and hence lower the charges by energy suppliers, but they are yet to be economically feasible. In this study, the applied assumptions do not include realising the value of shared energy within the CES network. If an appropriate framework or regulation can be introduced to remunerate those who share more energy with the community, it will be promising for households to harvest further benefits. At the moment, there are some applications enabling households to trade electricity within a community by using different technologies.

In this study, the storage system investment consists of two components, batteries and system costs. The production costs of batteries are expected to decrease in the future due to the demand surge mainly driven by electric vehicles. Price developments of energy management units will probably be more expensive due to the complicated requirement mentioned in previous paragraphs. It is likely better to have a larger communal battery rather than several smaller ones if the total capacity is the same as having a centralised battery could possibly lower the costs and difficulty in system maintenance and shorten payback time of investment.

4.3.3. Environmental Analysis

Here, the environmental impact of the system is evaluated in terms of annual CO_2 avoidance and payback time of CO_2 emission from manufacture. Figure 4-17 shows the CO_2 avoidance of a community with three cases over 10 years. It is clear that Case 2 and 3 can reduce more CO_2 emissions than Case 1 and need less than 3 years to be environmentally beneficial for the community. Among the three cases, Case 1 is found to have the shortest CO_2 emission payback time of around 2.5 years based on the static carbon intensity on the grid, due to the lack of storage system. The calculation of CO_2 avoidance is based on the energy import savings and PV generation and therefore the reality could be slightly longer than these results, as they only consider the CO_2 emission from manufacture and exclude other sources, such as transport, maintenance and operation etc.

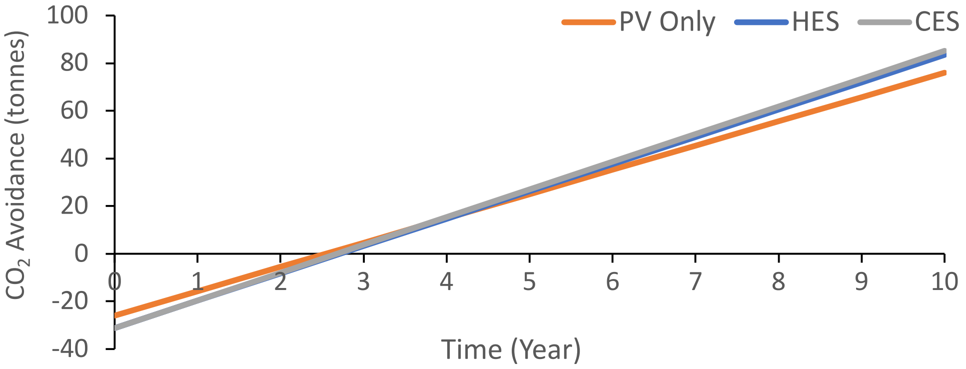


Figure 4-17 CO_2 Avoidance of a Community with 30 kWh Storage When Manufacture in UK

Table 4-4 shows a trend that more CO_2 can be avoided by increasing CES capacity and every extra 5 kWh CES can save approximately 50 kg more CO_2 per year for a community. For households, the results suggest that HH2 can only save around 160 kg more than HH0. For HH2, the amount of energy saving is mainly from the use of surplus PV energy of neighbours, rather than localising consumption by its own on-site generation. Across the whole year, the households are able to reduce CO_2 emissions by 0.9 - 1.1 tonnes.year^{-1}, in line with the results of Uddin et al. [22] who showed a reduction of 0.8 - 1.4 tonnes.year^{-1} for a 4kWp panel. It is therefore clear that household heterogeneity is unlikely to be the most influential factor in CO_2 avoidance.

Table 4-4 Annual CO_2 Avoidance and CO_2 Payback Time

CES Capacity	**CO_2 Avoidance (tonnes.Year^{-1})**			**CO_2 Payback Time (Years)**		
	Street	**HH0**	**HH2**	**Street**	**HH0**	**HH2**
20 kWh	9.84	0.90	1.05	3	3.3	2.8
25 kWh	9.90	0.90	1.06	3.1	3.4	2.9
30 kWh	9.95	0.91	1.06	3.1	3.4	2.9
35 kWh	9.99	0.91	1.07	3.2	3.5	3.0
40 kWh	10.04	0.91	1.07	3.3	3.6	3.1
45 kWh	10.08	0.91	1.07	3.4	3.7	3.2

From an environmental perspective, all three cases are found to be environmentally beneficial. While the majority of the CO_2 emissions are from manufacturing the PV panels, the energy storage systems are able to increase avoided carbon emissions. For a community, the PBT_{CO2} of total manufacture CO_2 emissions are roughly the same for all three cases and the increasing capacity of PV and storage can shorten their carbon payback times. In this study, the estimation of the total amount of emitted CO_2 is based on reference values (see Table 4-1) and for storage systems with the same capacity we have assumed the same amount of CO_2 is produced during manufacture; however, the CES will, in reality, produce less CO_2 due to the reduction in the supporting power management equipment required. This will result in shorter PBT_{CO2} for Case 3 than predicted here.

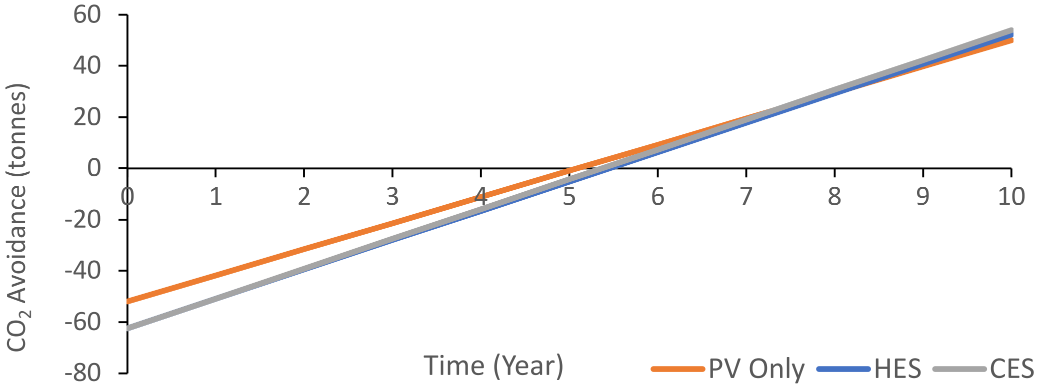


Figure 4-18 CO_2 Avoidance of a Community with 30 kWh Storage When Manufactured in China

In this research, it is assumed that both manufacture and installation of solar panel and battery storage are in the UK. Arcos-Vargas et al. [147] emphasise the importance of installation and manufacture location, suggesting that the carbon emissions can reach the lowest around 7 $g.kWh^{-1}$ when both manufacture and final commission happen in France due to its high proportion of nuclear generation. However, it seems unlikely because very few PV systems are produced in Europe nowadays and China has become the biggest solar panel supplier. The grid carbon intensity in China (883 $g.kWh^{-1}$) [148] is found to be much higher than the UK (323 $g.kWh^{-1}$), regardless of the ambition of China aiming to reduce it to 600 $g.kWh^{-1}$ by 2020 [149]. If we use the grid carbon intensity of China to calculate total carbon emission during manufacture, the PBT_{CO2} of the three cases are almost double (5 – 5.5 years) as shown in Figure 4-18. Additionally, installation location also plays an important role in carbon avoidance, as the solar radiation varies substantially with location and therefore the energy produced during PV's lifetime also varies significantly. Researchers suggest that the annual CO_2 avoidance by the PV can achieve at least 0.963 tonnes.kWp^{-1} in Morocco [150], and 0.48 tonnes.kWp^{-1} in Malaysia [151].

Across the three cases presented in this section, both HES and CES in addition to PV are studied and the value of these applications is identified. Although HES performs better in some circumstances, such as for lighter energy users, CES is found to be more beneficial to the community compared to HES in terms of more effective peak demand shaving, higher self-sufficiency and better utilisation of PV generation. The results also suggest that CES can even have the same effective storage capacity with a capacity that is much smaller than the sum of the HES in individual households. The high costs still remain the main drawback of both systems – it will take households longer than 10 years to recover the upfront costs. With the closure of relevant subsidies, more revenue sources are needed and CES is proven to have great potential to obtain extra profit by enabling inter-house trading within the community microgrid and even providing grid service. The selection of connection points of a larger CES also provides an operational freedom that can improve the voltage quality of the local distribution grid [70]. For grid operators, this is obviously a better and cheaper alternative compared to expensive distribution and transmission network expansion [152]. Although HES could also get access to providing grid service as part of a virtual power plant, the smaller size makes this more difficult and CES is obviously more favourable due to lower management requirements and the associated financial losses [57]. Both HES and CES are of great environmental benefit and can effectively reduce approximately 1 tonne CO_2 emission per annum for a household. Considering the scaling effects of the battery, a CES system can be built with less CO_2 emission and also at a lower overall costs [153].

4.4. Conclusion

In this chapter, a techno-enviro-economic analysis of HES and CES is presented. The CES system has been modelled with different battery capacities compared to HES and PV-only cases. The PV systems coupled with storage systems are found to be beneficial to both community and individual households, helping them to achieve higher SCR, SSR and energy savings. However, for households, the installation of either HES or CES is likely to be reliant on the profile heterogeneity. HES is found more suitable for lighter energy users, while intensive energy user can benefit more from CES, although in some cases both storage options show similar results.

The economic benefits of storage systems are found to be significant in Case 2 and 3, which is able to reduce household energy bill by at least 30%. However, the expensive upfront cost still remains as the biggest challenge to achieve financial feasibility under current tariffs and subsidies, as most applications take more than 10 years to recover its original capital investment. Furthermore, the value of shared energy is yet to be recovered via some effective tariff proposals within a community, or it will still be less attractive and impractical than thermal energy storage under current assumptions. The study finds the value of energy traded within the CES network will be vital in the economic performance, especially after the closure of subsidies by the government. All three cases included in this study are found to be helpful to reduce carbon emissions, especially CES. The households are able to reduce CO_2 from 0.9 to 1.1 tonnes per year, and CES can contribute to slightly more. The carbon emission payback time at the moment is at between 2.5 and 3 years when the manufacture and installation are in UK. However, the carbon PBT will be doubled, more than 5 years if both PV and storage are manufactured in China. It is expected to be shorter in future due to technology advancement and increasing penetration of renewable power supply.

The increasing SCR and SSR of a community are significantly helpful to the distribution networks, especially to those with constrains, by reducing peak demand and PV export. A PV plus storage system can make effective use of on-site generation and possibly avoid unnecessary curtailment. The economic analysis above shows that both HES and CES system are yet to be economically feasible to consumers. More innovative solutions are therefore needed in the future, such as stacking different revenues by combining difference services and different system operation strategies. These alternatives for enhancing the system feasibility are investigated in the next chapter.

Chapter 5 Improving the Feasibility

5.1. Introduction

In Chapter 4, both HES and CES struggled to be profitable within their lifetime, but CES can significantly enhance PV self-consumption and energy savings. It is therefore essential to investigate alternative reimbursement schemes, different pricing tariffs, better allocation of CES capacity and the provision of different services to improve overall sustainability. The main contributions of this chapter are generalised as follows:

- power management strategies are developed for both HES and CES to utilise the TOU tariff for demand side management according to different operating goals (i.e. maximising PV consumption and minimising energy costs);
- the performance of HES and CES under a TOU tariff are investigated and compared to systems that adopt a flat tariff;
- the potential alternatives to enhance the business case for CES are explored;
- the impact of future system cost reduction and policy changes on system payback time is investigated.

The main results from this chapter were published in:

- **Dong, S**., Kremers, E., Brucoli, M., Rothman, R. and Brown, S., 2020. Improving the feasibility of household and community energy storage: A techno-enviro-economic study for the UK. *Renewable and Sustainable Energy Reviews*, *131*, p.110009.

5.2. Data Input

The demand data adopted in this chapter is described in Section 3.3. Five different types of load profiles are used in this study. The Solar radiance data is obtained from the Microgen Database developed by Sheffield Solar [129]. Each household owns a 3kWp PV system with the same specification, in order to eliminate the discrepancies of electricity production from PV.

The TOU tariff adopted in this research is the TIDE tariff from GreenEnergy [154]. During weekdays, there are three prices for peak, off-peak and shoulder periods, while the weekends only have two price rates. This time-dependent electricity tariff provides an incentive and possibility for households to charge the battery with cheap electricity and discharge during the expensive peak demand period. The flat tariff rate is £0.186 kWh^{-1} based on the typical domestic consumption values (TDCVs) of a dual-fuel user whose annual electricity consumption is ca. 3100 kWh and electricity bill is £577, according to Ofgem [155]. The flat tariff also includes £0.2 day^{-1} as the standing charge [156]. More details of the two tariffs are presented in Table 5-1.

Table 5-1 Tariff Information Used in This Chapter

Tariff Name	**Day**	**Time**	**Electricity Price (£.kWh^{-1})**	**Standing Charge (£.day^{-1})**
TIDE Tariff [154]	Weekdays	00:00 – 06:59	0.09	0.32
		07:00 – 15:59	0.16	
		16:00 – 19:59	0.32	
		20:00 – 23:59	0.16	
	Weekends	00:00 – 06:59	0.09	
		07:00 - 23:59	0.16	
Flat Tariff [155,156]	All-time		0.186	0.20

The economic and environmental parameters are shown in Table 5-2.

Table 5-2 Economic and Environmental Values Adopted in This Study

Parameter	**Value**	**Unit**
Li-ion Battery [132]	570	£.kWh^{-1}
Li-ion Battery Lifespan [132]	10	Years
Battery Inverter [157]	500	£.kWh^{-1}
Battery Casing [132]	293	£
PV inverter [158]	500	£.kWh^{-1}
Solar Panel [159]	0.4	£.Wp^{-1}
Solar Panel Lifespan [159]	25	Years
Solar Optimiser [159]	0.25	£.Wp^{-1}
PV mounter [159]	328	£
Accessories [159]	150	£
O&M Cost [159]	50	£.year^{-1}
Discount Rate [160]	5	%.year^{-1}
Carbon Factor of Grid Electricity [161]	0.256	kg.kWh^{-1}
CO_2 Emission During Inverter Manufacture [137]	12.03	kg.kWh^{-1}
CO_2 Emission During PV Manufacture [138]	865.44	kg.kWp^{-1}
CO_2 Emission During Battery Manufacture [137]	175	kg.kWh^{-1}

5.3. Results and Discussion

5.3.1. Technical Assessment

5.3.1.1. Impacts on Communities

Figure 5-1 shows a comparison of the communities with HES and CES with both 20 kWh and 40 kWh. All three operation modes contribute to higher SCR and SSR for CES than HES, and CES working in Self-Consumption mode under TOU tariff (CES-SC) and in Self-Consumption mode under flat tariff (CES-Flat) have the best performance, while the HES systems have much lower SCR and SSR. For the community with a 20 kWh HES system, the annual SCR of CES-SC mode can be around 10% lower than the CES system with the same capacity. The monthly SCR and SSR are showing a similar trend, and CES is around 5% higher than the HES system during summer, but the SSR variability is minimal during winter. The CES system is seen to be better at utilising solar power than HES, as the energy sharing can make the community more self-sufficient.

Across the three operations, the results suggest HES and CES operate more frequently under the flat tariff and meet more demand locally because they aim to maximise consumption of PV generated electricity. However, TOU tariff operation relies upon the forecast function based on supply and demand and varying tariff rates. Therefore, the power discharging from the battery is also determined by the potential energy cost savings on top of maximising the use of PV electricity. Although the improvement of SCR and SSR via operational mode is found to be negligible, the electricity bill can be effectively reduced under TOU tariffs, which will be presented later.

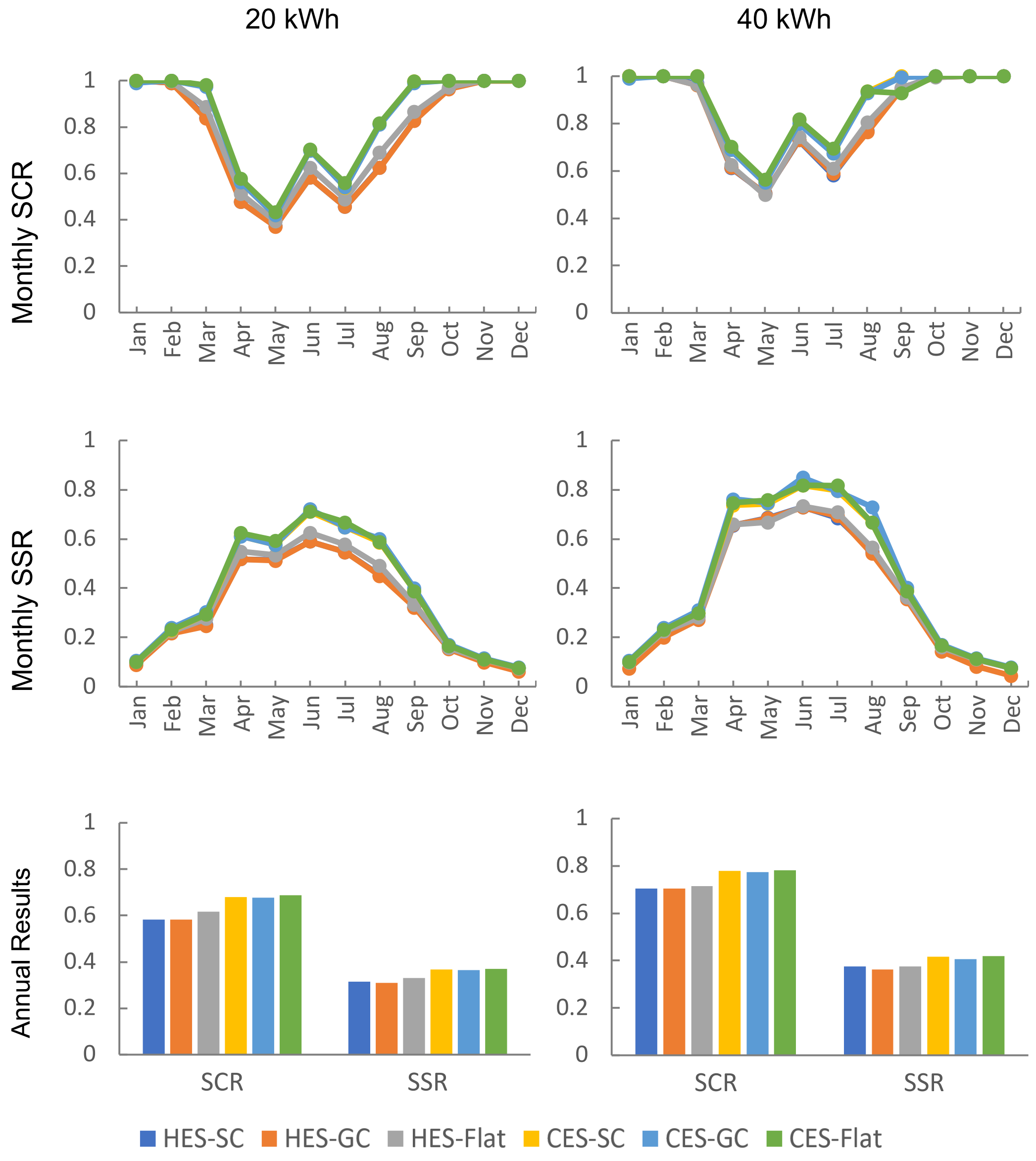


Figure 5-1 Monthly and Annual SCR and SSR of The Community

The community performance also improves with increasing storage capacity. The extra 20 kWh of storage contributes to around 10% increase in SCR and 5% in SSR over a year. In addition, the performance difference between HES and CES becomes clearer at 40 kWh and monthly SCR and SSR of CES are markedly higher than those of HES system. The larger system can provide more flexibility and capacity to offset more surplus PV energy and avoid unnecessary curtailment, but it can be economically unfeasible. On the other hand, the annual SCR and SSR of the HES community with 40 kWh is only 1% higher than CES community with 20 kWh, which makes it possible to use a smaller CES system to achieve similar performance of a larger community with HESs.

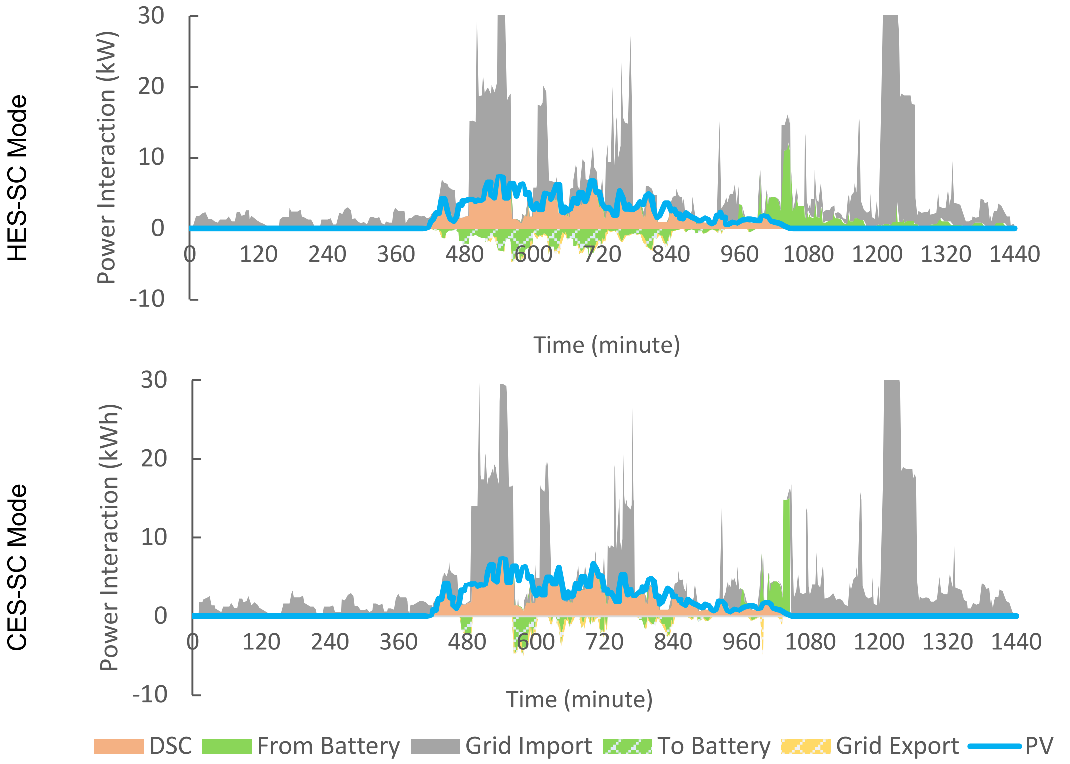


Figure 5-2 Grid Interaction of Community Operating in HES-SC and CES-SC Modes in March

Figure 5-2 shows the power interactions of a community operating in HES/CES-SC Mode in March. The discharging power in HES is continuous and also higher than that of the CES community due to the inter-house electricity trading within the network. Both the HES and CES start to discharge at the 960th minute (16:00) and the HES remains active till the end of the day. The higher power rating enables the CES to fully supply the community demand but for a shorter period of time, due to insufficient electricity stored in the CES. It is therefore important to introduce alternatives to enhance the battery operation in case of insufficient PV generation.

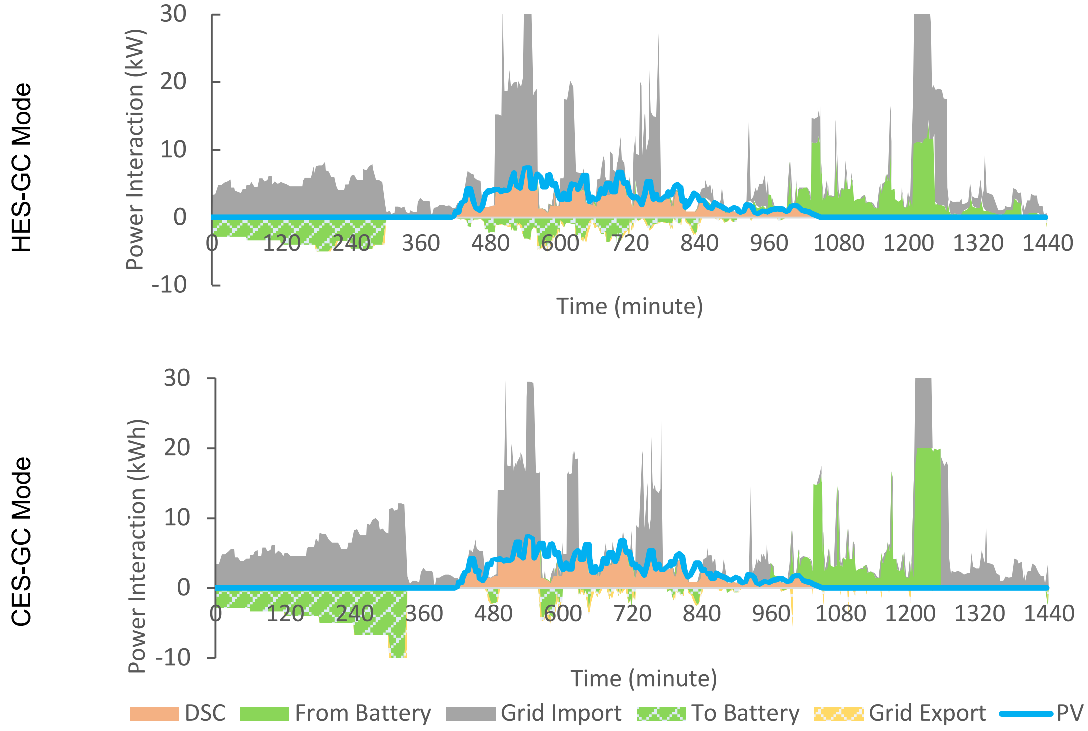


Figure 5-3 Grid Interaction of Community Operating in HES-GC and CES-GC Modes in March

Figure 5-3 shows the power interaction of the community with the same system set-up operating in HES/CES-GC Mode. The overnight charged electricity enables both communities to effectively reduce the power import and the peak demand during peak tariff period (16:00 – 19:59). Due to the HES only meeting the energy demand where it is installed, the correlation of demand between households plays an important role. If a community consists of households where the majority have similar consumption patterns, the HES community will be able to markedly decrease the power import; conversely, the CES is more advantageous for communities with more heterogeneous demand profiles. However, Figure 5-3 also shows a growing demand from midnight to approximately the 300th minute as all the storage systems charge from the power grid. This can potentially cause some problems for the DNOs, especially for a community with a high adoption rate of storage systems or electricity vehicles.

5.3.1.2. Impacts on Households

Figure 5-4 compares the monthly and annual KPIs of HH0 and HH2, representing light and intensive energy consumers, respectively. For HH0, the SCRs are better when connected to the CES network, while SSRs are much higher while having a HES system on-site. Both monthly SCR and SSR trends still suggest seasonal change plays an important role in their performances. For heavy energy users such as HH2, the utilisation of PV electricity and supply localisation in CES are found to be marginally better than HES. Additionally, the change in operational strategy is unlikely to cause significant variation in system performances.

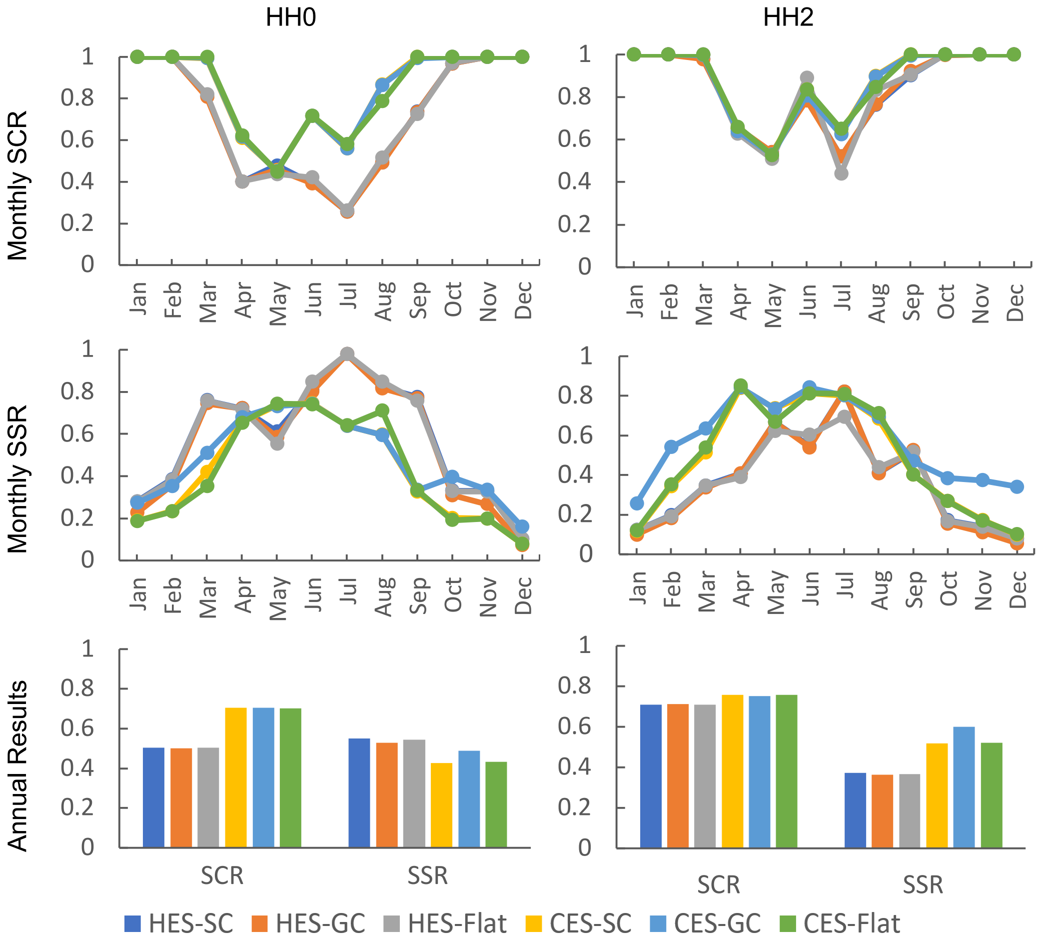


Figure 5-4 Monthly and Annual SCR and SSR of HH0 and HH2

Figure 5-5 compares the power flows of HH2 operating in HES/CES-SC Modes. The HH2 with HES struggles to meet the demand locally and most demand is supplied by the grid. However, if connected to CES, the electricity shared from neighbours accounts for a significant part of the power supply besides the grid. The power supply from the HES system lasts slightly longer than CES, but the insufficient PV leads to ineffective use of both HES and CES. Electricity supplied by neighbours is found to be an important source of supply and contributes to higher SCR and SSR for HH2 with CES. Although not technically produced from the household itself, this still enables the household to localise their power supply within the community.

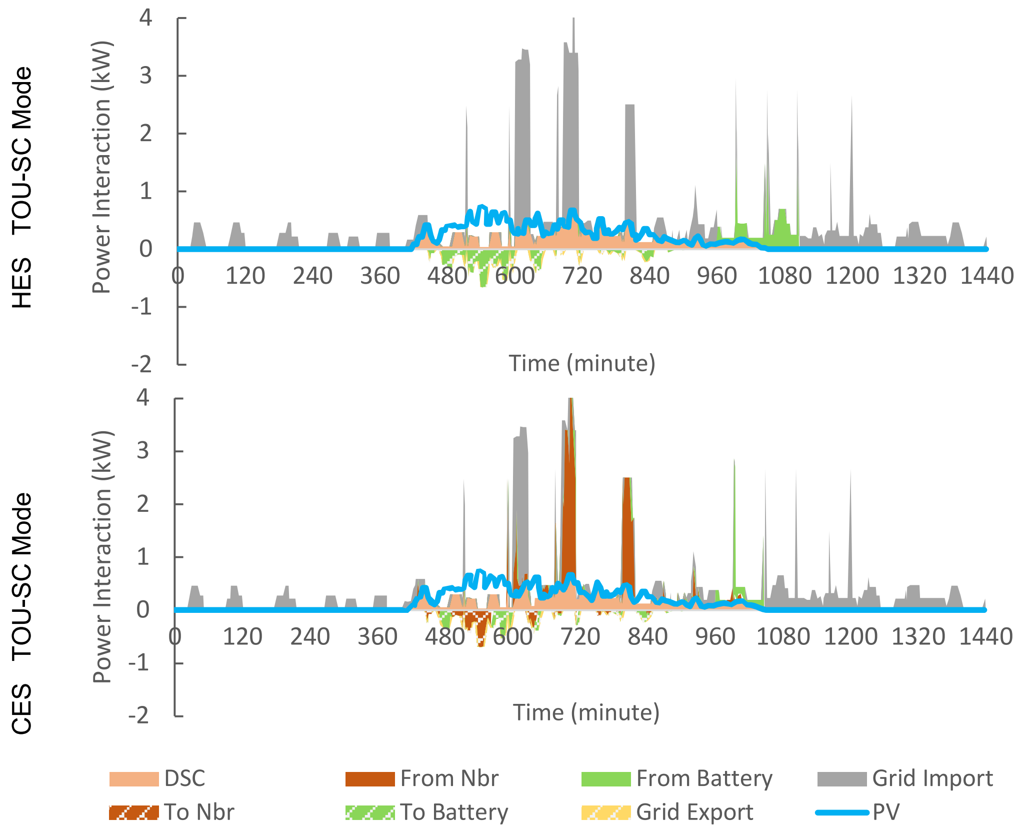


Figure 5-5 Power Interaction of HH2 in HES-SC and CES-SC Modes in March

Figure 5-6 shows the power flow of the HH2 operating under HES/CES-GC Modes. Compared to Figure 5-5, it is clear that both HES and CES power supply last longer and reduce more power import during peak time. Due to insufficient PV generation, HES/CES-GC manages to use the cheap electricity that is charged overnight to meet the demand during peak-price time. As a result, the HES/CES-GC can reduce both the peak demand and energy costs, this will be addressed further in Section 4.3.

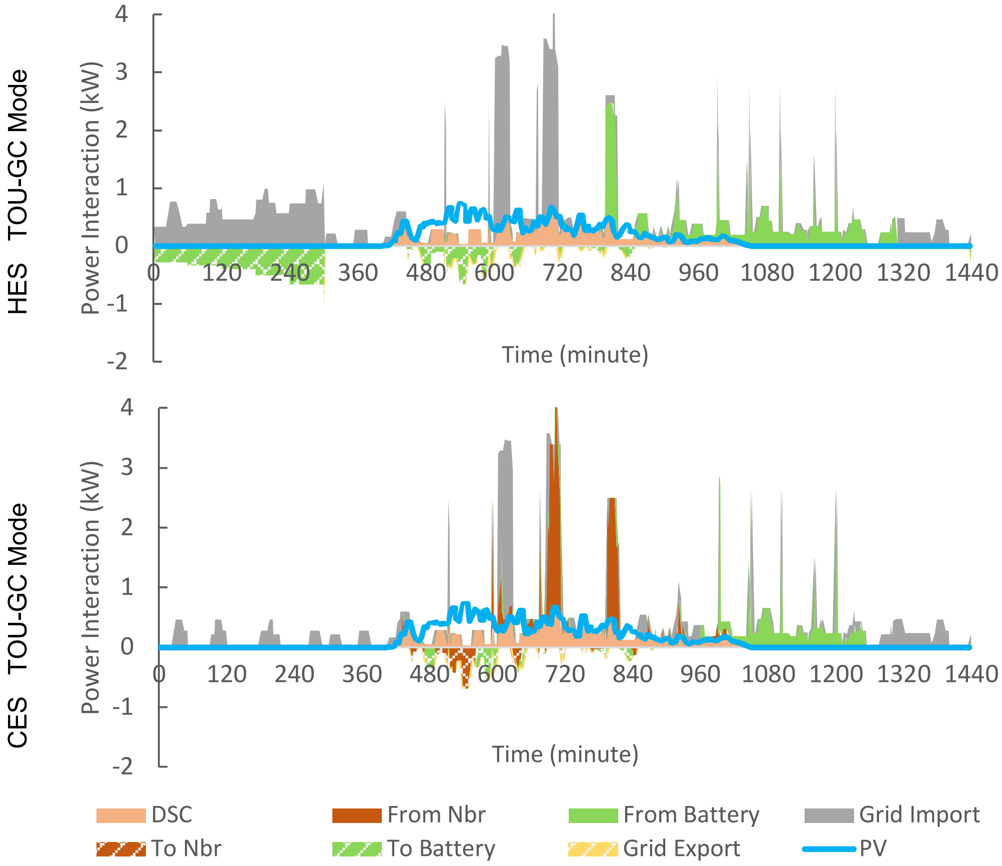


Figure 5-6 Power Interaction of HH2 in HES-GC and CES-GC Modes in March

5.3.1.3. Equivalent Full Cycles (EFCs) and Capacity Degradation

Figure 5-7 shows the EFCs of CES and HES with a total capacity at 30 kWh. Both HES and CES operate under 10 EFCs in winter, which is much lower than the summer average of around 30 EFCs. In the HES/CES-GC Modes, the HES and CES both complete pre-set one EFC everyday over a year, but it leads to some unnecessary PV power curtailment, particularly in summer. In contrast, under HES/CES-Flat, both HES and CES operate constantly to maximise the self-consumption, regardless of any economic factors, and hence they can achieve more EFCs when power production is sufficient. Therefore, the storage system follows a seasonal trend where the HES and CES capacity degrade faster during summer compared to winter.

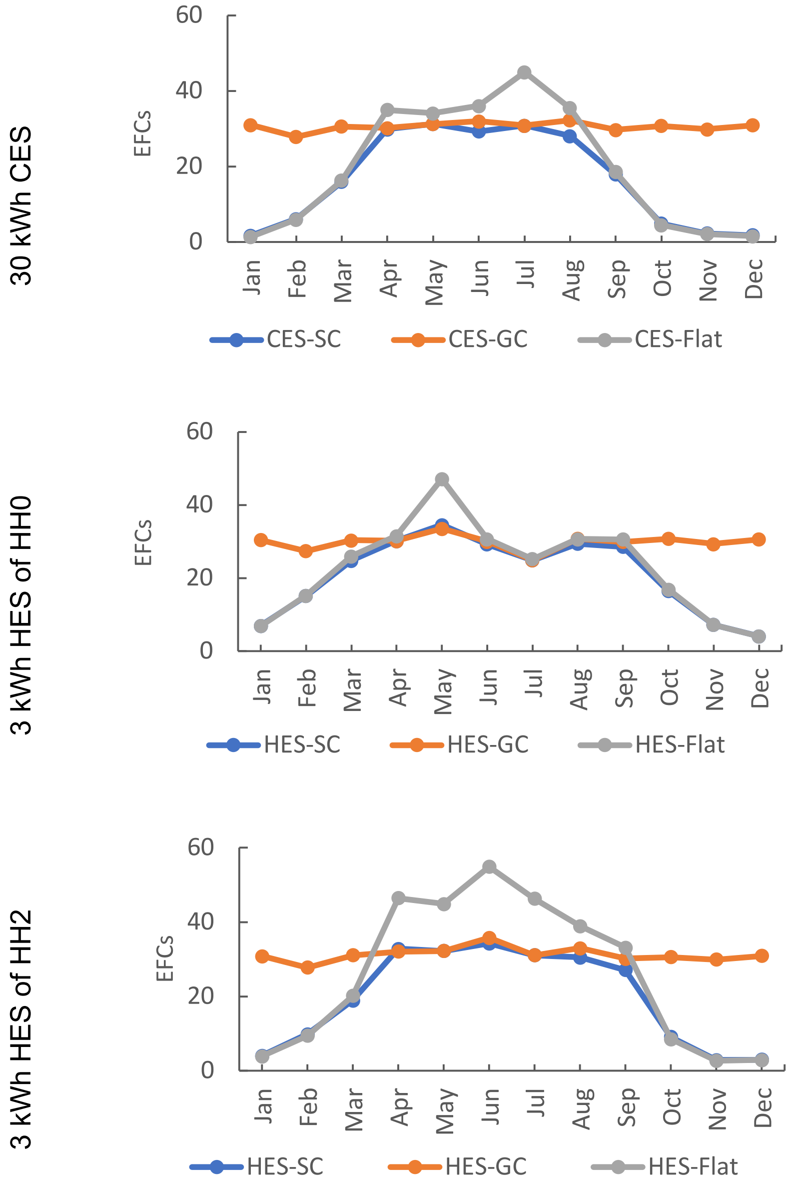


Figure 5-7 EFCs of HES and CES Operating in Three Modes

Figure 5-8 shows the relation between annual EFCs of CES and HES and storage capacity. It is obvious that the increasing storage capacity results in fewer EFCs with a 20-kWh capacity increase can lead to a 25% reduction in the EFCs. The HES-GC and CES-GC Modes have the most duty cycles amongst all operational strategies and the annual capacity degradation is not significant at roughly 2-3% year^{-1}.

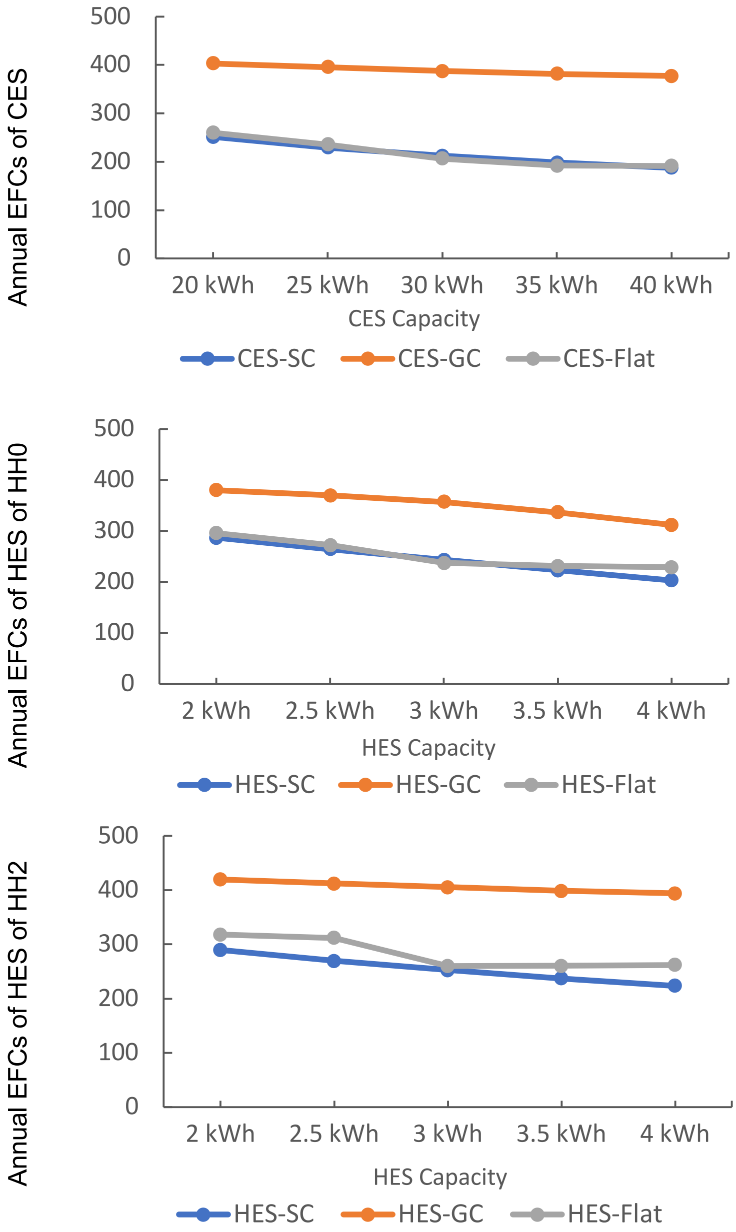


Figure 5-8 Annual EFCs of HES and CES

In this section, a combination of tariffs and operational strategies are used to investigate their impacts on the technical performance of the system. The results suggest that the flat tariff enables households to utilise PV electricity more effectively due to the lack of economic incentive to regulate the battery operation. In contrast, the TOU tariff can lower the system's SCR and SSR but can markedly reduce peak demand. The CES is found more helpful for DNOs than HES, which can reduce energy imports during peak usage time and ease the burden on the distribution network, especially under TOU tariff. However, under HES/CES-GC Modes, it leads to a demand surge as all the storage systems charge during off-peak price time, which is very likely to happen when PV generation is insufficient. This phenomenon will become more challenging in the future with the greater penetration of electric vehicles and HES, which requires measures to limit and mitigate the impacts on networks [97]. As a result, both HES and CES can operate more frequently than other modes in winter, which also lead to a faster degradation around 3-4% year^{-1}.

5.3.2. Environmental Assessment

Two households, HH1 and HH4, are chosen to represent light and intensive energy users, whose annual consumption are 2561 kWh and 4752 kWh respectively. A fixed carbon factor 0.256 kg.kWh^{-1} is adopted here instead of a dynamic one related to the power production mix. The results for both HES and CES without PV are excluded, as using batteries to arbitrage will not benefit the households environmentally. Figure 5-9 shows the annual CO_2 avoidance of two households in six different operation modes. For light user HH1, three operations with HES can save approximately 10% more annual CO_2 emissions. When the HH1 is installed with 4 kWh storage capacity, it leads to an overall increase in CO_2 avoidance of less than 10%. However, CO_2 saved from the three HES modes are almost the same, 800 kg.year^{-1} (2 kWh) and

850 kg.year^{-1} (4 kWh). For intensive consumer HH4, CES can avoid more CO_2 than HES. Among all the operational modes, the HH4 under CES-GC manages to save at least 100 kg more CO_2 than others with 2 kWh storage. The advantage of CES-GC is even clearer when it expands to 4 kWh, saving almost 1.3 tonnes CO_2 year^{-1}.

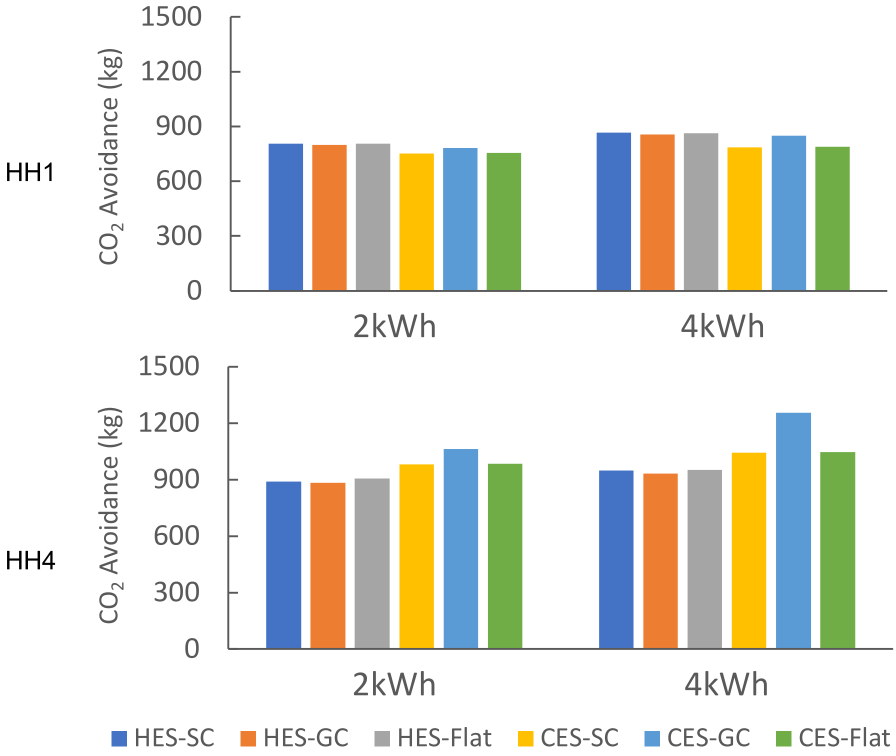


Figure 5-9 Annual CO_2 Avoidance of HH1 and HH4

Figure 5-10 shows the CO_2 avoidance of the community with 40 kWh storage. The CES can facilitate more CO_2 savings, and the CES-GC is found to be the most effective operation strategy, making the community carbon neutral within three years. The production of HES and CES would emit similar amount of CO_2, but all the cases using HES are found to have longer carbon neutral period of time than the others, around 3.8 years. When the system is manufactured in China, the PBT_{CO2} of all applications are about two times longer, because higher gird carbon intensity in China leads to higher manufacturing CO_2 emissions. The PBT_{CO2} is at least 6.2 years for CES, and others are taking 7 to 8 years to compensate the total carbon emissions.

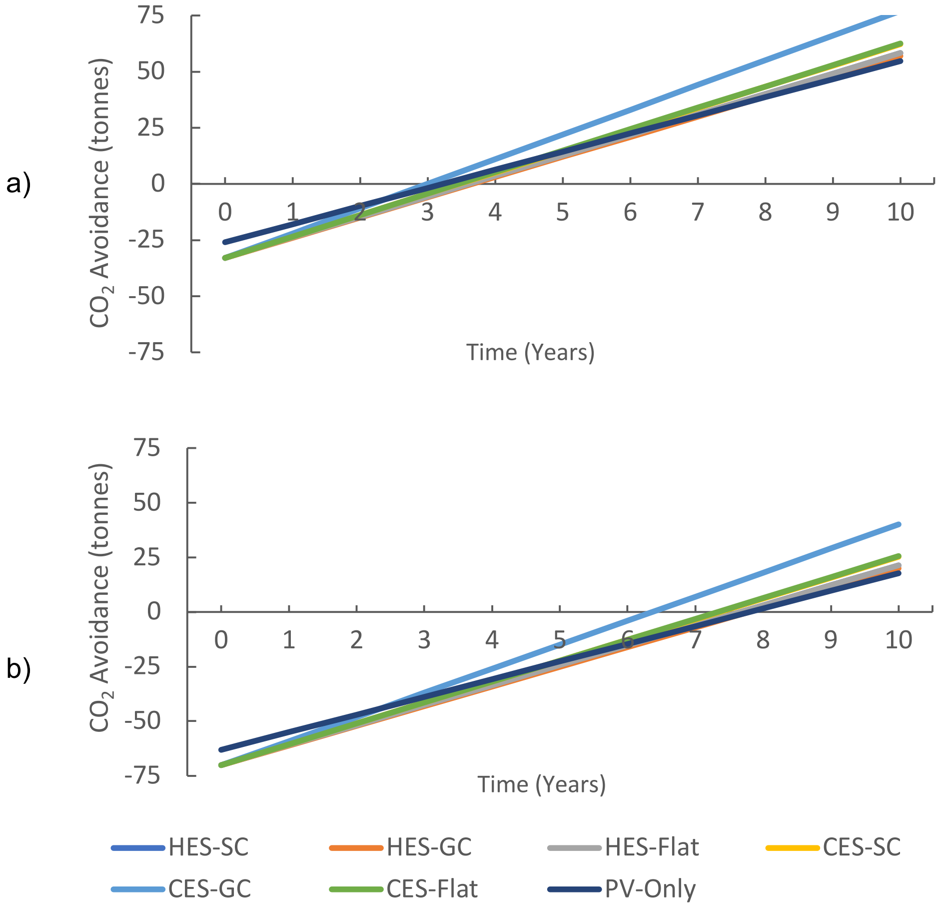


Figure 5-10 Community's CO_2 Avoidance with 40 kWh Storage Manufactured in a) UK and b) China

This analysis suggests that PV plus storage system has an extraordinary ability to avoid carbon emission, particularly CES, which makes the community carbon neutral within four years if the manufacture is in the UK. The PBT_{CO2} will be doubled when the system is manufactured in China, where the grid carbon intensity is almost three times higher than the UK. Given that most emissions are from the manufacturing process, the total emissions are expected to be further reduced due to the advancement of technologies and the greener grid electricity used for manufacture. The PBT_{CO2} closely relates to both manufacture and installation locations. Our study has shown the great potential of the CES in reducing CO_2 emission, and it is more beneficial for countries with greater proportion of fossil fuels in the energy mix. The grid carbon intensity in the UK has been decreasing over the past decades [162], suggesting that energy sector is undergoing a transition towards being more sustainable and environmentally friendly manner. The increasing renewable energy generation will further lower the grid carbon intensity and the CO_2 savings in future will be lower than that observed here.

5.3.3. Economic Assessment

Table 5-3 shows the results that the annual energy costs of households in different operation modes. When the household demand is fully grid-supplied, the energy bill for HH1 is £599.3 (TOU tariff) and £549.5 (flat tariff), while HH2 spends £1021.1 (TOU tariff) and £957.1 (flat tariff) annually. In comparison, households with a storage system can also effectively reduce the cost at least £80 by arbitrage and the increasing capacity can reduce energy costs further. Table 5-3 also suggest that the addition of PV with storage can further decrease the energy bill by at least 50%. The energy bill reduction by using PV plus storage system under the flat tariff is less than those using TOU tariff, which means the optimal design and operation of PV plus storage can be more economically attractive to customers in future, especially CES. Amongst all the combinations, both HH1 and HH4 can obtain the most costs savings by HES/CES-GC, but the HES-GC contributes a slightly lower revenue. The inter-house trading within the CES is an important revenue source, which relies upon the sharing tariff rate. It is therefore important to investigate the significance of the sharing tariff and the results are shown in Figure 5-11.

Table 5-3 Annual Energy Costs of HH1 and HH4 in Different Cases

Annual Bill (£)		**Fully Grid Supplied**		**ES under TOU**		**PV and ES Under TOU Tariff**				**PV and ES under Flat Tariff**	
House Type	Storage Capacity (kWh)	TOU Tariff	Flat Tariff	HES	CES	HES-SC	HES-GC	CES-SC	CES-GC	HES-Flat	CES-Flat
HH1	20	599	549.5	461.2	433.3	253.3	226.4	224.9	213.1	281.4	236.9
	40			401.9	257.6	213.6	159.1	180.6	157.3	242.1	201.4
HH4	20	1021	957.1	793.3	456.8	611.6	570.2	589.1	563.6	632.3	604.1
	40			869.2	694.8	560.6	473.5	534.3	464.5	598.0	556.5

The sharing tariff in the CES rate is mainly determined by the FIT and the supplier tariff. To encourage households to participate in electricity trading within the CES, it requires a competitive rate between suppliers' tariffs and subsidies. Therefore, the sharing tariff investigated ranges from 5 to 17 £p.kWh^{-1}. Figure 5-11 shows that the increasing sharing tariff leads to different results for HH1 and HH4. As a light user, HH1 tends to export more electricity to its neighbour in exchange for profits due to its excessive generation. Hence higher sharing tariffs will contribute to more revenues and bill reduction for HH1. On the contrary, HH4 consumes much more energy and the cheaper CES sharing tariff will effectively incentivise HH4 to consume less expensive supply from the CES rather than to import from the grid.

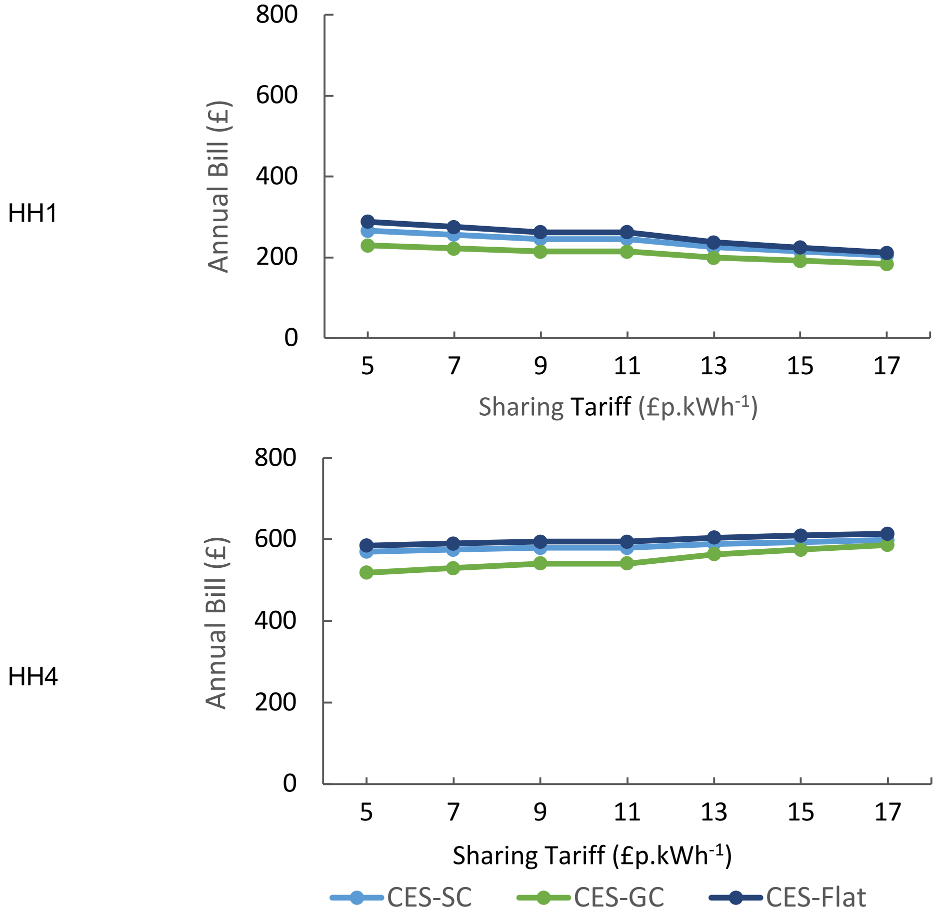


Figure 5-11 Annual Bill Charges of HH1 and HH4 with Sharing Tariff with A 20 kWh CES

As stated earlier, every household is assumed to have the same PV and annual generation. Therefore, the LCOE of PV for all the households in the community is the same, around £0.25 kWh^{-1} across its 25-year lifespan. However, the consumption variation has caused markedly different LCOSs of HH1 and HH4. Figure 5-12 shows the LCOSs of different storage options and capacities for two households. For HH1, LCOEs of HES (around £0.7 kWh^{-1}) are much lower compared to LCOEs of CES (ranging from £1.09 kWh^{-1} to £2.03 kWh^{-1}) when HH1 has a 2kWh storage. The difference becomes smaller when the storage capacity increases. When the storage with 4kWh, most LCOS of HES are around half of CES, but CES-GC turns out to be the same as HES, around £0.52 kWh^{-1}. For HH4, the overall LCOS of HES and CES are below £1 kWh^{-1} and CES is found to be the better option and CES-GC has the lowest LCOS around £0.30 kWh^{-1} and reach its lowest around £0.17 kWh^{-1} at 40 kWh. However, the LCOS is still too high for most of households except for HH4 with CES.

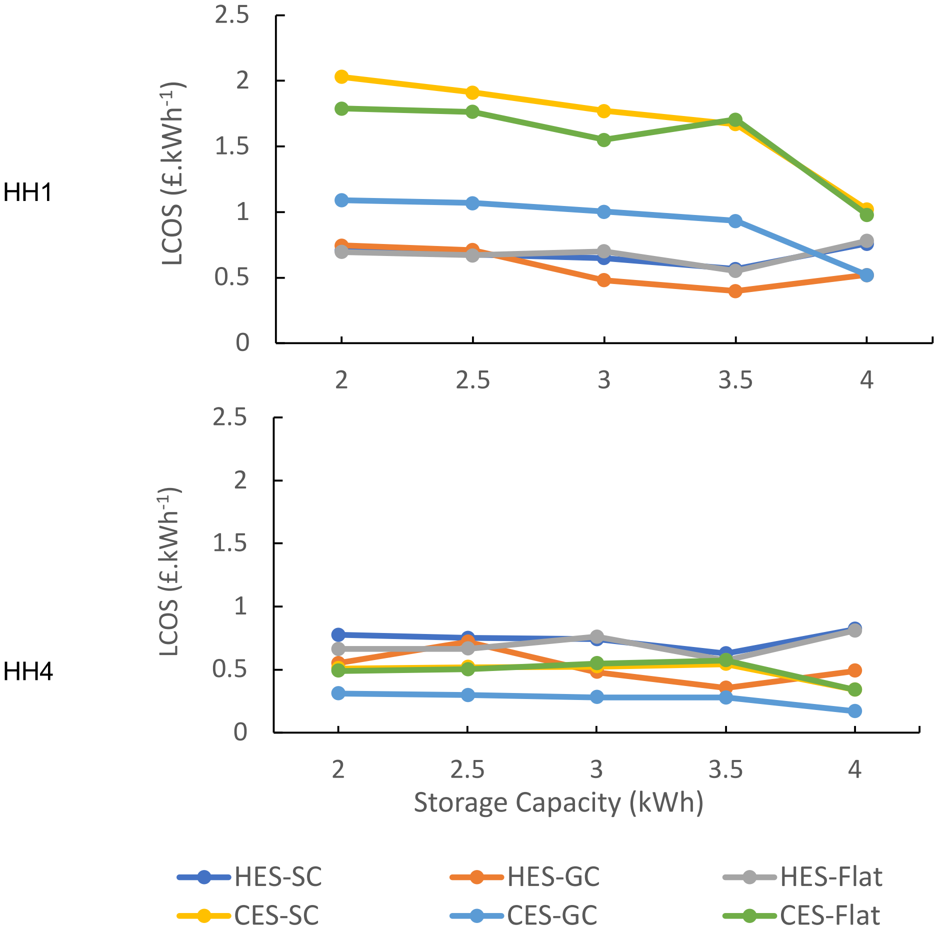


Figure 5-12 LCOS of Storage in Different Applications

Figure 5-13 shows the total profit of HH1 over 30 years. When the community has a 40 kWh CES, the breakeven time of HH1 is the shortest among all the applications, approximately 9 years when they operate to arbitrage. However, the other applications have much longer $SPBTs_{system}$, more than 28 years. The HES-Flat is found to be the least cost-effective option with a $SPBT_{system}$ longer than 30 years. In contrast, for the community with 20 kWh total storage capacity, most applications are found to have lower revenues, but the $SPBTs_{system}$ are similar to those with 40 kWh. It is certain that the addition of PV and storage can improve bill savings, but the expensive upfront investment and maintenance make it impossible to achieve payback within the lifespan. Additionally, the total cost of CES is cheaper than HES system with the same capacity. As the community investigated here only consists of 10 households, the upfront cost of CES paid by each household is expected to be lower in a larger community. Although the CES is found helpful in reducing energy costs, the profitability still remains questionable without accesses to extra revenues, such as by participating in other services, or greater cost reductions of PV and battery storage.

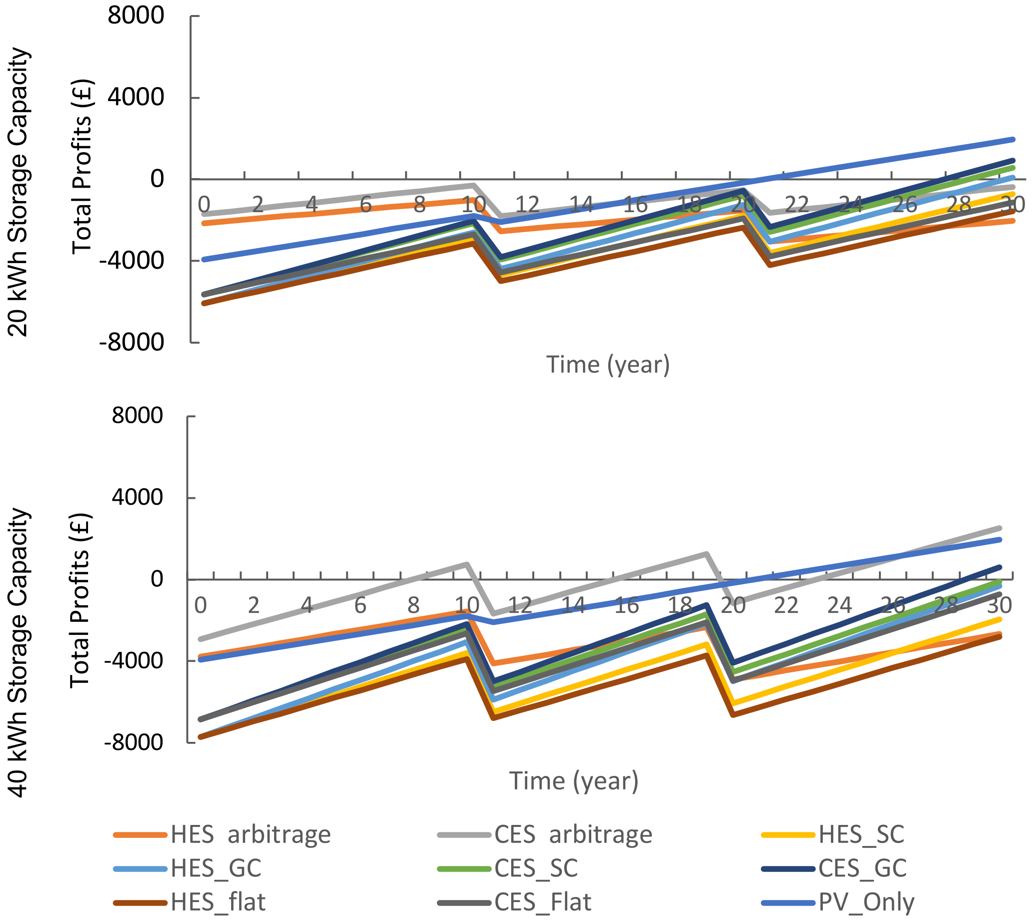


Figure 5-13 Total Profits of HH1 Over Time

Figure 5-14 shows a comparison of the $SPBTs_{system}$ of HH1 and HH4 for the PV plus storage system price in 2030 and 2040. The technology advancement and mass production will further facilitate costs reduction of PV [163] and battery systems [164]. If HH1 and HH4 operate in HES/CES-GC modes in 2030, the $SPBTs_{system}$ of HH4 are 8 and 9.5 years for PV plus CES and HES, respectively, while $SPBTs_{system}$ of HH1 are longer than 15 years. The system cost reduction is found helpful to shorten $SPBT_{system}$ and both households can payback system costs within 10 years in 2040.

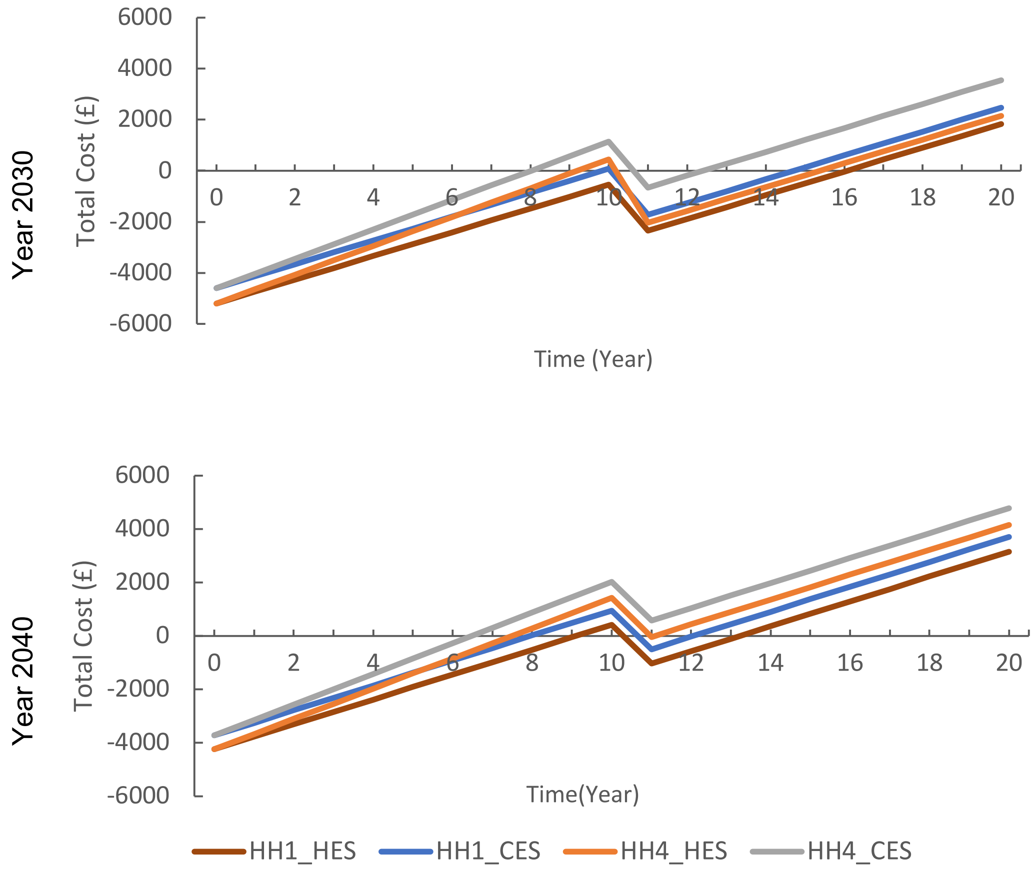


Figure 5-14 Total Profits of HH4 Over Time with Reduced System Costs

An assessment at community level is also undertaken, suggesting that the PV plus storage can effectively reduce the energy costs, but limit the application economic feasibility. The current revenues are mainly from the cost savings from reduced imports, subsidies for PV generation and exports via FIT, and the revenues from inter-house trading. However, these are not enough to payback the upfront investment and subsequent maintenance charges within the battery warranty. This means that the cost-effectiveness of HES is still questionable. The FIT scheme has stopped supporting newly commissioned projects [20] and will be replaced by the Smart Export Guarantee [165] that provides a time-dependent rate based on the actual amount of exported electricity instead of half of the total on-site generation. This further diminishes the project profitability.

Inter-house trading within CES seems to be a good opportunity to shorten the $\text{SPBT}_{\text{system}}$. To incentivise the participation of households in the CES, an attractive tariff is needed, consisting of two main components, the LCOE of PV and LCOS. According to literature, the LCOE of residential PV is around £0.13 kWh^{-1} [166] and the average LCOS of behind-the-meter Li-ion battery is around £0.47 kWh^{-1} shown in Table 5-4. Although the energy storage systems' configuration may vary from the one adopted in this study, the LCOSs of Li-ion batteries for behind the meter applications from the literature are lower than our results. The LCOS of Li-ion battery is determined by several factors, such as lifetime, capital costs, operation and maintenance cost, and charging costs. Amongst them, battery lifespan and its capital costs in Table 5-4 are better compared to the battery adopted in the study, which can potentially facilitate substantial enhancement in LCOS. Although the future advancement technologies may enable PV and storage to reduce the manufacturing costs, the total levelised costs of PV and storage are still higher than the current average and future predicted supplier tariffs. It is therefore not affordable and requires legislative support from the government and effort to further lower system costs [41].

Another solution is to obtain extra revenue by aggregating HES and CES to provide grid services. According to [167], a household with 4kWp PV coupled with a 4 kWh storage system can harvest £33.24 revenues by peak shaving over a month, compared to £5.4 for just self-consumption. For this study, the aggregator and its participation in grid services are beneficial, but unlikely to improve the feasibility significantly. Additionally, giving aggregators access to the CES will inevitably cause considerable reduction in the SCR and SSR of consumers. It is certain that the aggregation service is particularly helpful for the participants with bigger storage that can ensure enough capacity for self-consumption and flexibility used by aggregators. Although the current systems struggle to meet the requirements in this study, the combination of functions of PV and storage will play a more important role in future distributed energy systems.

Table 5-4 LCOS of Li-ion Battery for Behind the Meter Applications in Literature

Author	Lifetime (years)	CAPEX (£.kW^{-1})	OPEX (£.kW^{-1})	Charging Cost (£.kWh^{-1})	LCOE (£.kWh^{-1})
Apricum [168]	15	398	8	0.05	0.28
Jülch [169]	20	590 - 940	10 - 17	0	0.18 -0.29
Lazard [8]	10	640 - 1027	0	0.09 - 0.1	0.37 - 0.58
World Energy Council [170]	5 – 20	239 - 2948	5.6 - 59	0	0.12 – 0.56

5.4. Discussion

In this study, the community is designed to play different roles as an energy supplier, a consumer and a network operator. The expensive LCOE of PV and LCOS of the battery still represents the major obstacle for their feasibility, though the inter-house trading may be a valuable additional revenue source. However, many challenges need to be solved so that the applications investigated can be applicable.

Traditional DNOs mainly facilitate the power flow towards energy consumers. However, the increasing DERs have imposed new challenges on distribution networks [171], such as voltage deviation, line losses, system balancing and reserve issues. Demand response is capable of mitigating these influences, which is usually carried out by large scale industrial and commercial companies. The increasing demand and renewable supply will impose stress on already constrained networks, which requires reinforcement and costly network expansion, but there are much cheaper alternatives to solve the issues. This study suggests that solutions can be undertaken on the near-user side, where the HES and CES have shown their flexibility and capability of peak reduction. Alternatively, aggregators can provide an important route to market for demand response, which groups a variety of small customers or a community as a single entity to engage in energy markets with their DERs [172]. The storage is an essential component of aggregation due to its flexibility and its potential for deployment at various scales and providing a variety of services. Efforts have been made to enhance the regulatory clarity and provide a great environment to encourage more storage applications, such as clarifying the definition of storage [173], levy exemption [173], ownership [73], and network connection [174]. However, many questions and ambiguities still need to be answered and clarified, such as the role of independent aggregators [175], and access to the balancing market [83].

In this research, the households and community act as both energy consumers and suppliers. The inter-household trading, or peer-to-peer (P2P) trading, refers to one or a group of local energy customers, including generators, consumers and prosumers, who can exchange energy directly with each other without intermediation by conventional energy suppliers [176]. However, in the UK the energy system is still based on households buying energy from suppliers and the current regulation only allows customers to have one licensed supplier who manages all the energy transactions. This limits consumers' control over how to reduce costs other than to shop around for better deals. The emergence of P2P trading has imposed a challenge that will weaken the established relation between consumers and conventional utilities [177]. However, the access to multiple suppliers will make the billing process trickier and is dependent on whether the current metering facilities can accurately monitor the consumption data. A further issue is how to settle the reimbursement, since the inter-house trading can harvest more profits than exporting the surplus PV energy to suppliers. Similarly, the inter-household trading and CESM require significant amount of consumption and generation data of households. The smart meters in domestic properties and small business entities can potentially provide a platform for the trade settlement [178], but its capability of tracking all the required data is still unclear.

5.5. Conclusion

Several operational strategies for different purposes are proposed in this study. The communities with HES and CES are simulated with various system configurations and a multi-criteria assessment is undertaken at community and household levels, respectively. The results suggest that a flat Tariff can contributes to better usage of on-site generated PV electricity. The TOU tariff is helpful to shave peak demand, but it also leads to marginal SSR drops and increasing PV curtailment. Under a TOU tariff, the TOU-GC can improve the usage of battery when PV generation is insufficient, although it cannot enhance SCR and SSR. All the cases included are environmentally beneficial, especially for energy intensive consumers. Although manufacturing location plays an important role in $PBTs_{CO2}$, all the cases investigated in this study can pay back the total CO_2 emission within 8 years.

The economic analysis suggests the TOU Tariff can save households at least 20% energy costs compared to flat tariffs. Amongst all operational strategies, the best is found to be TOU-GC, which is capable of saving up to 60% costs and most applications are unlikely to recover their upfront investment within the lifetime due to limited cost savings and revenue sources. The LCOE of PV (£0.25 kWh^{-1}) and LCOS of HES (£0.4 ~ £0.81 kWh^{-1}) and CES (£1.09 ~ £2.03 kWh^{-1}) are beyond households' affordability, which requires more innovative ways to enhance profitability and feasibility. The CES is found to be the better option, as the inter-house trading can contribute to additional revenues for households and significant reduction in peak demand. The CES is proven to be the better alternative for both household and DNOs.

It is certain that the addition of PV plus storage and TOU Tariffs are beneficial to the households and DNOs, particularly CES. However, as stated earlier, the economic feasibility still remains the biggest issue, which needs further changes and improvements in several aspects. Firstly, combining multiple functions and tariffs will become increasingly critical for residential PV plus storage applications so that the project can be profitable. Secondly, legislative and financial supports need to be in place to ensure DERs are financially accessible to domestic consumers. Thirdly, a comprehensive legislative and financial environment should be established for inter-house trading to encourage the households and local business entities to participate in balancing local energy demand and supply. Finally, traditional utility companies and suppliers require more innovative solutions to ensure variety and feasibility of their business models to encounter the challenges brought by the distributed energy system, and ultimately encourage efficiently energy use, prolong the lifespan of extant networks and optimise revenues with existing resources.

Chapter 6 DE vs UK Case Study

6.1. Introduction

Chapter 5 identified the advantages of CES for communities and end-users, and also addressed the significance of realising the value of inter-house energy trading within the CES network. However, key regulatory frameworks and schemes are still yet to be in place, which requires a clear guidance on the ownership and operation of the CES. The results from previous two chapters have addressed the value of CES and the significance of financial support and costs reduction in batteries. There has been significant research on comparing the performances and identifying the key impacting factors in different countries. It is important to investigate and compare CES in the UK with a country that has a well-established solar and energy storage development, such as Germany. This chapter aims to compare and analyse the performances of the HES and CES in the UK and Germany (DE) so that the key impacting factors can be identified and hence improve the economic feasibility of future applications in the UK.

The main results from this chapter were published in:

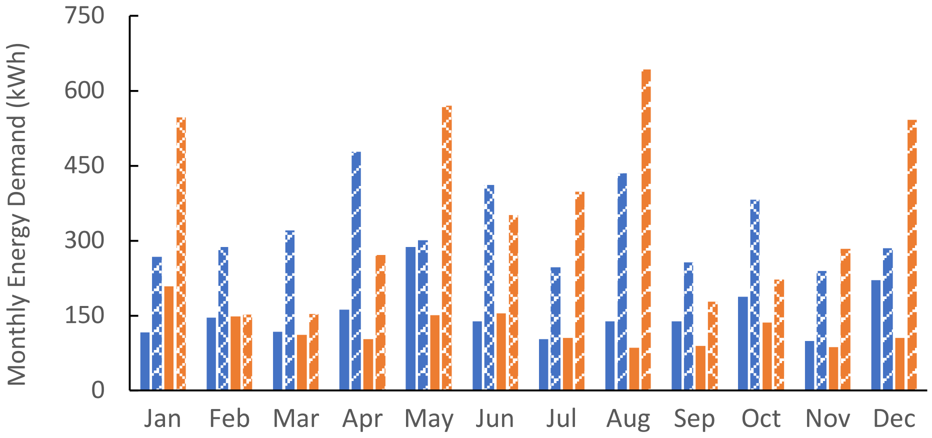
- **Dong, S.,** Kremers, E., Brucoli, M., Rothman, R. and Brown, S., 2021. Establishing the value of community energy storage: A comparative analysis of the UK and Germany. *Journal of Energy Storage*, *40*, p.102709.

6.2. Data Input

The demand data adopted in this chapter is described in Section 3.3. Five different types of load profiles representing typical households in DE and UK are chosen. The household types and corresponding annual energy consumption are shown in The load profiles of Germany are obtained in a similar method. The profile generator developed at the Technical University Chemnitz [127] can simulate the behaviour of the residents based on a demand model, and includes operation patterns for electrical devices. The complexity and detailed consumption patterns are extremely useful for the ABM used in this study. The load profile is calculated by adding up the energy use of each device of a chosen predefined household. Five different types of households in Germany are chosen to represent the household diversity.

Table 3-1. For the analysis, two households are chosen to represent light and heavy energy users for each country. CHR19 and HH2 are chosen to represent the intensive consumers, while CHR29 and HH0 are selected as light energy users. Their monthly and annual energy demand are shown in Figure 6-1.

a)



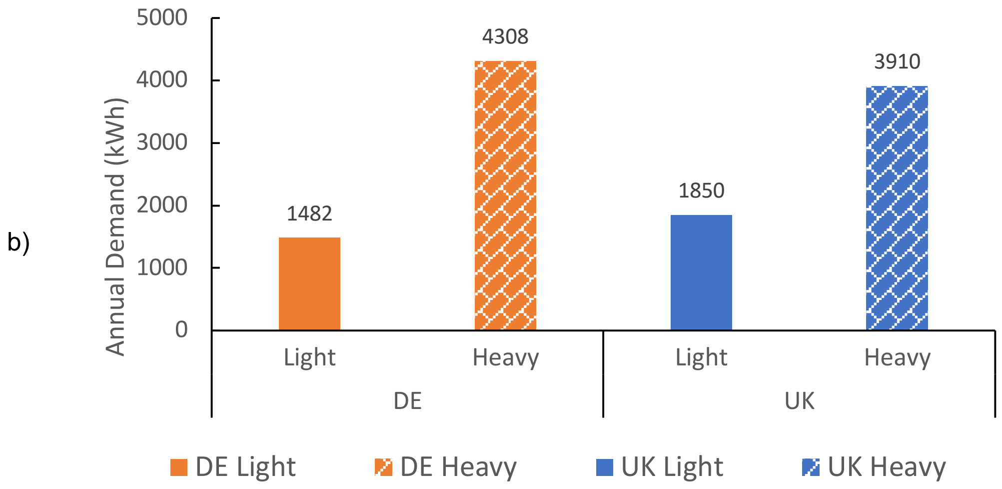


Figure 6-1 Monthly and Annual Demand of Light and Heavy Users in the UK and Germany

German PV data is based on a measured time series in Southern Germany in 15 min time slots for the year 2013 [130]. UK Solar radiance data is obtained from the Microgen Database developed by Sheffield Solar [129]. As mentioned previously, all the households are assumed to install a 3 kWp rooftop solar panel with a different Li-ion battery capacity. The PV panel is assumed to have a 25-year lifespan, while the Li-ion battery has a 10-year lifespan. Both PV and Li-ion battery are assumed to share the same annual discount rate, 5% and total maintenance cost around £50 per year. Hence the difference in PV production can only be attributed to geographical reasons. Figure 6-2 illustrates the monthly PV production in the UK and DE.

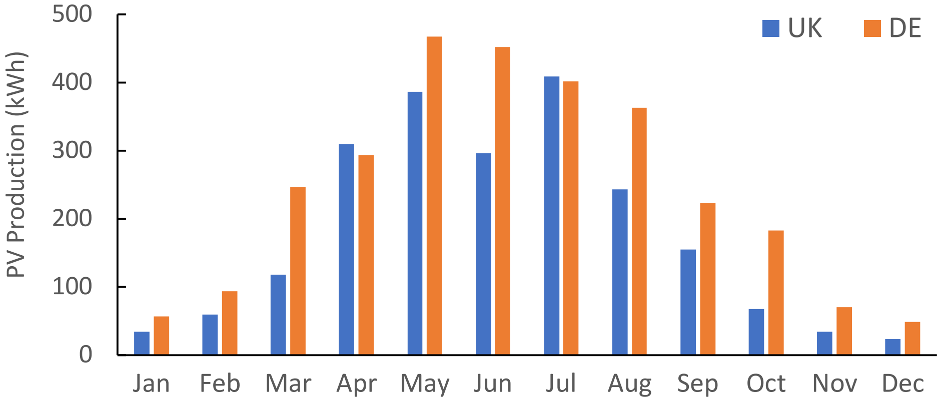


Figure 6-2 Monthly Production from a 3kWp PV in the UK and DE

The FIT scheme is a programme widely introduced around the world, including UK and Germany. Table 6-1 shows the monthly FIT rates for both UK and Germany in pence (1€ = £0.85).

Table 6-1 FIT Rates for the UK [71] and DE [179]

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
FIT Rates ($£p. kWh^{-1}$)	**DE**	9.75	9.65	9.55	9.44	9.31	9.17	9.04	8.91	8.78	8.65	8.57	8.47
	UK	3.79	3.79	3.79	3.79	3.79	3.79	3.79	3.79	3.79	3.79	3.79	3.79

Global electricity prices have increased in the past decade. In Germany, retail electricity prices are amongst the highest in Europe [55], resulting from the increasing costs of renewable energy source (RES) technologies and the continuous support for national energy transition [180]. In recent years, whole electricity price prices have on average declined, but the bill rises with other charges, such as surcharges, taxes and network costs. The electricity tariff in Germany is around £0.302 kWh^{-1}. The electricity tariffs in the UK are relatively high in the Europe, at £0.186 kWh^{-1}, but lower than Germany. The UK has a low absolute contribution from taxes and levies of around 20%, while the energy and supply component makes a great proportion of the total UK electricity price [181]. In the UK, electricity production still heavily relies upon traditional fossil fuel sourced generation, and hence the UK's electricity price is in line with global coal and gas price changes. The addition of carbon price on the top of EU Emission Trading System price further increases the generation costs of energy suppliers [182]. Therefore, it further increases the wholesale price and make it the largest share of the UK's domestic electricity price.

In the past few years, with the public endorsement of smart homes and the regulator's desire to mandate more accurate settlement for electricity users, TOU tariffs are becoming increasingly popular. In the UK, GreenEnergy was the first energy supplier offering a three-tier TOU tariff called TIDE, as shown in Table 6-2 [154], providing a three-tier tariff during weekdays and two-tier tariff during weekends. In Germany, there is a variable tariff introduced by aWATTar to the market [183] in which electricity tariff rate varies with the wholesale energy price [184] on hourly/half-hourly basis so that it enables consumers to shift their consumption more freely to reduce their energy bill. More details regarding the tariff are shown in Table 6-3.

Table 6-2 TIDE Tariff in the UK

Tariff Name	Day	Time	Electricity Price (£.kWh^{-1})	Standing Charge (£.day^{-1})
TIDE Tariff [154]	**Weekdays**	00:00 – 06:59	0.09	0.32
		07:00 – 15:59	0.16	
		16:00 – 19:59	0.32	
		20:00 – 23:59	0.16	
	Weekends	00:00 – 06:59	0.09	
		07:00 - 23:59	0.16	

Table 6-3 aWATTar Tariff Information [183]

Parameter	Price	Unit
Basic Price	EPEX Spot DE + 0.21	£.kWh^{-1}
Maximum Basic Price	0.17	£.kWh^{-1}
Minimum Basic Price	-0.17	£.kWh^{-1}
Network Usage	0.05	£.kWh^{-1}
Levies, Duties, Taxes	0.11	£.kWh^{-1}
Measuring Point Operation	0	£.kWh^{-1}
Monthly Connection Charge	10.8	£

Other economic values and environmental parameters adopted in this Chapter are shown in Table 6-4 and Table 6-5.

Table 6-4 Economic Values Adopted in This Chapter

Parameter	Value	Unit
Li-ion Battery [132]	570	£.kWh^{-1}
Li-ion Battery Lifespan [132]	10	Years
Battery Inverter [157]	500	£.kWh^{-1}
Battery Casing [132]	293	£
PV inverter [158]	500	£.kWh^{-1}
Solar Panel [159]	0.4	£.Wp^{-1}
Solar Panel Lifespan [159]	25	Years
Solar Optimiser [159]	0.25	£.Wp^{-1}
PV mounter [159]	328	£
Accessories [159]	150	£
O&M Cost [159]	50	£.year^{-1}
Discount Rate [160]	5	%.year^{-1}

Table 6-5 Environmental Parameters Adopted in This Chapter

Parameter	Value	Unit
Grid Carbon Intensity of the UK [161]	0.26	kg.kWh^{-1}
Grid Carbon Intensity of Germany [185]	0.49	kg.kWh^{-1}
Grid Carbon Intensity of China [148]	0.84	kg.kWh^{-1}
CO_2 Emission During Inverter Manufacture [137]	12.03	kg.kWh^{-1}
CO_2 Emission During PV Manufacture [138]	865.44	kg.kWh^{-1}
CO_2 Emission During Battery Manufacture [137]	175	kg.kWh^{-1}

6.3. Assessment Results

6.3.1. Technical Assessment

6.3.1.1. Assessment at Community Level

Figure 6-3 compares the technical performances of communities with different operating modes. It is obvious that the energy savings are directly linked to PV production, where more energy imports can be avoided by on-site generated PV electricity in Germany than the UK, especially with a storage system. In contrast, for communities without a storage system, the UK can save more energy than Germany, which means that the majority of energy saving is from direct self-consumption. This may be because the energy of UK communities is consumed during the time of PV production, effectively lowering the export of surplus electricity, while the majority of energy in Germany may be consumed after production. This is also supported by the growth in energy savings with increasing storage capacity. For the German community, an extra 2 kWh per household can contribute to nearly 5800 kWh energy savings and almost 30% higher SCR and SSR respectively, compared to approximately 2600 kWh extra saved energy in the UK. A battery storage system is therefore more useful for German users compared to households in the UK. In addition, the CES in both countries tends to have higher SCR and SSR, especially when CES operates under the Flat tariff. The higher average SCR in the UK suggests that the community can make slightly more efficient use of PV-sourced electricity, while higher average SSR of a German community indicates that more demand can be met by the local generation. Considering the difference in the annual community demands of the two countries, the addition of a storage system to the existing PV is certainly more beneficial for the German community, especially with CES.

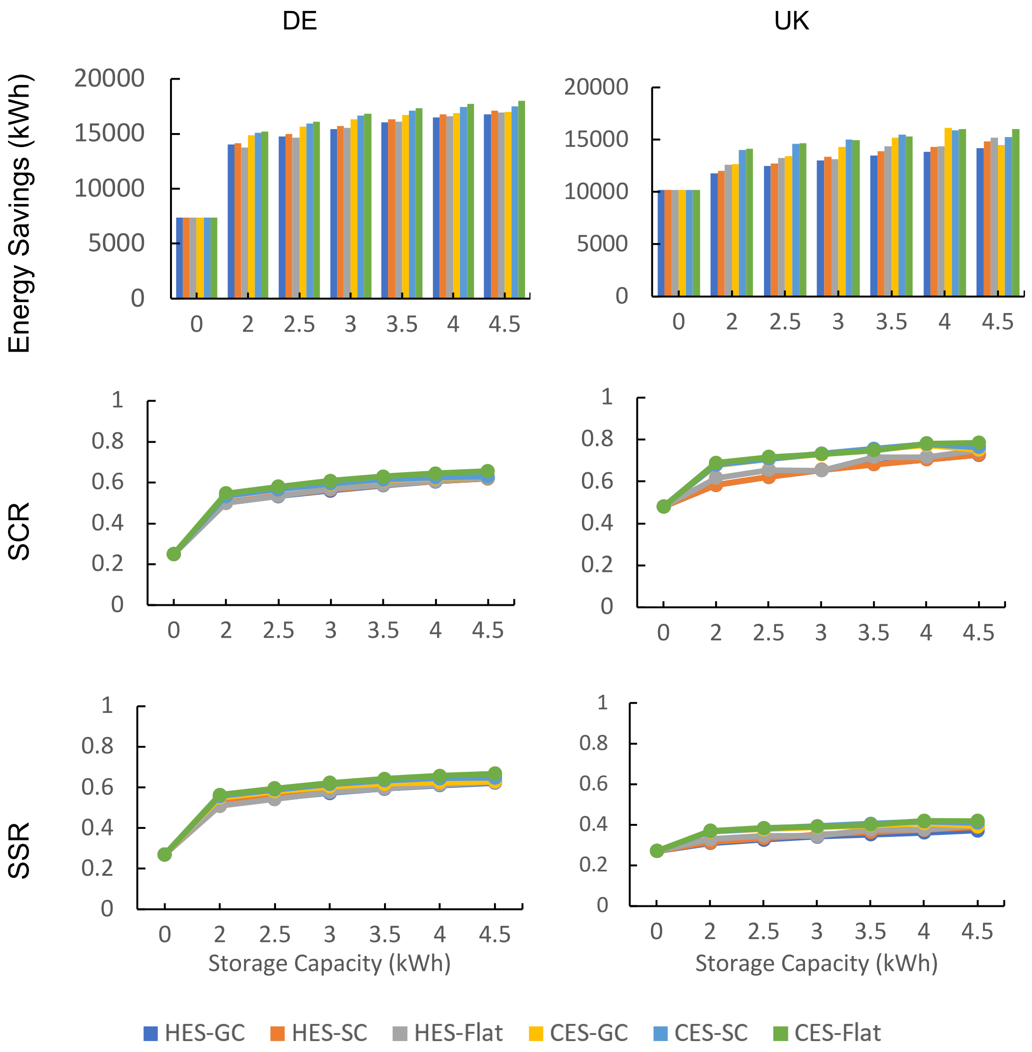


Figure 6-3 Comparison of Communities' Annual Performances of DE and UK

Figure 6-4 compares the monthly SCR and SSR of a community with 30 kWp PV and 30 kWh storage under various operational modes. Both SCRs and SSRs vary with the season, where the SCRs are around 1 in winter and become relatively low during summer, around 0.5. The SCRs of the UK community are similar to the German community, though SCRs fluctuate slightly in summer. Regarding the SSR, sufficient PV generation in Germany contributes to higher overall SSRs, much higher than the UK. For example, the SSRs reach the lowest in January during the whole year, but the SSRs of the German community are around 0.2, while the UK community is around 0.1. When it comes to summer, the German community can be highly self-sufficient and SSRs are around 0.9, but the SSRs of the UK community are approximately 0.75. Additionally, the operation strategies seem unlikely to markedly influence the community, regardless of a marginal difference in the summer. Overall, the community performances are predominantly determined by the PV generation, however the type of storage becomes increasingly important with limited generation. Therefore, the installation of CES in the UK is more beneficial than in Germany.

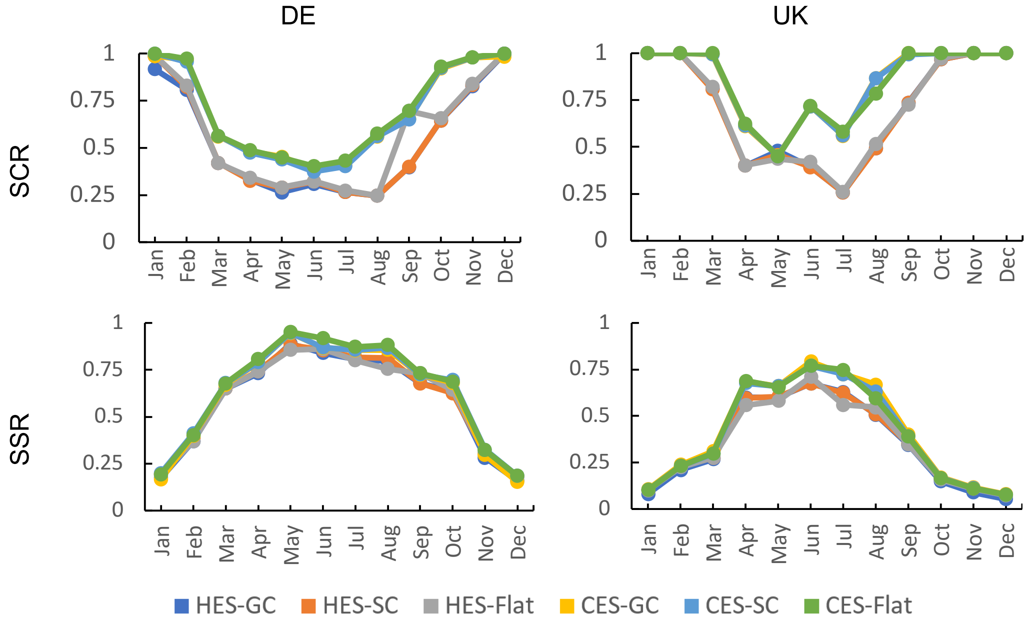


Figure 6-4 Monthly SCR and SSR of a Community with 30kWp PV and 30 kWh Storage

As shown in Figure 6-4, SSRs of communities are around the highest in June across the whole year and the German and UK communities have similar monthly energy consumption in June. It is therefore helpful to look into daily power flows and identify the differences of two communities. As shown in Figure 6-5, the DE community produce higher average PV electricity compared to UK community, although both communities have the similar peak output power, around 20 kW. The community in southern Germany can produce PV power for longer time compared to the UK community, which enables the CES in DE community to be more self-sufficient. In contrast, HES-Flat also can contribute to high SSRs of communities, but the community can be markedly self-supplied when connecting to CES. In this way, it is obvious that the CES is more advantageous and beneficial compared to HES, especially with sufficient local PV generation.

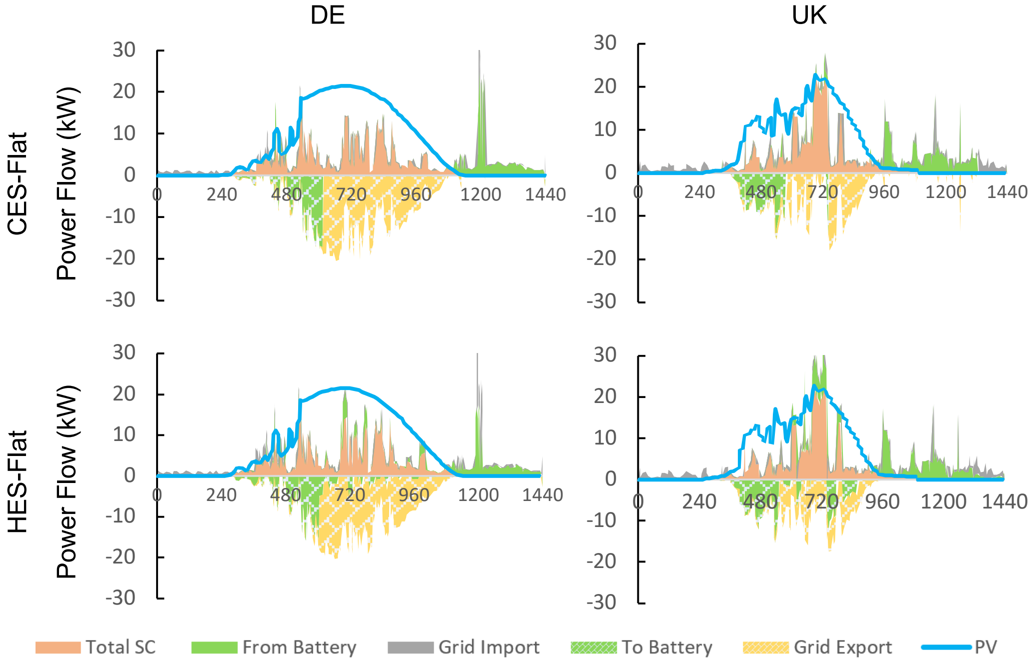
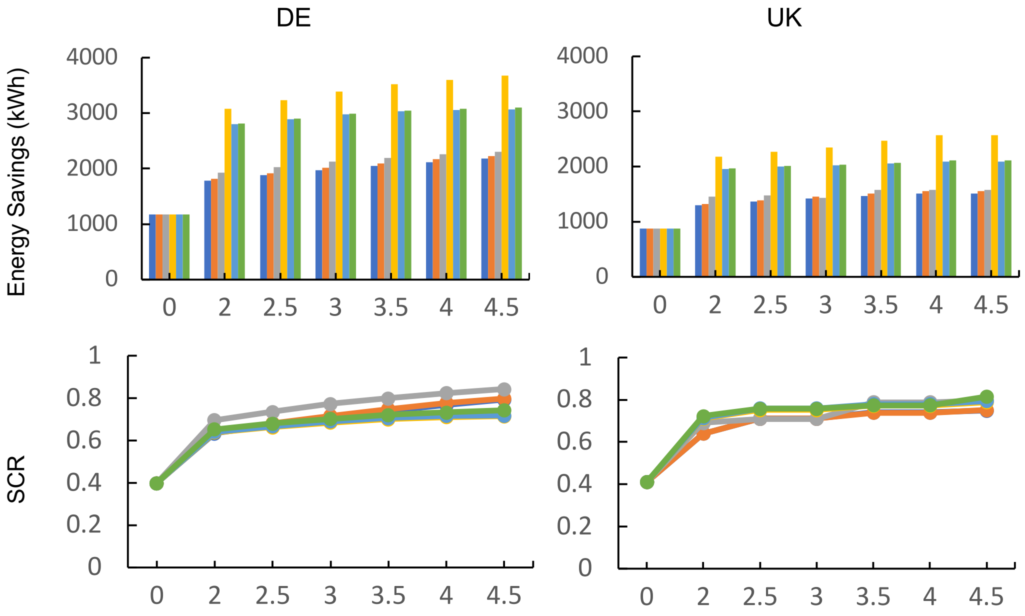


Figure 6-5 Power Flow Profiles of UK and DE Communities in June

6.3.1.2. Assessment at Household Level

Figure 6-6 shows the comparison of heavy users in DE and UK and how the addition of a storage system contributes to significant energy savings compared to those without storage. The minimum annual energy savings of a heavy consumer in Germany is 1780 kWh, which equals the maximum energy savings of the UK household. For heavy users, it is obvious that CES can make more effective utilisation of PV electricity than HES, while in the UK the opposite trend is seen. However, the differences in the SCR for both countries are marginal. Regarding the SSR, though the heavy users in both DE and UK benefit more from CES, the DE households can supply more demand locally compared to the UK, and the highest SSR can achieve 0.85 when connecting to a 45 kWh CES working under CES-GC mode. However, it is important to address part of the energy saving from CES-GC mode is by using cheap grid-imported electricity stored in the CES. In this way, the CES-GC does not necessarily reduce the total grid import, but the benefits can be harvested economically that will be presented later.



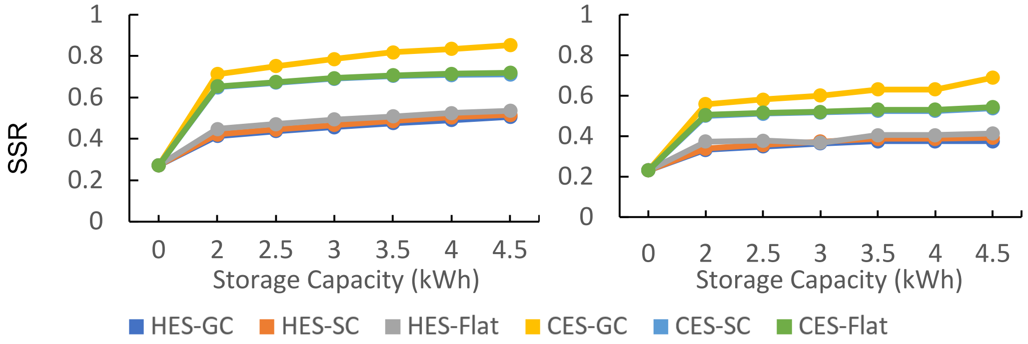


Figure 6-6 Comparison of Heavy Users' Annual Performances of DE and UK

Figure 6-7 shows the monthly SCR and SSR of heavy users with 3 kWp PV and 3 kWh storage, which are similar to the trend described previously in Figure 6-6. Heavy users in both countries can make relatively efficient use of PV production, but the DE user with HES can utilise more PV electricity compared to the UK users. Although SSRs of DE and UK users are high, DE heavy user with CES can even reach 0.97 SSR during summer, much higher than using HES and all the cases of UK users.

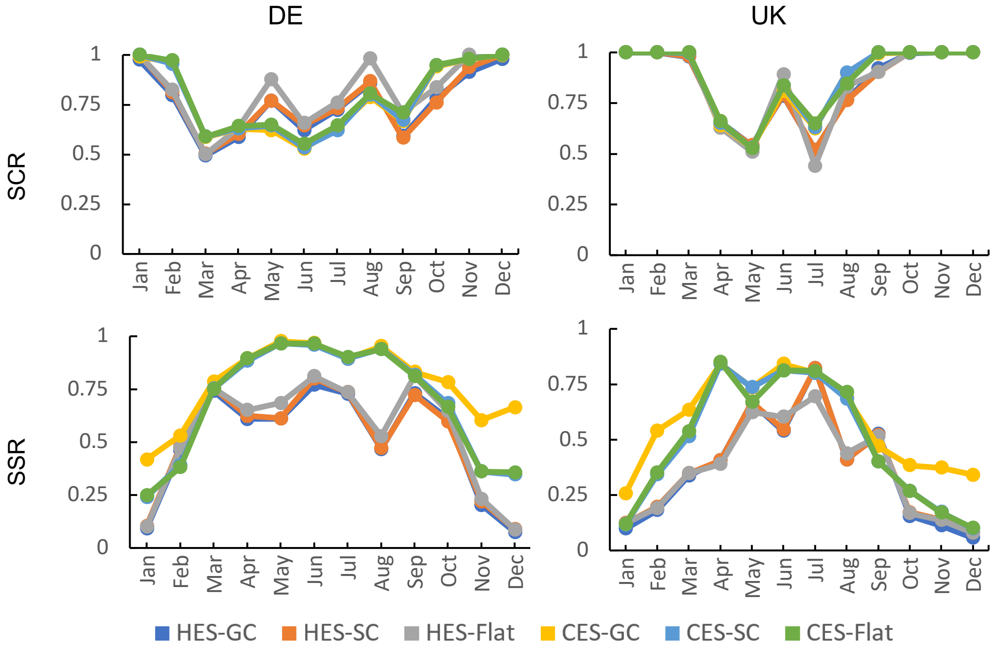


Figure 6-7 Monthly SCR and SSR of Heavy Users with 3kWp PV and 3kWh Storage

Figure 6-8 shows the energy savings of light consumers, around 1000 kWh, are significantly less even after the installation of a storage system compared to heavy consumers. The UK users have an obvious divergence that CES is much higher than HES regardless of the operation mode. For the DE light user, CES-Flat achieves the highest SCR because the majority of the PV production is exported to supply the neighbours that also connect to the CES, and the difference in SCRs of each operation modes are very noticeable. This is because the German light users curtail more energy compared to their UK counterpart. More PV production and lower demand therefore collectively contribute to the higher SSR of the DE light users. Figure 6-9 shows the monthly SCR and SSR of light users with 3kWp PV coupled with 3 kWh storage. The SCRs and SSRs mirror the findings in Figure 6-8.

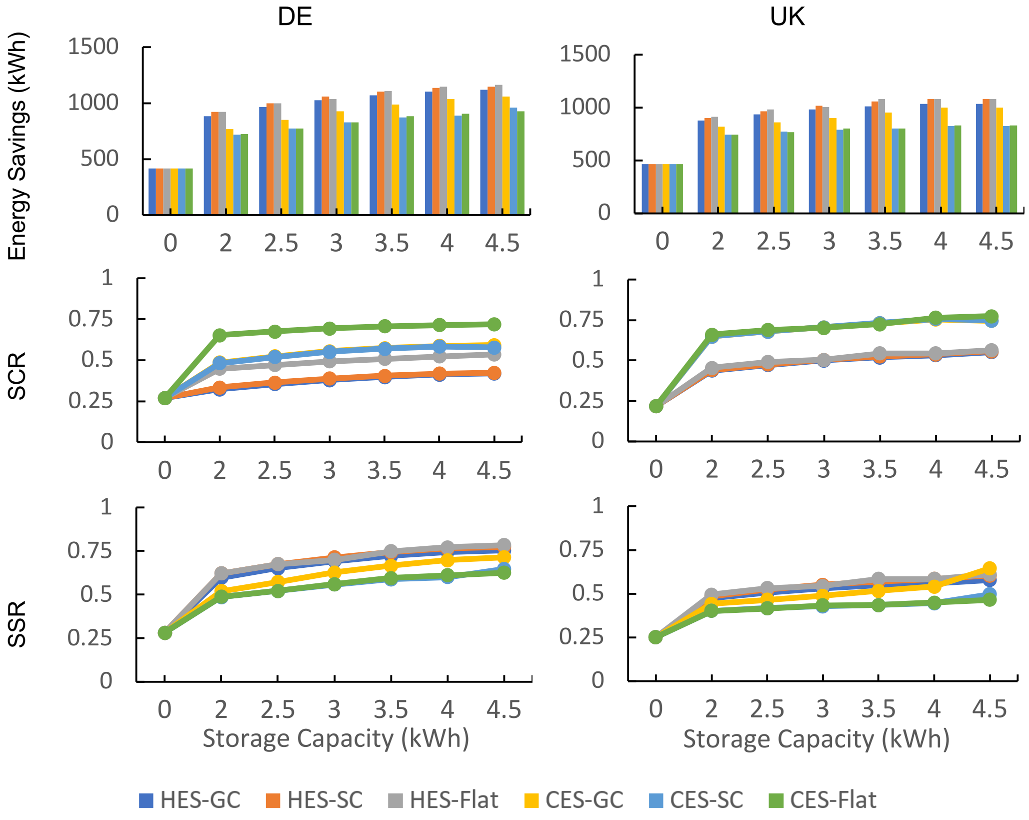


Figure 6-8 Comparison of Light Users' Annual Performances of DE and UK

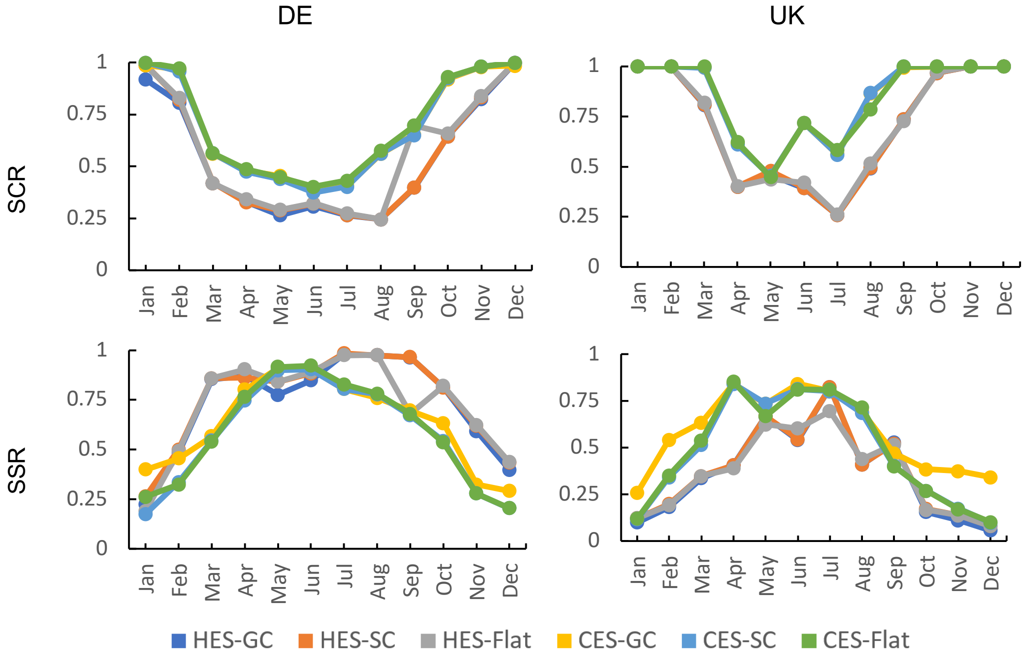
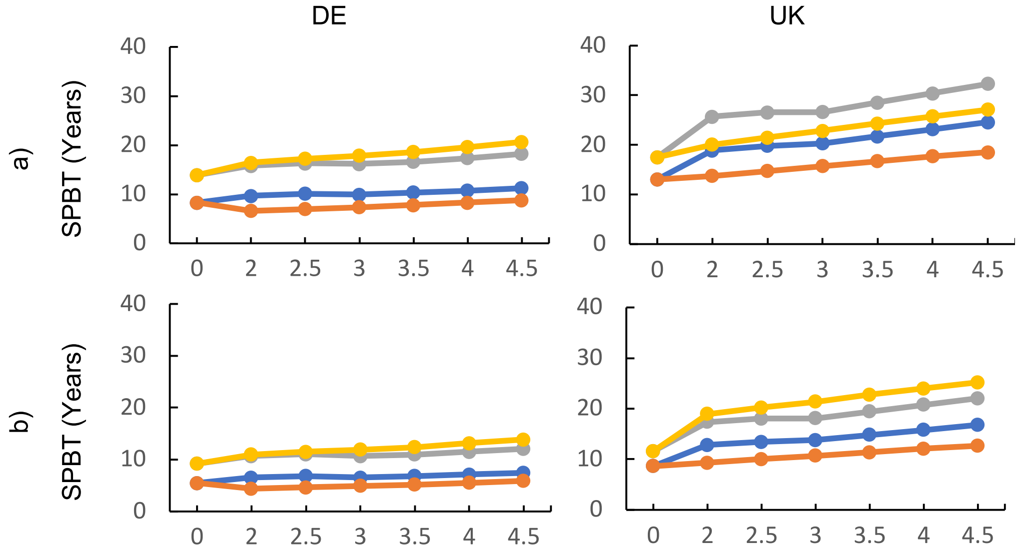


Figure 6-9 Monthly SCR and SSR of Light Users with 3kWp PV and 3kWh Storage

The solar resource is the primary factor affecting system performance. The SSRs and energy savings of DE communities and users are much higher than their UK counterparts, while the SCRs of UK communities and users are higher due to the higher direct self-consumption and less curtailment. In addition, CES is found to be the optimal option for both countries, as it enables the communities to supply a considerable consumption locally and effectively extend the self-sufficient duration, especially with sufficient solar production. For households, CES is suitable for intensive users while HES is better for light users. Additionally, HES/CES-Flat can operate the battery more frequently, and hence more energy savings, SSRs, SCRs can be achieved. However, some operational strategies may not contribute to significant technical improvements, but the communities and households benefit from them economically, as presented in the next section.

6.3.2. Economic Assessment

As stated earlier, SPBT, LCOE and LCOS are used to indicate the economic feasibility of the systems. Figure 6-10 shows the SPBT of the systems for both heavy and light users in Germany and the UK when they adopt flat tariffs. It is obvious that the SPBTs of DE users are much shorter. In Year 2020, the SPBTs of heavy users in DE can payback the initial capital investment within 10 years, while light users can only pay back upfront costs between 13 and 20 years. In contrast, the SPBTs of users in the UK are much longer, up to 32 years. According to [164], the costs of residential energy storage technologies will reduce by 35% and 50% compared to the current price. In this way, the estimated SPBTs of households installing the systems with the same specifications in Year 2030 and 2040 are also included. As shown in Figure 6-10, the cost reduction can effectively shorten the SPBT. Both light and heavy users in Germany can payback the system within 10 years, and heavy users can even payback a HES/CES at 4.5 kWh within 5 years. Compared to the users in the UK, the SPBTs are reduced to below 20 years while the heavy users connecting to the CES can even recover the initial investment within 10 years.



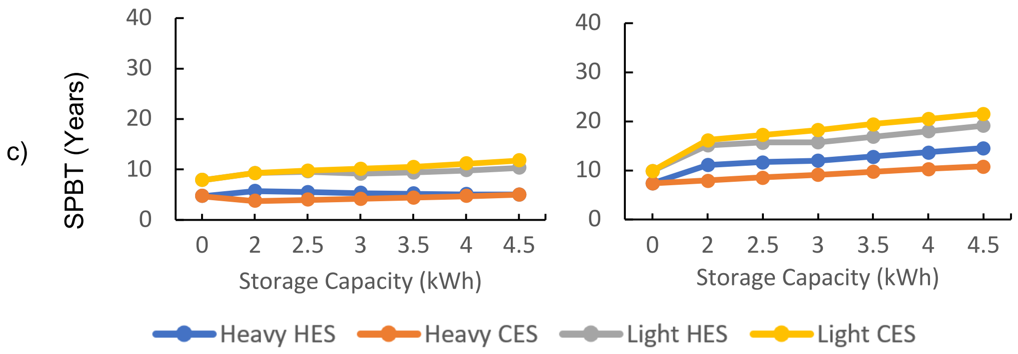


Figure 6-10 SPBTs for Heavy and Light Users in Year a) 2020, b) 2030 and c) 2040

In the study, it is assumed that the PV have a lifespan of 25 years and the battery storage system can operate for 10 years. Due to the same configuration of PV, the LCOE of PV in UK is £0.16 kWh^{-1} compared to £0.12 kWh^{-1} in Germany. Figure 6-11 shows the LCOS of HES and CES at different capacities. It is clear that the LCOSs are still quite high at the moment, even for Germany. For example, in Figure 6-11 a), the LCOSs of light users are above £0.6 kWh^{-1}, while the heavy users with HES has the lowest LCOS around £0.5 kWh^{-1}. In contrast, the LCOSs of all the UK households are higher than £0.6 kWh^{-1} and it even reaches £1.1 kWh^{-1} when the capacity is 4.5 kWh. After a significant cost reduction, the LCOE of PV manages to reduce to £0.07 kWh^{-1} (DE) and £0.1 kWh^{-1} (UK) respectively in 2040. In in Figure 6-11 c), the LCOSs of DE users are below £0.34 kWh^{-1}, even the light user with 4.5 kWh HES can achieve a much lower LCOS at £0.33 kWh^{-1}. Though the LOCSs of the UK users are not as low as DE users, the LCOSs for light and heavy consumers are lower than £0.46 kWh^{-1}, which are much lower than 2020.

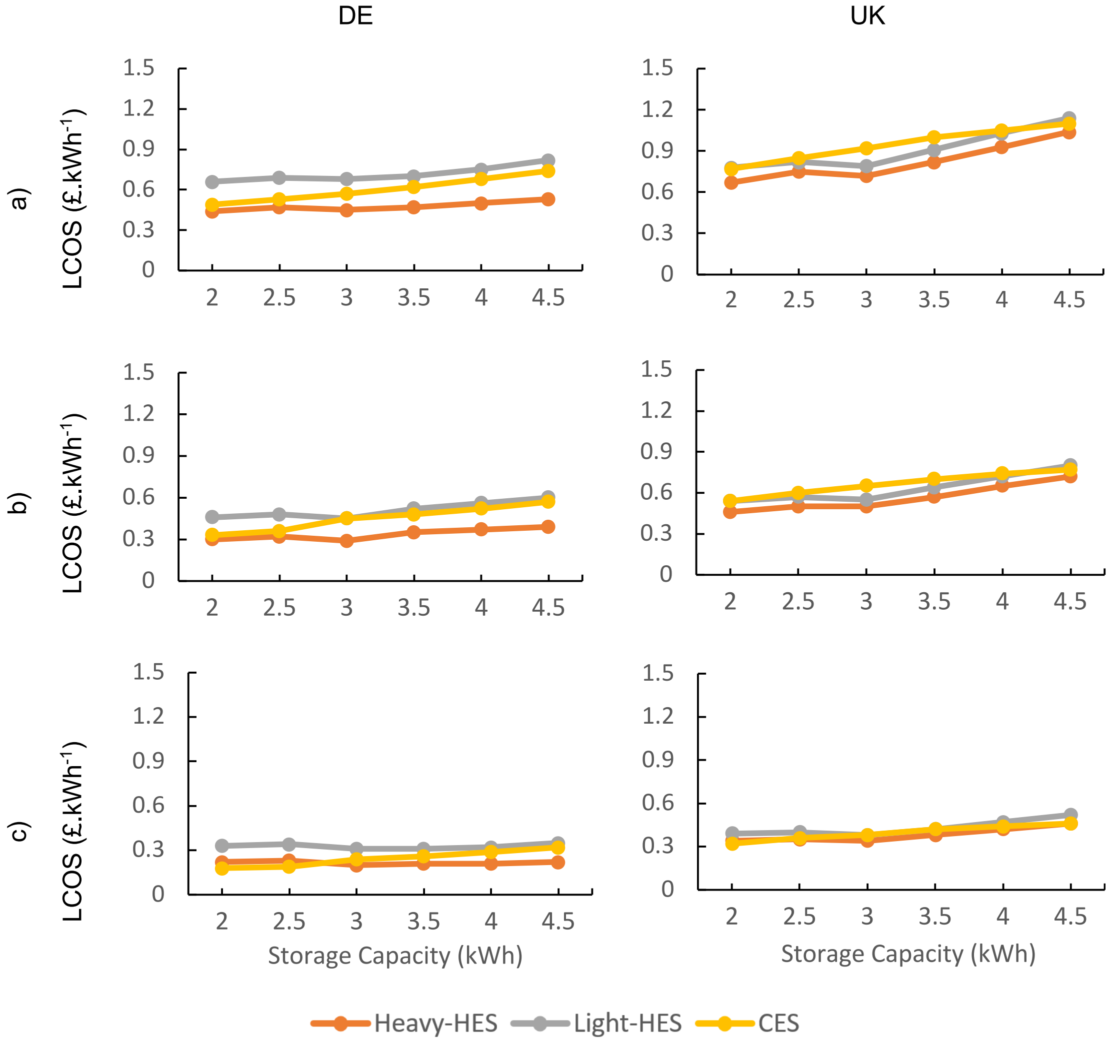


Figure 6-11 LCOS for Heavy and Light Users in DE and UK Year a) 2020, b) 2030 and c) 2040

Table 6-6 compares the LCOSs of heavy energy users with 3kWh storage system under various operation strategies. The LCOSs of DE users range from £0.38 kWh^{-1} to £0.58 kWh^{-1} much lower than those of UK users. When the HES operate under HES-SC mode, the design of this strategy is to reduce the energy bills at the costs of more PV curtailment and less battery operation. The HES-GC mode enables UK heavy users to charge electricity from the grid when there is not enough PV production, which increase the use of battery and hence lower the LCOS around £0.51 kWh^{-1}. In contrast, the DE households have lower LCOSs compared to UK users, but they are still beyond £0.38 kWh^{-1}. Additionally, in order to incentivise the installation of storage, many financial supports for storage are provided. The Bavarian state government provide €500 for a storage system at least 3kWh and further €100 for each additional 1kWh storage capacity to a maximum of €3200 [186]. The impact of the subsidy for storage is apparent and the LCOSs of a 3.5 kWh HES are around even cheaper than a 2.5 kWh, which are almost around half of the LCOSs of UK users' HES.

Table 6-6 LCOSs of Heavy User with 3kWh Storage in DE and UK

Capacity (kWh)	**DE**			**UK**		
	HES-GC	**HES-SC**	**HES-Flat**	**HES-GC**	**HES-SC**	**HES-Flat**
2	0.45	0.52	0.44	0.52	0.76	0.65
2.5	0.46	0.54	0.47	0.52	0.79	0.68
3	0.41	0.50	0.45	0.51	0.82	0.86
3.5	0.38	0.47	0.47	0.51	0.86	0.78
4	0.43	0.54	0.50	0.51	0.91	0.85
4.5	0.45	0.58	0.53	0.51	0.94	0.91

Table 6-7 shows the LCOSs of CES with different capacities under various operation strategies. The increasing capacity contributes to higher LCOSs, but the CES-SC and CES-Flat have significantly higher LCOSs than other cases. For the CES in Germany, the sufficient PV production can ensure an effective operation of the CES, even if the charging/discharging process of the CES is triggered after the instantaneous inter-house surplus energy trading. In comparison, the LCOSs in the UK are much higher, unless the storage system can charge from the grid, but it does not necessarily reduce the energy bills for the users. Therefore, more alternatives are needed to further reduce the LCOSs.

Table 6-7 LCOS of 30kWh CES Operating in Different Modes in DE and UK

Capacity (kWh)	DE			UK		
	CES-GC	**CES-SC**	**CES-Flat**	**CES-GC**	**CES-SC**	**CES-Flat**
20	0.42	0.52	0.49	0.46	0.75	0.77
25	0.43	0.56	0.53	0.48	0.82	0.85
30	0.44	0.60	0.57	0.48	0.89	0.92
35	0.47	0.65	0.62	0.49	0.95	1.00
40	0.50	0.72	0.68	0.50	1.00	1.05
45	0.54	0.78	0.74	0.52	1.01	1.10

It is certain that heavy users can harvest more energy cost savings by installing a PV panel and type of battery storage system, especially in Germany. The expensive electricity tariff and sufficient solar radiance are more likely to incentivise households to install distributed generation technologies to mitigate the reliance upon the grid. In addition, though the FIT in Germany is lower than before, the current rates are still high enough to encourage PV generation, in contrast to the UK. The expensive costs of PV and battery packs have been widely recognised as the main obstacles worldwide. There are some legislative and financial support provided to enhance the accessibility of energy storage to domestic users, but it still needs more alternative solutions to strengthen the profitability.

6.3.3. Environmental Assessment

The environmental impacts of the solar plus storage are investigated in this section. Figure 6-12 shows the annual carbon avoidance by the two communities. The amount of carbon can be avoided by a household in Germany ranges from 1433 - 2591 kg.year^{-1}, compared to that of a UK household of around 820 kg CO_2.year^{-1} avoided, due to the more energy savings and higher grid carbon intensity in Germany. It is also obvious that heavy energy users connecting to CES are able to save the most annual CO_2 emissions, which grows with the increasing storage capacity. In contrast, the light users can save slightly more CO_2 compared to the PV-only case (1433 kg.year^{-1}).

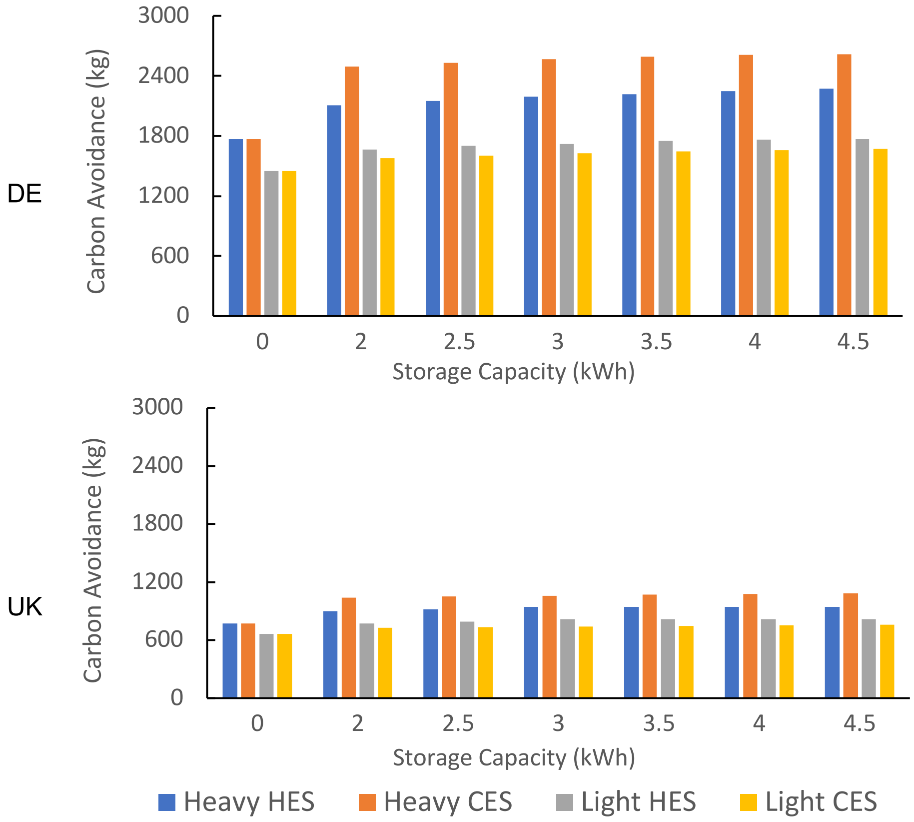


Figure 6-12 Annual Carbon Avoidance

Table 6-8 shows the PBT_{co2} of households with 3kWp PV plus 3kWh storage from different manufacture locations. The UK households have more than double the payback time that the DE users have due to less annual carbon avoidance presented in Figure 6-12. The manufacture locations also play an important role in the PBT_{co2}, because of the carbon intensity. In China, the electricity is still mainly produced by coal-power plants and hence the carbon intensity of China is much higher compared to the UK and DE, which contributes to the longest $PBTs_{co2}$. In contrast, the increasing penetration of low-carbon energy production in the UK significantly lowers the carbon intensity, which can make the households payback the carbon emission from manufacture much sooner, less than 3 years. Overall, it is certain that the addition of PV plus storage system can effectively reduce the carbon emissions. Although the total carbon emission during manufacture may vary with the locations, the systems are found environmentally beneficial overall.

Table 6-8 Impacts of Different Manufacture Locations on PBT_{co2} of Household

Manufacture Location	**Household Type**	**DE**			**UK**		
		PV-Only	HES	CES	PV-Only	HES	CES
DE	**Light**	2.3	2.2	2.3	4.9	4.6	5.1
	Heavy	1.8	1.7	1.5	4.2	4.0	3.6
UK	**Light**	1.3	1.4	1.5	2.9	3.0	3.3
	Heavy	1.1	1.1	1.0	2.5	2.6	2.3
CN	**Light**	4.4	4.0	4.2	9.5	8.4	9.2
	Heavy	3.6	3.1	2.7	8.2	7.3	6.4

6.4. Discussion

The solar resource in south Germany is much more abundant than in the northern UK; a DE household (2900 kWh) can produce markedly higher electricity than a UK household (2136 kWh) with the same rooftop PV configuration. This enables DE users to generate more energy savings when coupling with storage systems compared to UK households. Improving energy efficiency and reducing energy demand are certainly helpful to enhance the self-sufficiency. The main question for Germany households is how to capture and maximise the value of the existing solar resource, whilst for the UK the question is how to diversify and enhance generation as there is limited solar generation. A UK community could adopt a hybrid system, for example PV plus wind turbine system to increase generation. The complementarity between wind and solar can potentially enhance the generation output and total energy exports [187], and also can reduce total system costs and required storage capacity [188]. For users similar to DE households, the addition of larger storage systems would be beneficial. The performances of the communities in two countries vary significantly, though they have households with similar demand consumptions. Different approaches are therefore required for renewable energy system planning, such as considering the renewable energy resource distribution and energy demand density [34].

Urbanisation has imposed a challenge to the energy system [189], and energy demand is determined by the location, land use, shape and the inherent demand type. The density of renewable energy resources can be significantly lower than demand density, which further limits renewable energy production. The inequality between renewable energy density and demand density will become more common with the increasing size and number of cities and will also question the security of electricity supply and the durability of the existing utility infrastructures in the future. Therefore, tailored planning may need to combine multiple solutions, including combined heat and power [190], district energy, and PV or wind power generation [191], as well as other flexibility options, such as energy efficiency [62] and demand response [14]. In this study the performances of a small 10-hosehold community varies significantly in Germany and UK, and it is expected that a community with the same size may behave differently in other countries. To determine the optimal system setup, a more comprehensive planning method is required, including analysis of demand heterogeneity, renewable energy resource distribution, etc. However, the greatest challenge remains the economic feasibility. Although there are several solutions, they can be generalised into two main categories [192], increasing financial returns and lowering the investment risk.

The financial returns of a project are mainly from the revenues and savings the project generates, and the FIT payment is one of the most important revenues. Recently, the FIT for domestic solar in the UK has decreased significantly, particularly compared to the significantly higher FIT rates in Germany. The Smart Export Guarantee [165] enforced recently has removed the deemed export and further reduces profits obtained from domestic solar applications. In addition, the profit margin is also subject to the retail electricity tariffs, because the increasing electricity price is one of the reasons for the growing shift towards self-consumption [193]. In Germany, the expensive electricity tariff rates provide households stronger incentives to reduce grid electricity imports by introducing a domestic PV plus storage system. The consumption of every kWh of PV electricity can contribute to a £0.255 saving and £0.09 profit via the FIT scheme, which is much higher than the UK. It is therefore necessary to seek other alternative to enhance the financial returns in the UK.

The growing popularity of li-ion batteries is mainly attributed to their high power, energy density and capability of rapid charge/discharge process [194]. The battery power dispatching needs to match the power and energy profiles of different applications, but most of the applications do not require the battery's capacity the entire time. As a result, idle capacity can be used in additional applications and provide multiple services, including end-user self-consumption and arbitrage, network services, generation services and ancillary services. Researchers from Switzerland [192] and the UK [167] have found that revenue stacking can effectively improve the battery profitability, but the market is yet to be exploited. More measures and supports are also needed to lower the investment risks. The solar plus storage systems are more accessible to households in Germany with the extensive supports from the government and industry, such as subsidies [186] and loans [195] for storage systems. However, there is much work to be done in the UK. Gardiner et al. [167] suggest that several policy options should be considered, including 1) improving availability of TOU tariffs; 2) adjusting the VAT rate for retrofit installations; 3) direct subsidy; 4) reforming deemed PV export payment; 5) establishing a market for network savings. Cost reduction must be achieved so that the storage will eventually become accessible without subsidies, and Pena-Bello et al. [98] argue that further up to 55% cost reduction in li-ion batteries is required. Mass production will effectively decrease the production costs and improve the technology to give longer lifespan, which should lower the LCOS.

6.5. Conclusion

In this chapter, a multi-discipline assessment is undertaken to study PV plus a HES/CES system in Germany and the UK. The primary attribute to the system performance is the solar resource. The SSRs (at least 0.5) and annual energy savings (at least 14100 kWh) of DE communities and users are much higher compared to the UK. Additionally, CES is best for communities and heavy users in both UK and Germany, while the light users are better with HES. A more comprehensive and location-specific approach is required for the planning of renewable energy systems, due to the difference in renewable resource distribution and energy demand density.

Households in Germany can payback their system within 20 years compared to the UK households, but the SPBT of light users in both countries are the longest. The current PV plus storage system price is still too high, but the system is expected to recover its upfront investment within 10 years if the cost of PV and storage can reduce by 30%. The LCOE in Germany ranges from £0.5 - £0.8 kWh^{-1} while that of the UK is between £0.65 - £1.1 kWh^{-1}. The LCOE of CES is in between the LCOEs of HES of heavy and light users in Germany, while in the UK LCOS of CES is the highest. In addition, the grid-charging function and government subsidy can effectively reduce the LCOEs, but all the cases investigated are still not profitable.

It is certain that the addition of PV plus storage and TOU Tariffs are beneficial to households and communities in both countries, particularly CES. However, as stated earlier, the economic feasibility still remains questionable, which needs further changes and improvements in several aspects. For the UK, more options are needed to improve electricity output besides PV panel, such as increasing PV capacity and integrating with another generation technology. For Germany, it is necessary to minimise the PV curtailment due to the sufficient generation. In addition, legislative and financial supports are also needed to increase the financial returns and lower the investment risk, such as subsidies for storage, or establish relevant markets to enable storage owners to stack revenues.

Chapter 7 Conclusions and Future Works

With the increasing penetration of renewable energy, energy storage is very likely to be an essential component of future energy system. The expensive capital cost of a residential generation and storage system will have to be solved considering the massive potential uptake of distributed energy resources for residential consumers. This thesis has investigated the value of CES as an alternative option to HES. It has looked at the community storage from technical, economic and environmental perspectives, exploring several operational strategies, and how the feasibility can be improved in the UK under current circumstances. This chapter generalises the main findings and conclusions, and also recommends directions for future work.

7.1. Thesis Summary and Key Chapter Conclusions

Chapter 2 presented an introduction to renewable energy and energy storage. Intermittency is a common issue shared by most types of renewable energy generation, which can be enhanced by the addition of energy storage. Residential consumers have started to adopt on-site generation due to increasing electricity tariffs and reduced subsidies, giving a shift in operation towards self-consumption. Amongst all the options, energy storage and demand side management are expected to be vital in the self-consumption of residential PV plus household storage. The expensive costs still hinder the feasibility which was expected to be improved by community energy storage. The wide deployment of CES is still questioned because of the lack of experience, regulatory framework, implementation experiences and financial incentives. Many previous studies have confirmed its potential advantages and benefits for residential participants and distribution network operators. However, the power interactions of households and subsequent impacts at household level within a community energy storage network are barely studied.

Chapter 3 chose agent-based modelling as the approach for the research. An agent-based model was developed for the study, including three communities to represent three types of communities. Development of each component of the model was discussed, including the demand model, battery storage model and its management system model. Several battery operational strategies were proposed to manage the battery power under different tariffs. Additionally, the evaluation criteria were presented, and several key performance indicators are introduced, including self-consumption rate, self-sufficiency rate, simple payback time, levelised cost of energy, levelised cost of storage and payback time of carbon emission during manufacture.

Chapter 4 compared the household energy storage and community energy storage for a residential community of 10 households. Both storage options were found helpful for the communities, which could reduce the grid peak power import and export, improve the community self-consumption and self-sufficiency rates, and able to reduce household energy bills by at least 30%. Furthermore, optimising the CES capacity led to more effective use of PV power and better demand localisation during high PV-generation periods. It was also found that an important challenge for CES systems was to realise the value of the shared electricity equitably amongst the participants and potentially to seek other revenue streams.

Chapter 5 explored the potential alternatives to improve the feasibility of CES, including demand side management under a TOU tariff and inter-house trading. The results suggested that TOU tariffs could effectively shave peak demand and lower energy bills but could not improve self-consumption or self-sufficiency rate. This study indicated that all cases considered were environmentally friendly and could payback the total CO_2 emissions associated with the manufacturing within eight years. However, the LCOS was still beyond a household’s affordability, though CES was proven more effective at improving self-consumption for consumers and shaving peak demand for network operators. The feasibility could be improved by 1) combining different services and tariffs to obtain more revenues for households; 2) more legislative and financial support to reduce system costs; and 3) more innovative business models and policies to optimise revenues with existing resources.

Chapter 6 compared and contrasted community energy storage in the UK and Germany – two countries with different solar profiles and different electricity tariffs. Results indicated that the primary impacting factor on self-sufficiency was the solar generation, and therefore households and communities in Germany could be more self-sufficient than their UK counterparts. Additionally, the profitability of households in Germany was also higher due to the subsidies for storage and on-site generation. The results highlighted the importance of using a location-specific approach for system planning. For example, households in Germany should aimed to fully exploit on-site generation, whilst UK households should improve generation output, for example by using a hybrid system. In addition, more financial and legislative support is needed in the UK to improve feasibility.

7.2. Recommendations for Future CES Development in the UK

This thesis has analysed the possibility of CES as a replacement of HES in the UK. The results show that the CES is able to outperform HES in most conditions, including the utilisation of on-site generated PV electricity, trimming the demand during peak times, possibly reduction in initial system planning costs. For the networks, the benefits brought by CES are significant as well. For instance, CES can reduce peaks of surplus PV electricity being sent to the grid and hence contributes to a lower peak power surge during the day. Moreover, CES also provides more flexibility to the users and the network operators in demand side management and more potential options to stack revenues. From an environmental perspective, CES deployment is also important. Across the three result chapters, CES together with PV has showed an extraordinary capability for carbon avoidance. With technological advancement, less carbon emissions will be produced during the manufacturing process, which will further decarbonise the energy industry. However, in many cases, CES still seems economically infeasible under current situations, and requires further financial and regulatory support.

The traditional centralised energy system is encountering challenges caused by increasing DERs. Although the grid-scale development in the UK will still remain predominant in the foreseen future, the development at residential level is vital to the revolution. Community energy systems have been proven very intriguing and beneficial, which provides the potential and possibility for energy consumers to localise their demand and supply. However, this will require a number of vast changes in the regulatory frameworks, including modifying operation codes, re-assessing the licensing process for energy generators, and opening access of electricity market to other participants. For example, in Section 5.4, the difficulty of implementing inter-house trading has already been identified due to the currently existing requirement that an end user is only allowed to have one energy supplier. For the CES, it is still hard to achieve its economic feasibility at the moment, which will require extra supports from the government and industry. This can start with enhancing the remuneration for renewable generation and storage, such as raising tariff rates of Smart Export Guarantee, remunerating the new installed solar PV and storage devices by waiving VAT or providing tax credits. From the industry side, more rapid development of storage technologies is required so that a storage system can be more affordable for the consumers. Additionally, more innovative business models should be proposed as well, such as the leasing of the battery storage devices and accumulating revenues from multiple sources. The former will require the government to loosen the requirements for the ownership of the battery storage, while the latter requires the regulators to make the market more accessible to all the potential players.

CES has great potential for the future. The benefits are obvious for energy consumers, suppliers and network operators. It is important to reassess current real estate planning methods and consider community energy storage at the initial stage of planning. Developers could work with energy suppliers, network operators and city councils to build properties with on-site DERs. This would help the community energy system localise more energy and reduce dependence on the power grid, hopefully making the community energy neutral. This type of system can also be easily scaled up. If the regulators can grant market access to more potential participants, the independent operators or aggregators can form a virtual power plant to provide grid services if needed, which will not only enhance grid resilience but also make the market more competitive to benefit the energy consumers eventually. In the past few years, there has been an increasing number of independent and small energy suppliers emerging in the energy market and challenging the traditional big five energy suppliers in the UK.

7.3. Recommendations for Future Research

This thesis has contributed to the body of knowledge on energy storage by: investigating the value of community energy storage for the domestic users and low-voltage network; exploring the feasibility of community energy storage and identifying the key hinderances and barriers; and also examining the potential applicable measures for improvements compared to Germany. Various issues regarding the deployment of community energy storage have been addressed in this thesis. However, the study could be further continued to investigate other problems such as:

a) The model algorithm developed in Chapter 3 could provide a more complex comparison of different energy generation and storage technologies. The results from Chapter 6 suggested that the use of community energy storage in the UK is not as effective as Germany due to limited solar resources. It is therefore important to look into other technologies such as small wind turbines or small hydro generation systems. In the UK, there are quite abundant wind and hydro resources in the coastal or mountainous areas, which therefore potentially can contribute to higher energy output compared to solar PV. In addition, the hydro and wind resources can also possibly provide more consistent power generation, which further enhance the demand localisation of the households and communities. Additionally, other storage technologies are also worthy of investigation, such as lead-acid batteries due to their maturity and cheap costs, which may significantly lower the system cost and improve the cost-effectiveness.

b) Interhouse trading was valuable to generate extra profits and recover the upfront costs. However, in this thesis, limited focus has been allocated to this area. Many researchers have been working on potential solutions for interhouse trading, such as using blockchain [196]. Future work should investigate the mechanism for local energy trading, which can be undertaken on technical, economic and legislative aspects. Furthermore, a successful example of local energy market has been undertaken in Cornwall, UK, which makes it worth investigating how the system works and how it can integrate with the current CES network. As addressed in Chapter 5, interhouse trading will be vital to stack the revenues, and it is therefore important to expand the study further. The traditional energy market is designed to balance the supply and demand at a national level, but it usually cannot reflect the energy production at the local level. In this way, a local energy market can associate the electricity price with local demand and supply, which can be even lower than the price of energy suppliers. It can potentially increase the competitiveness of the energy market and benefit the end users.

c) With the rapid development and exciting outlook of electric vehicles, the additional demand of electric vehicles will markedly affect household electricity demand. It is important to understand the behaviour of electric vehicles so that the impacts on networks can be fully addressed. In recent years, a concept called Vehicle to Grid has emerged as a potential alternative to fully or partially replace energy storage systems. Future research should investigate how the electric vehicles influence existing consumers’ demand profiles, and also how the vehicle battery can integrate with local renewable generation to fully and partially replace the existing HES and CES. Additionally, due to the different nature of the electric vehicles from the domestic appliances, it is also interesting to see how to optimise the use of battery capacity and how it can potentially contribute to grid service through local aggregation.

d) Aggregators are going to play an important role in future. It is therefore meaningful to see how an aggregator can make use of the HES or CES system. Currently, households still struggle to find storage systems economically feasible. Diversifying revenue streams will potentially increase the profitability. Similar to aggregating the electric vehicles mentioned previously, aggregators nowadays are able to operate and provide grid services in Germany. In the UK, grid service is still mainly provided by large suppliers, and this situation will possibly be challenged by aggregating the domestic storage systems. In return, the owners of storage system can obtain extra profits from it and hence shorten their system payback time. Therefore, it would be interesting to investigate how the aggregators can include community energy storage in their operation and business model, and how the additionally revenues can improve the economic feasibility.

e) Across this thesis, the current policy frameworks in the UK are not as encouraging as Germany or some states in the USA, such as California. The reduced subsidies for renewable generation have markedly hindered the uptake of domestic DERs, such as PV panels. Although the government has recently made some positive gestures for the energy storage, it still seems insufficient to fully unlock the potential of the DERs, especially at residential level. In this way, it is important to look into the existing policies and identify the key challenges to incentivise the uptake of relevant technologies. A case study of policies should be undertaken so that a more targeted solutions can be proposed.

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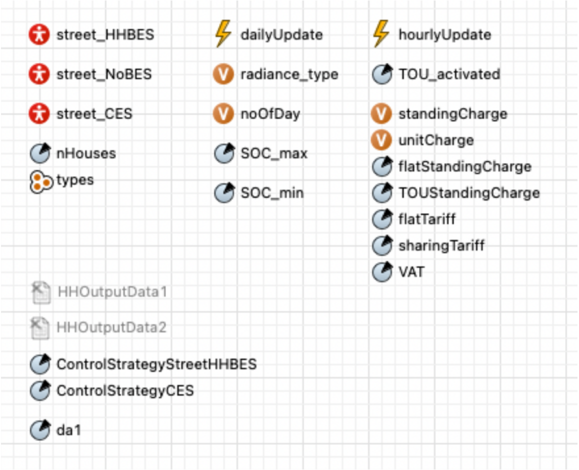
Appendix

Appendix A: Model Setup

System Model Overlook:

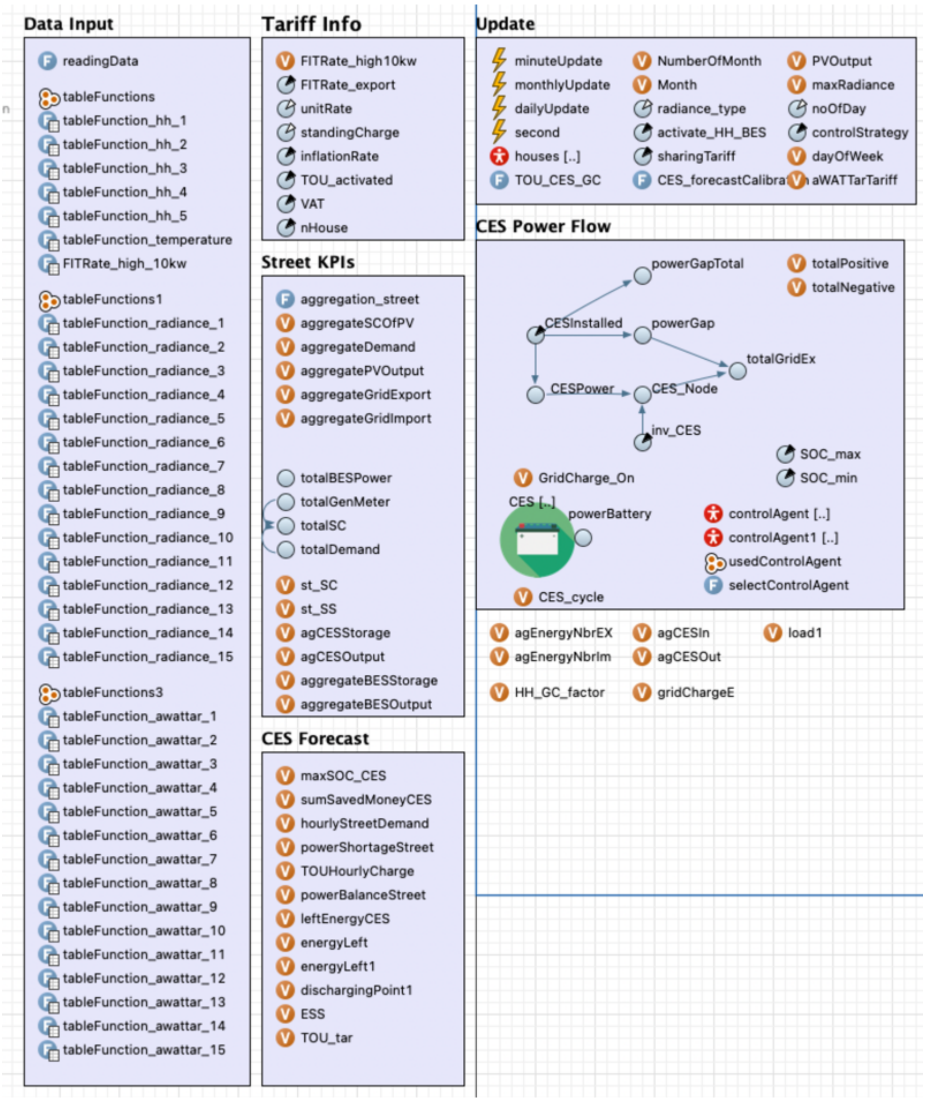


street_HHBES
street_NoBES
street_CES
nHouses
types
HHOutputData1
HHOutputData2
ControlStrategyStreetHHBES
ControlStrategyCES
da1

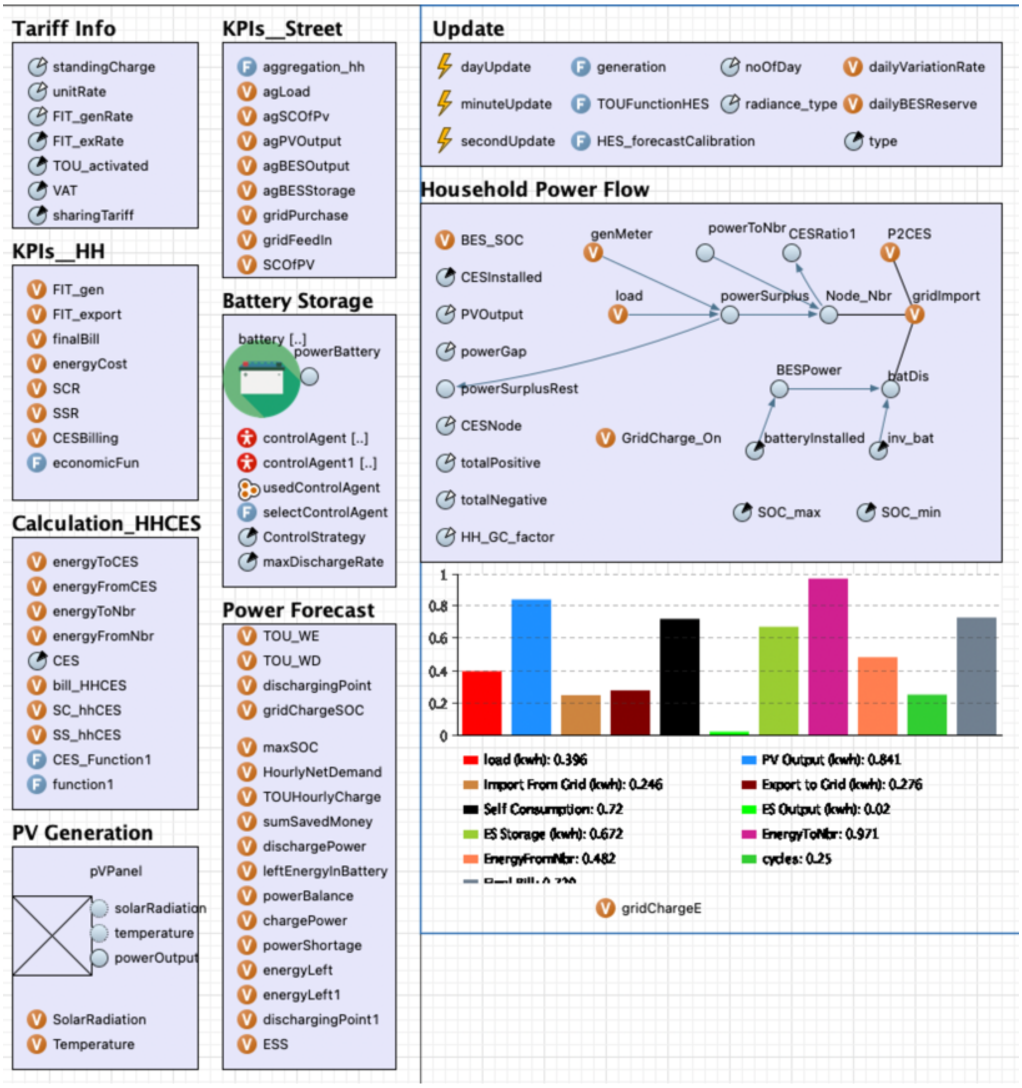
dailyUpdate
radiance_type
noOfDay
SOC_max
SOC_min

hourlyUpdate
TOU_activated
standingCharge
unitCharge
flatStandingCharge
TOUStandingCharge
flatTariff
sharingTariff
VAT

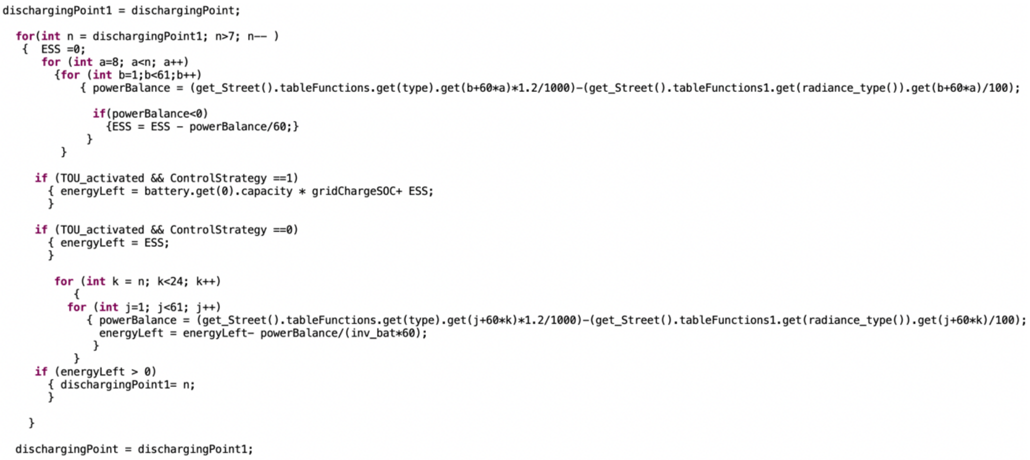
Street Agent Setup:



Household Agent Setup:

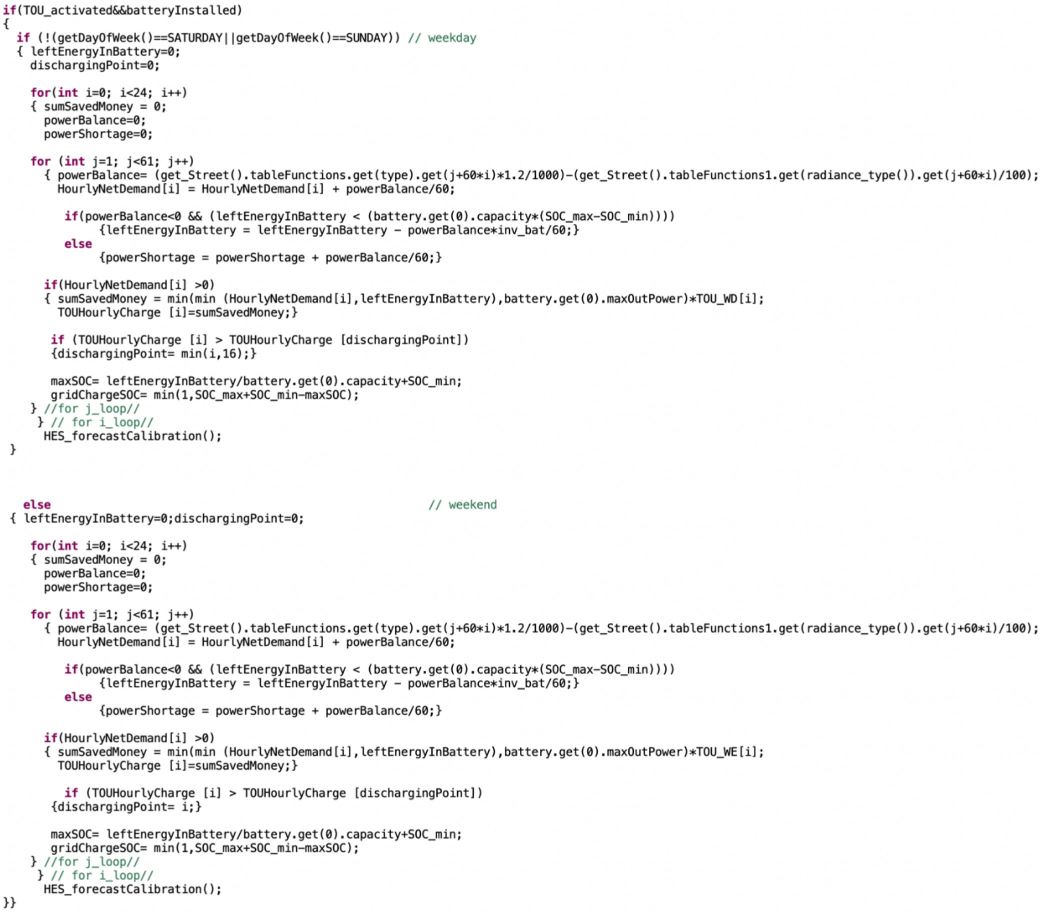


HES Forecast Function Script:



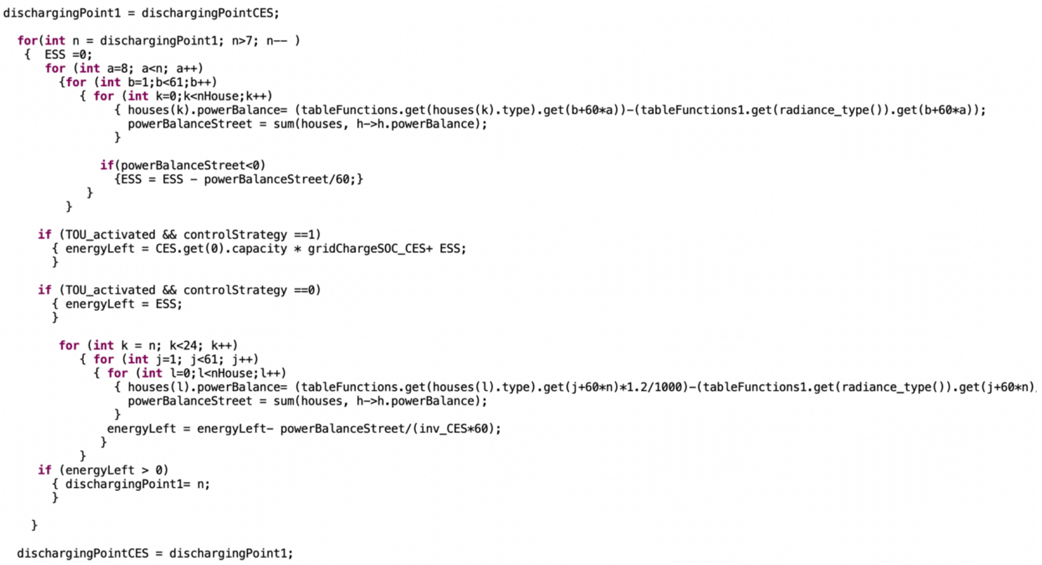
```
dischargingPoint1 = dischargingPoint;

  for(int n = dischargingPoint1; n>7; n-- )
   {  ESS =0;
      for (int a=8; a<n; a++)
        {for (int b=1;b<61;b++)
            { powerBalance = (get_Street().tableFunctions.get(type).get(b+60*a)*1.2/1000)-(get_Street().tableFunctions1.get(radiance_type()).get(b+60*a)/100);

              if(powerBalance<0)
                {ESS = ESS - powerBalance/60;}
             }
         }

     if (TOU_activated && ControlStrategy ==1)
       { energyLeft = battery.get(0).capacity * gridChargeSOC+ ESS;
       }

     if (TOU_activated && ControlStrategy ==0)
       { energyLeft = ESS;
       }

        for (int k = n; k<24; k++)
           {
         for (int j=1; j<61; j++)
            { powerBalance = (get_Street().tableFunctions.get(type).get(j+60*k)*1.2/1000)-(get_Street().tableFunctions1.get(radiance_type()).get(j+60*k)/100);
              energyLeft = energyLeft- powerBalance/(inv_bat*60);
             }
           }
     if (energyLeft > 0)
       { dischargingPoint1= n;
       }

    }

  dischargingPoint = dischargingPoint1;
```

HES Operation Under TOU Tariff Function Script:



```
if(TOU_activated&&batteryInstalled)
{
  if (!(getDayOfWeek()==SATURDAY||getDayOfWeek()==SUNDAY)) // weekday
  { leftEnergyInBattery=0;
    dischargingPoint=0;

    for(int i=0; i<24; i++)
    { sumSavedMoney = 0;
      powerBalance=0;
      powerShortage=0;

    for (int j=1; j<61; j++)
      { powerBalance= (get_Street().tableFunctions.get(type).get(j+60*i)*1.2/1000)-(get_Street().tableFunctions1.get(radiance_type()).get(j+60*i)/100);
        HourlyNetDemand[i] = HourlyNetDemand[i] + powerBalance/60;

         if(powerBalance<0 && (leftEnergyInBattery < (battery.get(0).capacity*(SOC_max-SOC_min))))
              {leftEnergyInBattery = leftEnergyInBattery - powerBalance*inv_bat/60;}
         else
              {powerShortage = powerShortage + powerBalance/60;}

      if(HourlyNetDemand[i] >0)
      { sumSavedMoney = min(min (HourlyNetDemand[i],leftEnergyInBattery),battery.get(0).maxOutPower)*TOU_WD[i];
        TOUHourlyCharge [i]=sumSavedMoney;}

       if (TOUHourlyCharge [i] > TOUHourlyCharge [dischargingPoint])
       {dischargingPoint= min(i,16);}

       maxSOC= leftEnergyInBattery/battery.get(0).capacity+SOC_min;
       gridChargeSOC= min(1,SOC_max+SOC_min-maxSOC);
    } //for j_loop//
     } // for i_loop//
      HES_forecastCalibration();
 }


   else                                              // weekend
 { leftEnergyInBattery=0;dischargingPoint=0;

    for(int i=0; i<24; i++)
    { sumSavedMoney = 0;
      powerBalance=0;
      powerShortage=0;

    for (int j=1; j<61; j++)
      { powerBalance= (get_Street().tableFunctions.get(type).get(j+60*i)*1.2/1000)-(get_Street().tableFunctions1.get(radiance_type()).get(j+60*i)/100);
        HourlyNetDemand[i] = HourlyNetDemand[i] + powerBalance/60;

         if(powerBalance<0 && (leftEnergyInBattery < (battery.get(0).capacity*(SOC_max-SOC_min))))
              {leftEnergyInBattery = leftEnergyInBattery - powerBalance*inv_bat/60;}
         else
              {powerShortage = powerShortage + powerBalance/60;}

      if(HourlyNetDemand[i] >0)
      { sumSavedMoney = min(min (HourlyNetDemand[i],leftEnergyInBattery),battery.get(0).maxOutPower)*TOU_WE[i];
        TOUHourlyCharge [i]=sumSavedMoney;}

         if (TOUHourlyCharge [i] > TOUHourlyCharge [dischargingPoint])
       {dischargingPoint= i;}

       maxSOC= leftEnergyInBattery/battery.get(0).capacity+SOC_min;
       gridChargeSOC= min(1,SOC_max+SOC_min-maxSOC);
    } //for j_loop//
     } // for i_loop//
      HES_forecastCalibration();
}}
```

CES Forecast Function Script:



```
dischargingPoint1 = dischargingPointCES;

  for(int n = dischargingPoint1; n>7; n-- )
   {  ESS =0;
      for (int a=8; a<n; a++)
        {for (int b=1;b<61;b++)
           { for (int k=0;k<nHouse;k++)
                { houses(k).powerBalance= (tableFunctions.get(houses(k).type).get(b+60*a))-(tableFunctions1.get(radiance_type()).get(b+60*a));
                  powerBalanceStreet = sum(houses, h->h.powerBalance);
                }

              if(powerBalanceStreet<0)
                {ESS = ESS - powerBalanceStreet/60;}
            }
         }

     if (TOU_activated && controlStrategy ==1)
       { energyLeft = CES.get(0).capacity * gridChargeSOC_CES+ ESS;
       }

     if (TOU_activated && controlStrategy ==0)
       { energyLeft = ESS;
       }

        for (int k = n; k<24; k++)
           { for (int j=1; j<61; j++)
              { for (int l=0;l<nHouse;l++)
                 { houses(l).powerBalance= (tableFunctions.get(houses(l).type).get(j+60*n)*1.2/1000)-(tableFunctions1.get(radiance_type()).get(j+60*n)
                   powerBalanceStreet = sum(houses, h->h.powerBalance);
                 }
                energyLeft = energyLeft- powerBalanceStreet/(inv_CES*60);
               }
            }
     if (energyLeft > 0)
       { dischargingPoint1= n;
       }

   }

  dischargingPointCES = dischargingPoint1;
```

CES Operation Under TOU Tariff Function Script:

```
dischargingPointCES=0;

if(TOU_activated&&CESInstalled)
{
   for(int z=0;<24;z++)
      {TOU_tar[z] = tableFunctions3.get(radiance_type()).get(1+60*i)/100;}       //reading tariff info//

    leftEnergyCES=0;

    for(int i=7; i<24; i++)
    {
      sumSavedMoneyCES = 0;
      powerBalanceStreet=0;
      powerShortageStreet=0;

    for (int j=1; j<61; j++)
      { for (int k=0;k<nHouse;k++)
         {houses(k).powerBalance= (tableFunctions.get(houses(k).type).get(j+60*i)*1.2/1000)-(tableFunctions1.get(radiance_type()).get(j+60*i)/100;}
          powerBalanceStreet = sum(houses, h->h.powerBalance);
          hourlyStreetDemand[i] = hourlyStreetDemand[i] + powerBalanceStreet/60*TOU_tar[i];         //hourlyStreetDemand[] is the savings//

         if(powerBalanceStreet<0 && (leftEnergyCES < (CES.get(0).capacity*(SOC_max-SOC_min))))
              {leftEnergyCES = leftEnergyCES - powerBalanceStreet*inv_CES/60;}
         else
              {powerShortageStreet = powerShortageStreet + powerBalanceStreet/60;}

     if(hourlyStreetDemand[i] >0)
      { sumSavedMoneyCES = min( min(hourlyStreetDemand[i],leftEnergyCES * TOU_tar[i]),CES.get(0).maxOutPower*TOU_tar[i]);
        TOUHourlyCharge[i]=sumSavedMoneyCES;}


     if (TOUHourlyCharge[i] > TOUHourlyCharge[dischargingPointCES])
      { dischargingPointCES= i;}

        maxSOC_CES= leftEnergyCES/CES.get(0).capacity+SOC_min;
        gridChargeSOC_CES= min(1, SOC_max+SOC_min-maxSOC_CES);
    }
  }
    CES_forecastCalibration();

}
```

Appendix B: Results of Chapter 4

Community’s SCR and SSR in January, March, May, July, September and November

SCR	20kWh	25kWh	30kWh	35kWh	40kWh	45kWh
Jan	0.99	0.99	0.99	0.99	0.99	0.99
Mar	0.97	0.98	0.96	0.97	0.98	0.98
May	0.40	0.43	0.46	0.47	0.53	0.50
Jul	0.56	0.59	0.62	0.66	0.69	0.72
Sep	0.99	0.98	0.98	0.98	0.98	0.98
Nov	0.99	0.99	0.99	0.99	0.99	0.99

SSR	20kWh	25kWh	30kWh	35kWh	40kWh	45kWh
Jan	0.09	0.09	0.09	0.09	0.09	0.09
Mar	0.30	0.30	0.26	0.26	0.26	0.26
May	0.56	0.60	0.64	0.71	0.71	0.80
Jul	0.55	0.57	0.70	0.73	0.77	0.80
Sep	0.39	0.39	0.33	0.33	0.33	0.33
Nov	0.10	0.10	0.10	0.10	0.10	0.10

SCR of HH0 and HH2 in January, March, May, July, September and November

Type0	SCR					
	20kWh	25kWh	30kWh	35kWh	40kWh	45kWh
January	0.99	0.99	0.99	0.99	0.99	0.99
March	0.97	0.99	1.00	1.00	1.00	1.00
May	0.36	0.39	0.43	0.44	0.50	0.48
July	0.50	0.54	0.58	0.62	0.65	0.69
September	1.00	1.00	1.00	1.00	0.99	1.00
November	0.99	0.99	0.99	0.99	1.00	0.99
Type2	20kWh	25kWh	30kWh	35kWh	40kWh	45kWh
January	0.99	0.99	0.99	0.99	0.99	0.99
March	0.87	0.88	0.88	0.88	0.90	0.88
May	0.44	0.48	0.51	0.52	0.57	0.54
July	0.57	0.61	0.64	0.68	0.70	0.74
September	0.97	0.97	0.97	0.97	0.97	0.97
November	0.97	0.97	0.97	0.97	0.97	0.97

SSR of HH0 and HH2 in January, March, May, July, September and November

Type0	SSR					
	20kWh	25kWh	30kWh	35kWh	40kWh	45kWh
January	0.17	0.17	0.17	0.17	0.18	0.17
March	0.17	0.17	0.17	0.17	0.15	0.16
May	0.62	0.64	0.70	0.76	0.76	0.83
July	0.40	0.42	0.43	0.43	0.44	0.42
September	0.21	0.21	0.21	0.21	0.22	0.21
November	0.17	0.17	0.17	0.17	0.18	0.17
Type2	20kWh	25kWh	30kWh	35kWh	40kWh	45kWh
January	0.10	0.10	0.10	0.10	0.11	0.10
March	0.50	0.50	0.50	0.50	0.48	0.50
May	0.62	0.64	0.67	0.72	0.70	0.81
July	0.66	0.70	0.73	0.74	0.76	0.76
September	0.33	0.33	0.33	0.33	0.33	0.33
November	0.15	0.15	0.15	0.15	0.17	0.15

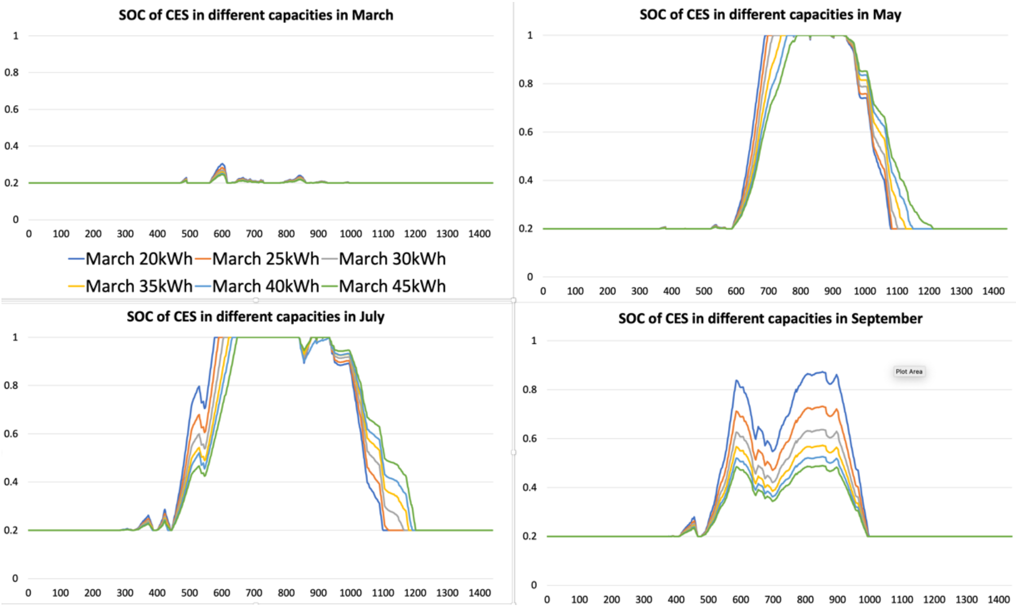
CO2 Avoidance of Households and Community

HH0	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total CO2 Avoidance
20 kWh	6.37	5.99	6.60	15.59	57.36	19.38	13.32	10.82	9.22	8.55	5.30	4.41	162.92
25 kWh	6.37	5.95	6.28	19.50	59.36	20.43	13.80	10.59	9.23	8.55	5.30	4.41	169.79
30 kWh	6.37	5.94	6.38	23.16	64.43	22.01	14.08	10.96	9.23	8.55	5.30	4.41	180.84
35 kWh	6.37	5.94	6.30	23.08	70.27	22.29	14.05	10.89	9.23	8.55	5.30	4.41	186.69
40 kWh	6.37	5.94	6.30	23.53	70.19	22.13	13.84	11.15	9.23	8.55	5.30	4.41	186.94
45 kWh	6.37	5.94	6.27	23.89	76.95	25.73	13.89	10.76	9.23	8.55	5.30	4.41	197.29
HH2	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total CO2 Avoidance
20 kWh	8.86	30.48	51.79	124.92	60.20	89.59	52.84	82.34	27.10	30.01	11.99	7.76	577.89
25 kWh	8.86	30.29	51.72	126.09	61.91	94.26	55.70	82.89	27.05	30.05	11.97	7.76	588.54
30 kWh	8.86	30.30	51.84	127.38	65.38	97.96	58.14	84.39	27.04	30.03	11.97	7.76	601.06
35 kWh	8.86	30.09	51.70	127.17	70.35	100.01	59.17	86.99	27.03	30.03	11.97	7.76	611.14
40 kWh	8.86	30.09	51.70	128.71	67.55	101.97	59.38	89.24	27.03	30.03	11.97	7.76	614.29
45 kWh	8.86	30.09	51.69	130.02	78.50	106.72	60.51	90.99	27.03	30.03	11.97	7.76	634.17
Street	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	PV Only
20 kWh	91.71	172.37	317.61	524.31	489.91	607.28	670.25	573.41	407.13	182.18	98.64	68.28	4203.08
25 kWh	91.71	172.32	321.05	549.79	523.88	632.18	711.58	596.09	406.62	182.21	98.61	68.00	4354.04
30 kWh	91.71	172.35	323.08	576.91	555.31	662.67	748.15	683.28	406.36	181.69	98.33	68.00	4567.84
35 kWh	91.71	172.21	322.73	597.57	620.81	674.42	780.97	634.09	405.95	181.69	98.43	68.00	4648.58
40 kWh	91.71	172.21	322.73	620.47	618.44	695.04	814.38	647.62	405.95	181.69	98.43	68.00	4736.68
45 kWh	91.71	172.21	322.72	643.53	697.76	721.17	848.33	658.51	405.94	181.54	98.43	68.00	4909.86

Monthly and Annual Energy Savings of Community

Energy Saving	20kWh	25kWh	30kWh	35kWh	40kWh	45kWh	PV-Only
Jan	283.98	283.92	283.92	283.92	283.92	283.92	305.622
Feb	533.66	533.50	533.58	533.16	533.16	533.16	460.909
Mar	983.31	993.97	1000.26	999.17	999.17	999.14	815.257
Apr	1623.24	1702.13	1786.09	1850.06	1920.98	1992.37	1141.708
May	1516.76	1621.92	1719.24	1922.01	1914.69	2160.25	1065.713
Jun	1880.13	1957.23	2051.61	2087.98	2151.83	2232.74	1408.391
Jul	2075.07	2203.05	2316.27	2417.87	2521.31	2626.40	1474.825
Aug	1775.26	1845.48	2115.43	1963.13	2005.02	2038.73	1319.752
Sep	1260.45	1258.87	1258.07	1256.80	1256.80	1256.78	1142.71
Oct	564.03	564.11	562.49	562.51	562.51	562.04	573.037
Nov	305.39	305.30	304.44	304.74	304.74	304.74	291.956
Dec	211.38	210.54	210.54	210.54	210.54	210.54	202.546
Annual	12801.28	13269.48	13931.40	14181.34	14454.11	14990.26	9999.88

SOC of CES with Different Capacities in March, May, July and September



Monthly Demand and PV Production of A Community for Validation Study

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Demand	1	3052.265	3059.867	4144.76	1754.704	1187.13	832.404	670.839	670.839	686.396	820.51	540.495	2397.459	19817.668
	2	2644.598	2674.493	4367.744	1510.133	1154.579	938.319	757.565	913.412	684.982	904.631	590.187	4400.172	21540.815
	3	3046.549	3206.284	3919.168	1515.766	1156.14	882.403	665.847	761.215	612.017	799.766	510.826	3070.876	20146.857
	4	2876.969	2848.465	3542.44	1861.564	1188.699	775.526	672.382	640.047	776.106	755.206	513.875	4421.732	20873.011
	5	2982.306	2108.293	4285.519	1083.745	1104.157	952.89	759.354	919.494	756.886	893.629	613.729	7459.198	23919.2
	6	2512.977	2770.048	3345.291	1392.206	1145.088	897.339	626.704	641.543	722.602	709.737	519.75	3167.895	18451.18
	7	2724.854	2468.677	3748.49	1571.273	945.143	806.676	598.865	692.315	651.786	796.799	483.126	4371.889	19859.893
	8	3020.466	2515.331	3365.301	1307.07	948.018	794.861	640.118	655.775	626.966	772.22	432.284	5398.733	20477.143
	9	2357.634	2143.721	3263.539	1072.697	1071.45	741.06	694.182	852.226	726.2	759.362	545.881	4676.073	18904.025
	10	3080.331	2800.847	4263.927	1401.516	1399.887	968.221	906.973	1113.463	948.806	992.133	713.213	6109.453	24698.77
	11	2464.653	2799.873	4442.936	1977.294	1185.009	1035.461	756.612	841.777	810.457	895.639	637.652	4846.82	22694.183
	12	1993.45	2264.581	3593.516	1599.266	958.453	837.497	611.959	680.843	655.51	724.407	515.743	3920.184	18355.409
	13	3200.378	2047.583	3897.255	791.932	1166.19	897.964	804.826	972.133	895.874	980.324	632.09	8325.766	24612.315
	14	2902.038	2489.391	3587.006	1298.619	1260.494	816.265	707.019	769.338	686.522	853.759	526.305	5615.18	21511.936
	15	2836.709	2079.464	3633.772	1440.914	957.133	843.358	752.328	684.288	728.66	754.92	610.893	5816.262	21138.701
	16	1908.78	1330.00	2351.89	875.16	512.00	687.13	653.53	708.80	603.02	754.69	502.17	3874.81	14761.98
	17	3769.00	2173.05	4129.83	1135.47	1048.69	944.24	793.66	801.06	824.03	934.00	601.76	4314.22	21469.00
	18	3254.26	3262.37	4419.06	1870.83	1265.69	887.49	715.23	730.86	731.82	874.81	576.26	2556.12	21144.81
	19	2819.62	2851.49	4656.80	1610.07	1230.99	1000.42	807.70	973.86	730.31	964.50	629.25	4691.37	22966.36
	20	3248.17	3418.47	4178.53	1616.08	1232.65	940.80	709.91	811.59	652.52	852.69	544.63	3274.10	21480.15
	21	3217.17	3185.29	3961.33	2081.69	1329.26	867.23	751.89	715.73	867.88	844.51	574.64	4944.60	23341.23
	22	3488.15	2465.89	5012.40	5012.40	1267.56	1114.51	888.15	1075.45	885.26	1045.20	717.83	8724.38	31697.19
	23	2529.96	2788.76	3367.89	1401.61	1152.82	903.40	630.94	645.88	727.48	714.53	523.26	3189.30	18575.84
	24	2743.26	2485.36	3773.82	1581.89	951.53	812.13	602.91	696.99	656.19	802.18	486.39	4401.43	19994.07
	25	3228.66	2688.71	3597.27	1397.16	1013.36	849.65	684.24	700.98	670.18	825.45	462.08	5770.86	21888.60
	26	2630.13	2391.50	3640.74	1196.68	1195.29	826.71	774.42	950.73	810.14	847.13	608.98	5216.54	21088.99
	27	2104.44	2390.67	3793.59	1688.31	1987.86	884.13	646.03	718.75	692.01	764.74	544.46	4138.45	20353.41
	28	2446.41	2779.14	4410.04	1962.65	1176.24	1027.80	751.01	835.55	804.46	889.01	632.93	4810.94	22526.16
	29	3200.38	2047.58	3897.26	791.93	1166.19	1166.19	804.83	972.13	895.87	980.32	632.09	8325.77	24880.54
	30	2902.04	2489.39	3587.01	1298.62	1260.49	816.27	707.02	769.34	686.52	853.76	526.31	5615.18	21511.94
	31	2836.71	2079.46	3633.77	1440.91	957.13	843.36	752.33	684.29	728.66	754.92	610.89	5816.26	21138.70
	Mean	2839.46	2551.74	3864.90	1565.81	1147.59	890.05	719.33	793.57	739.88	842.43	566.45	4956.84	21478.07
	SD	422.04	445.37	507.86	719.72	227.04	103.81	78.54	133.31	91.24	89.53	68.46	1607.67	2841.03
	Error	75.80	79.99	91.21	129.27	40.78	18.65	14.11	23.94	16.39	16.08	12.30	288.75	510.26

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
PV	2	227.91	307.88	1136.89	1336.30	1645.61	1758.33	1933.25	1724.36	1703.38	972.26	605.01	390.71	13741.88
	3	221.10	298.69	1102.93	1296.39	1596.45	1705.80	1875.50	1672.86	1652.50	726.28	451.94	291.86	12892.29
	4	221.10	298.69	1102.93	1296.39	1596.45	1705.80	1875.50	1672.86	1652.50	726.28	451.94	291.86	12892.29
	5	221.10	298.69	1102.93	1296.39	1596.45	1705.80	1875.50	1672.86	1652.50	726.28	451.94	291.86	12892.29
	6	227.91	307.90	1136.93	1336.36	1645.68	1758.40	1933.33	1724.44	1703.45	748.67	465.88	300.86	13289.81
	7	227.91	307.90	1136.93	1136.93	1336.36	1758.40	1933.33	1724.44	1703.45	748.67	465.88	300.86	12781.07
	8	238.86	322.68	1191.52	1400.52	1724.68	1842.82	2026.15	1807.22	1785.23	784.62	488.24	315.30	13927.81
	9	238.86	322.68	1191.52	1400.52	1724.68	1842.82	2026.15	1807.22	1785.23	784.62	488.24	315.30	13927.81
	10	238.86	322.68	1191.52	1400.52	1724.68	1842.82	2026.15	1807.22	1785.23	784.62	488.24	315.30	13927.81
	11	228.00	308.02	1137.38	1336.88	1646.32	1759.09	1934.09	1725.11	1704.11	748.97	466.06	300.98	13294.99
	12	228.00	308.02	1137.38	1336.88	3257.94	1759.09	1934.09	1725.11	1704.11	748.97	466.06	300.98	14906.61
	13	226.33	305.75	1129.01	1327.05	1634.21	1746.15	1919.86	1712.42	1691.58	743.46	462.63	298.76	13197.19
	14	175.71	237.37	876.50	1030.25	1268.71	1268.71	1490.48	1329.43	1313.25	577.18	359.16	231.94	10158.70
	15	175.71	237.37	876.50	1030.25	1268.71	1355.62	1490.48	1329.43	1313.25	577.18	359.16	231.94	10245.60
	16	175.71	237.37	876.50	1030.25	1268.71	1355.62	1490.48	1329.43	1313.25	577.18	359.16	231.94	10245.60
	17	293.356	396.304	1463.383	1720.07	2118.203	2263.293	2488.45	2488.45	2192.561	963.64	599.646	387.244	17374.6
	18	293.356	396.304	1463.383	1720.07	2118.203	2263.293	2488.45	2219.575	2192.561	963.64	599.646	387.244	17105.725
	19	293.356	396.304	1463.383	1720.07	2118.203	2263.293	2488.45	2219.575	2192.561	963.64	599.646	387.244	17105.725
	20	293.356	396.304	1463.383	1720.07	2118.203	2263.293	2488.45	2219.575	2192.561	963.64	599.646	387.244	17105.725
	21	326.505	441.087	1628.748	1914.442	2357.564	2519.049	2769.65	2470.391	2440.325	1072.534	667.407	431.003	19038.705
	22	326.505	441.087	1628.748	1914.442	2357.564	2519.049	2769.65	2470.391	2440.325	1072.534	667.407	431.003	19038.705
	23	326.505	441.087	1628.748	1914.442	2357.564	2519.049	2769.65	2470.391	2440.325	1072.534	667.407	431.003	19038.705
	24	310.196	419.054	1547.391	1818.814	2239.802	2393.221	2631.305	2346.994	2318.43	1018.96	634.069	409.474	18087.71
	25	310.196	419.054	1547.391	1818.814	2239.802	2393.221	2631.305	2346.994	2318.43	1018.96	634.069	409.474	18087.71
	26	211.536	285.771	1055.233	1240.328	1527.418	1632.041	1794.401	1600.517	1581.038	694.873	432.399	279.238	12334.793
	27	211.536	285.771	1055.233	1240.328	1527.418	1632.041	1794.401	1600.517	1581.038	694.873	432.399	279.238	12334.793
	28	175.708	237.369	876.504	1030.249	1268.713	1355.616	1490.476	1329.431	1313.251	577.18	359.162	231.943	10245.602
	29	175.708	237.369	876.504	1030.249	1268.713	1355.616	1490.476	1329.431	1313.251	577.18	359.162	231.943	10245.602
	30	175.708	237.369	876.504	1030.249	1268.713	1355.616	1490.476	1329.431	1313.251	577.18	359.162	231.943	10245.602
	31	175.708	237.369	876.504	1030.249	1268.713	1355.616	1490.476	1329.431	1313.251	577.18	359.162	231.943	10245.602
	Mean	239.08	322.98	1192.61	1395.16	1769.68	1841.62	2028.01	1817.85	1786.87	792.79	493.33	318.59	13998.57
	SD	51.26	69.25	255.72	304.26	469.85	399.51	434.85	400.58	383.15	171.63	106.80	68.97	3008.61
	Error	9.36	12.64	46.69	55.55	85.78	72.94	79.39	73.14	69.95	31.34	19.50	12.59	549.29

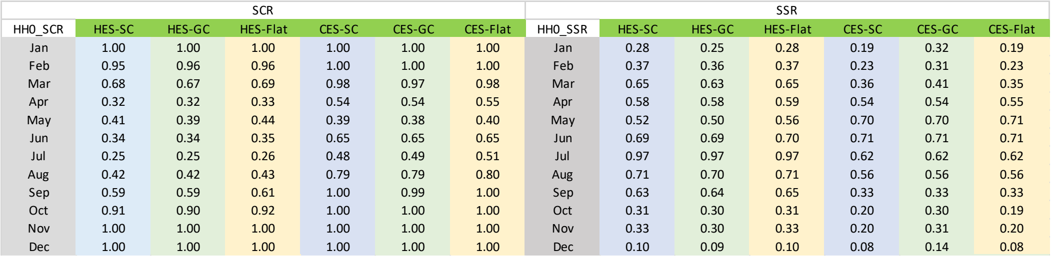
Monthly SCR and SSR of CES Community for Validation Study

	Combination	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
SCR	1	1.00	1.00	0.64	0.25	0.12	0.19	0.17	0.21	0.18	0.51	0.57	1.00	0.31
	2	1.00	1.00	1.00	0.76	0.69	0.57	0.44	0.50	0.53	0.89	0.82	1.00	0.67
	3	1.00	1.00	1.00	0.99	0.86	0.56	0.41	0.47	0.49	0.99	0.94	1.00	0.70
	4	1.00	1.00	1.00	0.95	0.83	0.62	0.46	0.62	0.49	1.00	0.97	1.00	0.73
	5	1.00	1.00	1.00	0.94	0.83	0.59	0.41	0.52	0.44	0.98	0.93	1.00	0.69
	6	1.00	1.00	1.00	1.00	0.87	0.53	0.41	0.45	0.56	0.97	0.93	1.00	0.70
	7	1.00	1.00	1.00	1.00	0.81	0.66	0.49	0.65	0.57	1.00	1.00	1.00	0.75
	8	1.00	1.00	1.00	0.85	0.72	0.52	0.34	0.39	0.45	0.91	0.88	1.00	0.63
	9	1.00	1.00	1.00	0.91	0.60	0.47	0.33	0.42	0.41	0.94	0.86	1.00	0.61
	10	1.00	1.00	1.00	0.84	0.64	0.49	0.36	0.42	0.42	0.95	0.85	1.00	0.62
	11	1.00	1.00	1.00	0.78	0.78	0.50	0.43	0.58	0.52	0.97	0.95	1.00	0.68
	12	1.00	1.00	1.00	0.94	0.65	0.54	0.36	0.45	0.45	0.95	0.91	1.00	0.65
	13	1.00	1.00	1.00	0.99	0.78	0.62	0.42	0.53	0.52	0.98	0.96	1.00	0.71
	14	1.00	1.00	1.00	0.73	0.95	0.95	0.58	0.76	0.74	1.00	1.00	1.00	0.83
	15	1.00	1.00	1.00	0.97	0.96	0.64	0.51	0.62	0.58	1.00	1.00	1.00	0.77
	16	1.00	1.00	1.00	1.00	0.82	0.65	0.54	0.56	0.61	1.00	1.00	1.00	0.76
	Mean	1.00	1.00	0.98	0.87	0.75	0.57	0.42	0.51	0.50	0.94	0.91	1.00	0.68
	SD	0.00	0.00	0.09	0.19	0.20	0.15	0.10	0.13	0.12	0.12	0.11	0.00	0.11
	Error	0.00	0.00	0.02	0.05	0.05	0.04	0.02	0.03	0.03	0.03	0.03	0.00	0.03

	Combination	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
SSR	1	0.32	0.62	0.82	1.00	1.00	1.00	1.00	1.00	1.00	0.98	0.98	0.17	0.63
	2	0.06	0.14	0.27	0.82	1.00	0.99	1.00	0.99	1.00	0.85	0.71	0.07	0.40
	3	0.07	0.09	0.25	0.65	1.00	1.00	1.00	1.00	1.00	0.77	0.64	0.11	0.40
	4	0.08	0.10	0.24	0.72	1.00	0.99	1.00	0.99	1.00	0.70	0.61	0.06	0.38
	5	0.07	0.09	0.26	0.70	1.00	0.99	1.00	1.00	1.00	0.78	0.66	0.09	0.39
	6	0.07	0.10	0.29	0.62	0.99	1.00	1.00	1.00	1.00	0.80	0.65	0.06	0.38
	7	0.07	0.12	0.23	0.23	0.81	0.98	1.00	0.99	1.00	0.67	0.57	0.94	0.54
	8	0.09	0.12	0.34	0.78	1.00	1.00	1.00	1.00	1.00	0.91	0.70	0.10	0.44
	9	0.09	0.13	0.31	0.75	1.00	1.00	1.00	1.00	1.00	0.85	0.74	0.07	0.40
	10	0.07	0.12	0.32	0.79	1.00	1.00	1.00	1.00	1.00	0.83	0.76	0.05	0.37
	11	0.09	0.13	0.31	0.81	1.00	1.00	1.00	1.00	1.00	0.80	0.63	0.06	0.40
	12	0.10	0.13	0.30	0.70	1.00	1.00	1.00	1.00	1.00	0.85	0.67	0.07	0.45
	13	0.09	0.11	0.25	0.63	0.99	0.99	1.00	1.00	1.00	0.76	0.61	0.06	0.39
	14	0.05	0.12	0.22	0.86	0.95	0.95	1.00	0.99	1.00	0.55	0.51	0.03	0.32
	15	0.06	0.10	0.24	0.72	0.90	0.98	1.00	0.99	1.00	0.63	0.60	0.04	0.34
	16	0.06	0.11	0.24	0.67	0.99	0.98	1.00	0.99	1.00	0.71	0.52	0.04	0.34
	Mean	0.09	0.15	0.31	0.71	0.97	0.99	1.00	0.99	1.00	0.78	0.66	0.13	0.41
	SD	0.06	0.13	0.14	0.16	0.05	0.01	0.00	0.00	0.00	0.11	0.11	0.22	0.08
	Error	0.02	0.03	0.04	0.04	0.01	0.00	0.00	0.00	0.00	0.03	0.03	0.06	0.02

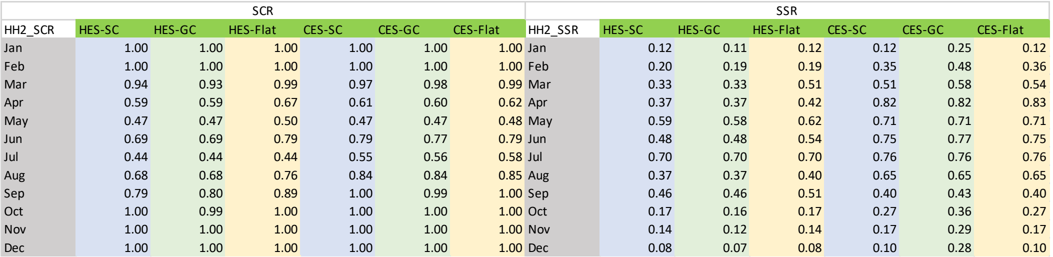
Appendix C: Results of Chapter 5

Monthly SCR and SSR of HH0



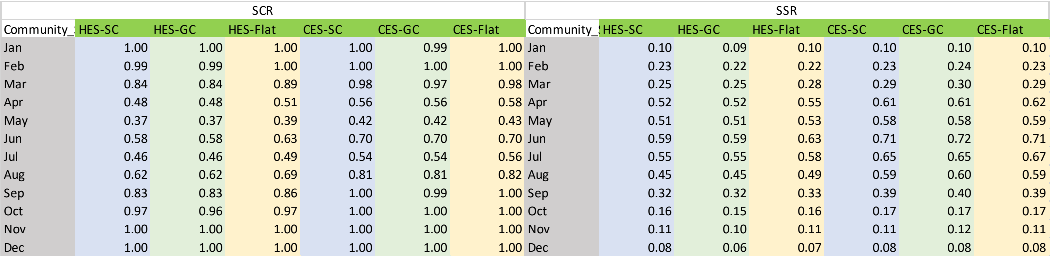
SCR							SSR						
HH0_SCR	HES-SC	HES-GC	HES-Flat	CES-SC	CES-GC	CES-Flat	HH0_SSR	HES-SC	HES-GC	HES-Flat	CES-SC	CES-GC	CES-Flat
Jan	1.00	1.00	1.00	1.00	1.00	1.00	Jan	0.28	0.25	0.28	0.19	0.32	0.19
Feb	0.95	0.96	0.96	1.00	1.00	1.00	Feb	0.37	0.36	0.37	0.23	0.31	0.23
Mar	0.68	0.67	0.69	0.98	0.97	0.98	Mar	0.65	0.63	0.65	0.36	0.41	0.35
Apr	0.32	0.32	0.33	0.54	0.54	0.55	Apr	0.58	0.58	0.59	0.54	0.54	0.55
May	0.41	0.39	0.44	0.39	0.38	0.40	May	0.52	0.50	0.56	0.70	0.70	0.71
Jun	0.34	0.34	0.35	0.65	0.65	0.65	Jun	0.69	0.69	0.70	0.71	0.71	0.71
Jul	0.25	0.25	0.26	0.48	0.49	0.51	Jul	0.97	0.97	0.97	0.62	0.62	0.62
Aug	0.42	0.42	0.43	0.79	0.79	0.80	Aug	0.71	0.70	0.71	0.56	0.56	0.56
Sep	0.59	0.59	0.61	1.00	0.99	1.00	Sep	0.63	0.64	0.65	0.33	0.33	0.33
Oct	0.91	0.90	0.92	1.00	1.00	1.00	Oct	0.31	0.30	0.31	0.20	0.30	0.19
Nov	1.00	1.00	1.00	1.00	1.00	1.00	Nov	0.33	0.30	0.33	0.20	0.31	0.20
Dec	1.00	1.00	1.00	1.00	1.00	1.00	Dec	0.10	0.09	0.10	0.08	0.14	0.08

Monthly SCR and SSR of HH2



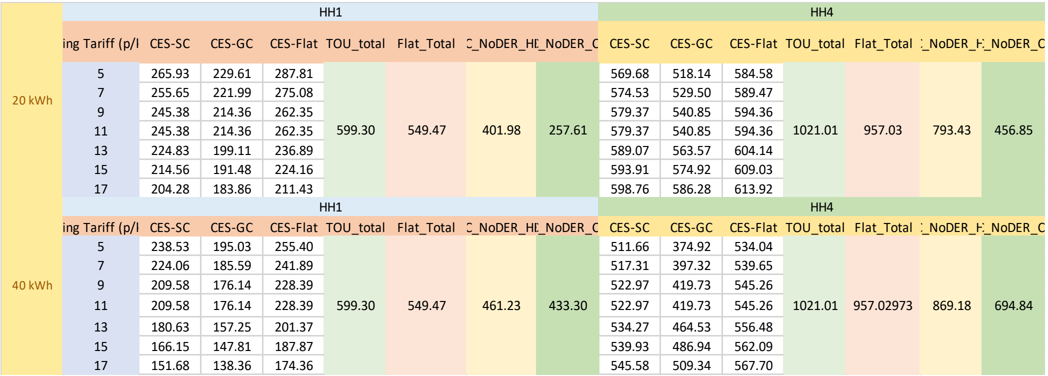
SCR							SSR						
HH2_SCR	HES-SC	HES-GC	HES-Flat	CES-SC	CES-GC	CES-Flat	HH2_SSR	HES-SC	HES-GC	HES-Flat	CES-SC	CES-GC	CES-Flat
Jan	1.00	1.00	1.00	1.00	1.00	1.00	Jan	0.12	0.11	0.12	0.12	0.25	0.12
Feb	1.00	1.00	1.00	1.00	1.00	1.00	Feb	0.20	0.19	0.19	0.35	0.48	0.36
Mar	0.94	0.93	0.99	0.97	0.98	0.99	Mar	0.33	0.33	0.51	0.51	0.58	0.54
Apr	0.59	0.59	0.67	0.61	0.60	0.62	Apr	0.37	0.37	0.42	0.82	0.82	0.83
May	0.47	0.47	0.50	0.47	0.47	0.48	May	0.59	0.58	0.62	0.71	0.71	0.71
Jun	0.69	0.69	0.79	0.79	0.77	0.79	Jun	0.48	0.48	0.54	0.75	0.77	0.75
Jul	0.44	0.44	0.44	0.55	0.56	0.58	Jul	0.70	0.70	0.70	0.76	0.76	0.76
Aug	0.68	0.68	0.76	0.84	0.84	0.85	Aug	0.37	0.37	0.40	0.65	0.65	0.65
Sep	0.79	0.80	0.89	1.00	0.99	1.00	Sep	0.46	0.46	0.51	0.40	0.43	0.40
Oct	1.00	0.99	1.00	1.00	1.00	1.00	Oct	0.17	0.16	0.17	0.27	0.36	0.27
Nov	1.00	1.00	1.00	1.00	1.00	1.00	Nov	0.14	0.12	0.14	0.17	0.29	0.17
Dec	1.00	1.00	1.00	1.00	1.00	1.00	Dec	0.08	0.07	0.08	0.10	0.28	0.10

Monthly SCR and SSR of Street



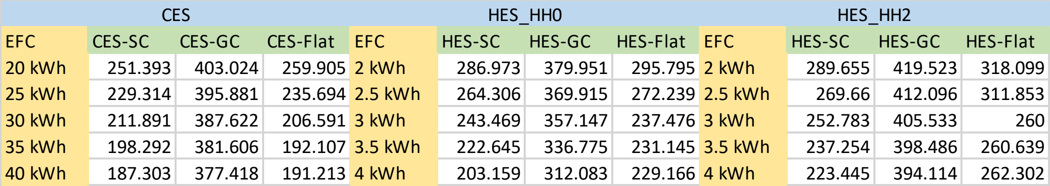
SCR							SSR						
Community_	HES-SC	HES-GC	HES-Flat	CES-SC	CES-GC	CES-Flat	Community_	HES-SC	HES-GC	HES-Flat	CES-SC	CES-GC	CES-Flat
Jan	1.00	1.00	1.00	1.00	0.99	1.00	Jan	0.10	0.09	0.10	0.10	0.10	0.10
Feb	0.99	0.99	1.00	1.00	1.00	1.00	Feb	0.23	0.22	0.22	0.23	0.24	0.23
Mar	0.84	0.84	0.89	0.98	0.97	0.98	Mar	0.25	0.25	0.28	0.29	0.30	0.29
Apr	0.48	0.48	0.51	0.56	0.56	0.58	Apr	0.52	0.52	0.55	0.61	0.61	0.62
May	0.37	0.37	0.39	0.42	0.42	0.43	May	0.51	0.51	0.53	0.58	0.58	0.59
Jun	0.58	0.58	0.63	0.70	0.70	0.70	Jun	0.59	0.59	0.63	0.71	0.72	0.71
Jul	0.46	0.46	0.49	0.54	0.54	0.56	Jul	0.55	0.55	0.58	0.65	0.65	0.67
Aug	0.62	0.62	0.69	0.81	0.81	0.82	Aug	0.45	0.45	0.49	0.59	0.60	0.59
Sep	0.83	0.83	0.86	1.00	0.99	1.00	Sep	0.32	0.32	0.33	0.39	0.40	0.39
Oct	0.97	0.96	0.97	1.00	1.00	1.00	Oct	0.16	0.15	0.16	0.17	0.17	0.17
Nov	1.00	1.00	1.00	1.00	1.00	1.00	Nov	0.11	0.10	0.11	0.11	0.12	0.11
Dec	1.00	1.00	1.00	1.00	1.00	1.00	Dec	0.08	0.06	0.07	0.08	0.08	0.08

Annual Energy Cost of Light and Intensive Energy Users



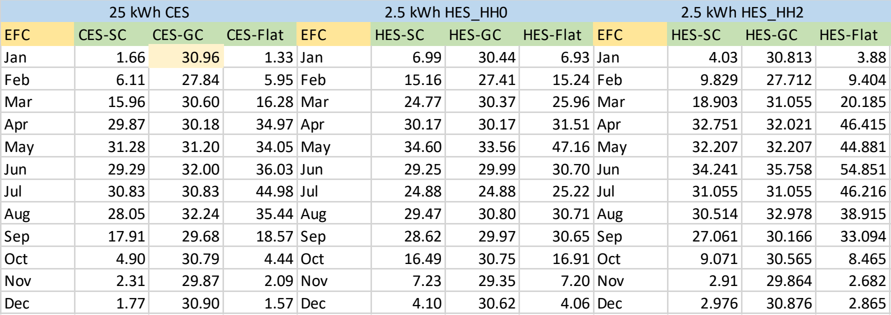
	HH1								HH4						
	ing Tariff (p/l	CES-SC	CES-GC	CES-Flat	TOU_total	Flat_Total	C_NoDER_HI	_NoDER_C	CES-SC	CES-GC	CES-Flat	TOU_total	Flat_Total	_NoDER_H	_NoDER_C
20 kWh	5	265.93	229.61	287.81	599.30	549.47	401.98	257.61	569.68	518.14	584.58	1021.01	957.03	793.43	456.85
	7	255.65	221.99	275.08					574.53	529.50	589.47				
	9	245.38	214.36	262.35					579.37	540.85	594.36				
	11	245.38	214.36	262.35					579.37	540.85	594.36				
	13	224.83	199.11	236.89					589.07	563.57	604.14				
	15	214.56	191.48	224.16					593.91	574.92	609.03				
	17	204.28	183.86	211.43					598.76	586.28	613.92				
	HH1								HH4						
	ing Tariff (p/l	CES-SC	CES-GC	CES-Flat	TOU_total	Flat_Total	C_NoDER_HI	_NoDER_C	CES-SC	CES-GC	CES-Flat	TOU_total	Flat_Total	_NoDER_H	_NoDER_C
40 kWh	5	238.53	195.03	255.40	599.30	549.47	461.23	433.30	511.66	374.92	534.04	1021.01	957.02973	869.18	694.84
	7	224.06	185.59	241.89					517.31	397.32	539.65				
	9	209.58	176.14	228.39					522.97	419.73	545.26				
	11	209.58	176.14	228.39					522.97	419.73	545.26				
	13	180.63	157.25	201.37					534.27	464.53	556.48				
	15	166.15	147.81	187.87					539.93	486.94	562.09				
	17	151.68	138.36	174.36					545.58	509.34	567.70				

Battery Equivalent Full Cycles of Light and Intensive Energy Users



CES				HES_HH0				HES_HH2			
EFC	CES-SC	CES-GC	CES-Flat	EFC	HES-SC	HES-GC	HES-Flat	EFC	HES-SC	HES-GC	HES-Flat
20 kWh	251.393	403.024	259.905	2 kWh	286.973	379.951	295.795	2 kWh	289.655	419.523	318.099
25 kWh	229.314	395.881	235.694	2.5 kWh	264.306	369.915	272.239	2.5 kWh	269.66	412.096	311.853
30 kWh	211.891	387.622	206.591	3 kWh	243.469	357.147	237.476	3 kWh	252.783	405.533	260
35 kWh	198.292	381.606	192.107	3.5 kWh	222.645	336.775	231.145	3.5 kWh	237.254	398.486	260.639
40 kWh	187.303	377.418	191.213	4 kWh	203.159	312.083	229.166	4 kWh	223.445	394.114	262.302

Battery Equivalent Full Cycles of Light and Intensive Energy Users



25 kWh CES				2.5 kWh HES_HH0				2.5 kWh HES_HH2			
EFC	CES-SC	CES-GC	CES-Flat	EFC	HES-SC	HES-GC	HES-Flat	EFC	HES-SC	HES-GC	HES-Flat
Jan	1.66	30.96	1.33	Jan	6.99	30.44	6.93	Jan	4.03	30.813	3.88
Feb	6.11	27.84	5.95	Feb	15.16	27.41	15.24	Feb	9.829	27.712	9.404
Mar	15.96	30.60	16.28	Mar	24.77	30.37	25.96	Mar	18.903	31.055	20.185
Apr	29.87	30.18	34.97	Apr	30.17	30.17	31.51	Apr	32.751	32.021	46.415
May	31.28	31.20	34.05	May	34.60	33.56	47.16	May	32.207	32.207	44.881
Jun	29.29	32.00	36.03	Jun	29.25	29.99	30.70	Jun	34.241	35.758	54.851
Jul	30.83	30.83	44.98	Jul	24.88	24.88	25.22	Jul	31.055	31.055	46.216
Aug	28.05	32.24	35.44	Aug	29.47	30.80	30.71	Aug	30.514	32.978	38.915
Sep	17.91	29.68	18.57	Sep	28.62	29.97	30.65	Sep	27.061	30.166	33.094
Oct	4.90	30.79	4.44	Oct	16.49	30.75	16.91	Oct	9.071	30.565	8.465
Nov	2.31	29.87	2.09	Nov	7.23	29.35	7.20	Nov	2.91	29.864	2.682
Dec	1.77	30.90	1.57	Dec	4.10	30.62	4.06	Dec	2.976	30.876	2.865

Appendix D: Results of Chapter 6

Annual SCR and SSR of Households in Germany

DE

Heavy Users

Energy Savi	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat	SCR	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat	SSR	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat
0.00	1170.88	1170.88	1170.88	1170.88	1170.88	1170.88	0.00	0.40	0.40	0.40	0.40	0.40	0.40	0.00	0.27	0.27	0.27	0.27	0.27	0.27
2.00	1780.42	1813.00	1927.97	3074.02	2800.11	2814.59	2.00	0.63	0.64	0.70	0.64	0.64	0.65	2.00	0.41	0.42	0.45	0.71	0.65	0.65
2.50	1881.66	1916.93	2030.04	3235.19	2892.40	2905.36	2.50	0.67	0.68	0.74	0.66	0.67	0.68	2.50	0.44	0.44	0.47	0.75	0.67	0.67
3.00	1969.26	2011.15	2124.44	3387.58	2979.19	2990.45	3.00	0.71	0.72	0.77	0.68	0.69	0.70	3.00	0.46	0.47	0.49	0.79	0.69	0.69
3.50	2047.72	2095.83	2191.81	3525.21	3031.51	3047.49	3.50	0.74	0.75	0.80	0.70	0.71	0.72	3.50	0.48	0.49	0.51	0.82	0.70	0.71
4.00	2116.46	2171.29	2258.40	3596.95	3053.88	3081.62	4.00	0.77	0.78	0.82	0.71	0.72	0.73	4.00	0.49	0.50	0.52	0.83	0.71	0.72
4.50	2181.68	2224.86	2307.57	3674.16	3066.13	3099.44	4.50	0.79	0.80	0.84	0.71	0.72	0.74	4.50	0.51	0.52	0.54	0.85	0.71	0.72

Light Users

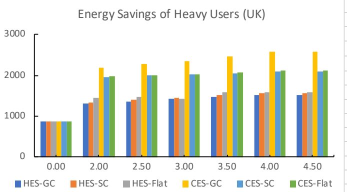
Energy Savi	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat	SCR	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat	SSR	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat
0.00	417.77	417.77	417.77	417.77	417.77	417.77	0.00	0.27	0.27	0.27	0.27	0.27	0.27	0.00	0.28	0.28	0.28	0.28	0.28	0.28
2.00	885.61	921.59	921.33	770.04	720.13	723.03	2.00	0.32	0.33	0.45	0.49	0.48	0.65	2.00	0.60	0.62	0.62	0.52	0.49	0.49
2.50	965.42	999.27	999.56	847.47	771.58	774.06	2.50	0.35	0.36	0.47	0.52	0.52	0.67	2.50	0.65	0.67	0.67	0.57	0.52	0.52
3.00	1025.92	1058.82	1037.06	929.23	829.01	830.11	3.00	0.38	0.39	0.49	0.56	0.55	0.69	3.00	0.69	0.71	0.70	0.63	0.56	0.56
3.50	1071.15	1102.23	1110.06	987.38	871.37	881.29	3.50	0.40	0.40	0.51	0.57	0.57	0.71	3.50	0.72	0.74	0.75	0.67	0.59	0.59
4.00	1103.80	1133.29	1144.12	1035.06	889.84	906.29	4.00	0.41	0.42	0.52	0.59	0.58	0.72	4.00	0.74	0.76	0.77	0.70	0.60	0.61
4.50	1117.99	1146.79	1161.11	1058.44	959.16	927.04	4.50	0.42	0.42	0.54	0.59	0.58	0.72	4.50	0.75	0.77	0.78	0.71	0.65	0.63

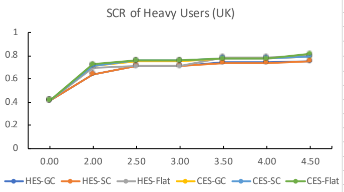
Community

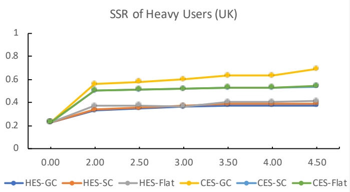
Energy Savi	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat	SCR	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat	SSR	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat
0.00	7366.23	7366.23	7366.23	7366.23	7366.23	7366.23	0.00	0.25	0.25	0.25	0.25	0.25	0.25	0.00	0.27	0.27	0.27	0.27	0.27	0.27
2.00	14012.64	14156.88	13752.97	14866.63	15069.73	15226.56	2.00	0.50	0.50	0.50	0.53	0.53	0.55	2.00	0.52	0.52	0.51	0.55	0.56	0.56
2.50	14764.09	14971.76	14651.85	15660.81	15927.87	16079.92	2.50	0.53	0.54	0.53	0.57	0.57	0.58	2.50	0.55	0.55	0.54	0.58	0.59	0.60
3.00	15451.44	15709.08	15568.27	16305.04	16649.73	16812.89	3.00	0.56	0.56	0.57	0.59	0.60	0.61	3.00	0.57	0.58	0.58	0.60	0.62	0.62
3.50	16039.22	16327.50	16079.23	16698.86	17132.77	17351.81	3.50	0.59	0.59	0.59	0.61	0.61	0.63	3.50	0.59	0.60	0.60	0.62	0.63	0.64
4.00	16487.27	16796.03	16580.85	16895.32	17417.95	17741.04	4.00	0.61	0.61	0.61	0.62	0.63	0.64	4.00	0.61	0.62	0.61	0.63	0.65	0.66
4.50	16796.81	17126.62	16931.80	16972.93	17499.02	18023.51	4.50	0.62	0.62	0.62	0.63	0.63	0.66	4.50	0.62	0.63	0.63	0.63	0.65	0.67

Annual SCR and SSR of Households in the UK

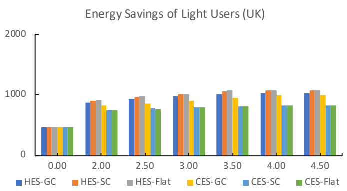
UK																				
Heavy Users																				
Energy Savi	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat	SCR	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat	SSR	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat
0.00	881.05	881.05	881.05	881.05	881.05	881.05	0.00	0.41	0.41	0.41	0.41	0.41	0.41	0.00	0.23	0.23	0.23	0.23	0.23	0.23
2.00	1299.71	1320.70	1456.47	2180.06	1955.23	1971.71	2.00	0.64	0.64	0.69	0.71	0.71	0.72	2.00	0.33	0.34	0.37	0.56	0.50	0.50
2.50	1365.39	1392.63	1474.31	2269.93	1997.12	2013.48	2.50	0.71	0.71	0.71	0.75	0.76	0.76	2.50	0.35	0.36	0.38	0.58	0.51	0.52
3.00	1421.92	1456.50	1433.85	2349.93	2022.14	2032.63	3.00	0.71	0.71	0.71	0.75	0.76	0.76	3.00	0.36	0.37	0.37	0.60	0.52	0.52
3.50	1467.08	1511.18	1580.80	2464.14	2054.05	2073.15	3.50	0.74	0.74	0.79	0.77	0.78	0.77	3.50	0.38	0.39	0.40	0.63	0.53	0.53
4.00	1510.43	1559.12	1582.44	2574.77	2091.92	2114.01	4.00	0.74	0.74	0.79	0.77	0.78	0.77	4.00	0.38	0.39	0.40	0.63	0.53	0.53
4.50	1510.43	1559.12	1582.44	2574.77	2091.92	2114.00	4.50	0.75	0.75	0.80	0.79	0.79	0.81	4.50	0.37	0.39	0.41	0.69	0.54	0.54

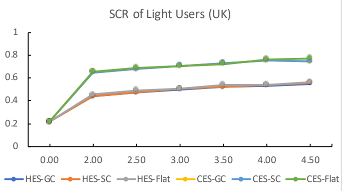


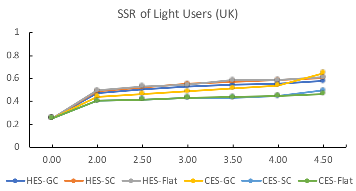




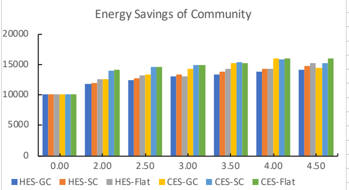
Light Users																				
Energy Savi	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat	SCR	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat	SSR	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat
0.00	464.85	464.85	464.85	464.85	464.85	464.85	0.00	0.22	0.22	0.22	0.22	0.22	0.22	0.00	0.25	0.25	0.25	0.25	0.25	0.25
2.00	877.52	900.21	914.50	818.37	744.67	744.05	2.00	0.44	0.44	0.45	0.65	0.65	0.66	2.00	0.47	0.49	0.49	0.44	0.40	0.40
2.50	936.13	965.97	982.13	858.67	771.15	769.99	2.50	0.47	0.48	0.49	0.68	0.68	0.69	2.50	0.51	0.52	0.53	0.46	0.42	0.42
3.00	980.27	1018.74	1006.09	901.28	792.23	800.02	3.00	0.50	0.50	0.50	0.71	0.71	0.70	3.00	0.53	0.55	0.54	0.49	0.43	0.43
3.50	1012.25	1055.78	1079.69	954.08	803.97	804.44	3.50	0.52	0.52	0.54	0.73	0.73	0.72	3.50	0.55	0.57	0.58	0.52	0.43	0.43
4.00	1032.40	1081.05	1079.69	1000.81	824.95	831.51	4.00	0.53	0.54	0.54	0.75	0.76	0.76	4.00	0.56	0.58	0.58	0.54	0.45	0.45
4.50	1032.40	1081.05	1079.70	1000.81	824.95	831.50	4.50	0.55	0.56	0.56	0.74	0.75	0.77	4.50	0.58	0.60	0.61	0.64	0.50	0.46

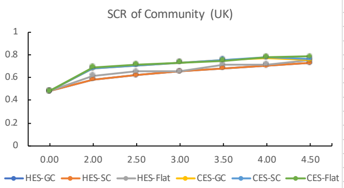


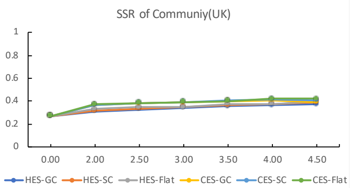




Community																				
Energy Savi	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat	SCR	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat	SSR	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat
0.00	10202.43	10202.43	10202.43	10202.43	10202.43	10202.43	0.00	0.48	0.48	0.48	0.48	0.48	0.48	0.00	0.27	0.27	0.27	0.27	0.27	0.27
2.00	11805.68	12020.04	12586.46	12640.18	14009.80	14155.00	2.00	0.58	0.58	0.62	0.68	0.68	0.69	2.00	0.31	0.32	0.33	0.37	0.37	0.37
2.50	12470.93	12748.58	13232.44	13444.29	14577.86	14682.52	2.50	0.62	0.62	0.65	0.71	0.71	0.72	2.50	0.33	0.33	0.35	0.38	0.38	0.38
3.00	13022.38	13370.49	13155.53	14301.39	15015.66	14971.21	3.00	0.65	0.65	0.65	0.73	0.73	0.73	3.00	0.34	0.35	0.34	0.39	0.39	0.39
3.50	13463.40	13883.86	14356.60	15198.56	15484.78	15300.86	3.50	0.68	0.68	0.72	0.75	0.76	0.75	3.50	0.35	0.36	0.38	0.40	0.41	0.40
4.00	13817.90	14329.54	14357.97	16113.85	15886.10	16007.57	4.00	0.70	0.70	0.72	0.77	0.78	0.78	4.00	0.36	0.38	0.38	0.41	0.42	0.42
4.50	14221.04	14821.65	15188.26	14475.10	15261.75	16003.15	4.50	0.73	0.73	0.75	0.75	0.76	0.78	4.50	0.37	0.39	0.40	0.39	0.41	0.42







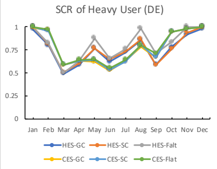
Comparison of Household Payback Time (Years)

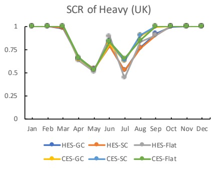
									2020				2030				2040			
	DE																			
	Energy savings (kWh)				Bill Savings (€)				Payback Time (Years)				Payback Time (Years)				Payback Time (Years)			
	Heavy		Light		Heavy		Light		Heavy		Light		Heavy		Light		Heavy		Light	
Capacity	HES	CES	HES	CES	HES	CES	HES	CES	HES	CES	HES	CES	HES	CES	HES	CES	HES	CES	HES	CES
0	1162.11	1162.11	417.77	417.77	299.01	299.01	107.49	107.49	8.28	8.28	13.89	13.89	5.49	5.49	9.20	9.20	4.68	4.68	7.86	7.86
2	1927.97	2814.59	921.33	723.03	496.07	724.19	237.06	186.04	9.70	6.60	15.79	16.44	6.56	4.40	10.68	10.94	5.71	3.73	9.29	9.28
2.5	2030.04	2905.36	999.56	774.06	522.33	747.55	257.19	199.16	10.10	7.00	16.29	17.25	6.85	4.67	11.05	11.50	5.49	3.95	9.60	9.75
3	2124.44	2990.45	1037.06	830.11	546.62	769.44	266.84	213.59	9.91	7.36	16.18	17.88	6.55	4.91	10.69	11.93	5.31	4.16	9.16	10.10
3.5	2191.81	3047.49	1110.06	881.29	563.95	784.12	285.62	226.76	10.35	7.79	16.59	18.59	6.84	5.20	10.97	12.41	5.18	4.40	9.39	10.51
4	2258.40	3081.62	1144.12	906.29	581.09	792.90	294.38	233.19	10.76	8.27	17.33	19.61	7.13	5.54	11.48	13.13	5.07	4.69	9.80	11.13
4.5	2307.57	3099.44	1161.11	927.04	593.74	797.49	298.75	238.53	11.23	8.78	18.21	20.65	7.44	5.90	12.07	13.87	4.98	5.00	10.30	11.76
5	2339.99	3113.99	1168.14	936.30	602.08	801.23	300.56	240.91	11.74	9.33	19.18	21.89	7.79	6.28	12.72	14.74	4.93	5.33	10.85	12.50
	UK																			
	Energy savings (kWh)				Bill Savings (€)				Payback Time (Years)				Payback Time (Years)				Payback Time (Years)			
	Heavy		Light		Heavy		Light		Heavy		Light		Heavy		Light		Heavy		Light	
Capacity	HES	CES	HES	CES	HES	CES	HES	CES	HES	CES	HES	CES	HES	CES	HES	CES	HES	CES	HES	CES
0	881.752	881.752	464.849	464.849	163.12	163.12	86.00	86.00	13.03	13.03	17.50	17.50	8.63	8.63	11.59	11.59	7.37	7.37	9.90	9.90
2	1383.41	1930.662	892.954	702.884	255.93	357.17	165.20	130.03	18.91	13.75	25.67	20.06	12.79	9.29	17.36	18.96	11.13	7.95	15.11	16.21
2.5	1445.054	1971.327	955.672	735.924	267.33	364.70	176.80	136.15	19.80	14.77	26.56	21.48	13.43	10.01	18.01	20.20	11.67	8.56	15.66	17.27
3	1541.974	2009.05	1060.472	764.451	285.27	371.67	196.19	141.42	20.29	15.70	26.63	22.81	13.79	10.67	18.10	21.36	11.97	9.13	15.72	18.27
3.5	1541.831	2042.054	1060.472	782.884	285.24	377.78	196.19	144.83	21.72	16.71	28.51	24.33	14.79	11.38	19.42	22.75	12.83	9.74	16.84	19.46
4	1541.831	2067.364	1060.472	802.147	285.24	382.46	196.19	148.40	23.15	17.68	30.39	25.72	15.79	12.06	20.73	23.98	13.69	10.32	17.97	20.52
4.5	1541.736	2106.502	1060.286	820.521	285.22	389.70	196.15	151.80	24.58	18.53	32.28	27.08	16.79	12.66	22.05	25.20	14.55	10.84	19.10	21.57

Monthly SCR and SSR of Households in the UK and Germany

Comparison of 30 kWp PV and 30 kWh Storage

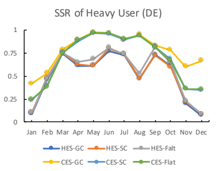
SCR	DE						UK					
	HES-GC	HES-SC	HES-Falt	CES-GC	CES-SC	CES-Flat	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat
Jan	0.97	1.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Feb	0.80	0.81	0.82	0.96	0.96	0.97	1.00	1.00	1.00	1.00	1.00	1.00
Mar	0.49	0.50	0.50	0.59	0.59	0.59	0.98	0.98	1.00	1.00	1.00	1.00
Apr	0.59	0.60	0.63	0.63	0.63	0.64	0.65	0.65	0.63	0.64	0.65	0.66
May	0.77	0.77	0.88	0.62	0.64	0.65	0.54	0.54	0.51	0.53	0.53	0.53
Jun	0.62	0.65	0.66	0.53	0.53	0.55	0.79	0.79	0.89	0.81	0.84	0.84
Jul	0.72	0.73	0.76	0.63	0.62	0.64	0.52	0.52	0.44	0.62	0.63	0.65
Aug	0.86	0.87	0.98	0.79	0.80	0.81	0.77	0.76	0.83	0.90	0.90	0.85
Sep	0.59	0.58	0.71	0.67	0.67	0.71	0.92	0.90	0.90	1.00	1.00	1.00
Oct	0.78	0.76	0.84	0.94	0.95	0.95	1.00	1.00	1.00	1.00	1.00	1.00
Nov	0.91	0.94	1.00	0.98	0.98	0.98	1.00	1.00	1.00	1.00	1.00	1.00
Dec	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

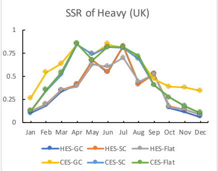

SCR of Heavy User (DE)


SCR of Heavy (UK)

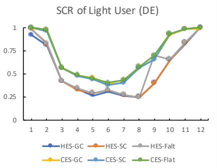
Heavy Users

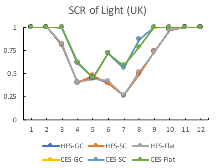
	DE						UK					
SSR	HES-GC	HES-SC	HES-Falt	CES-GC	CES-SC	CES-Flat	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat
Jan	0.09	0.10	0.10	0.42	0.24	0.25	0.10	0.12	0.12	0.26	0.12	0.12
Feb	0.46	0.48	0.47	0.53	0.39	0.38	0.18	0.20	0.19	0.54	0.34	0.35
Mar	0.74	0.76	0.75	0.79	0.75	0.75	0.34	0.35	0.35	0.63	0.51	0.54
Apr	0.61	0.62	0.65	0.90	0.88	0.89	0.41	0.41	0.39	0.84	0.84	0.85
May	0.61	0.61	0.68	0.98	0.97	0.97	0.67	0.67	0.62	0.73	0.74	0.67
Jun	0.77	0.80	0.81	0.97	0.96	0.96	0.54	0.55	0.60	0.84	0.81	0.81
Jul	0.73	0.74	0.74	0.89	0.89	0.90	0.82	0.82	0.69	0.80	0.80	0.81
Aug	0.47	0.47	0.53	0.95	0.94	0.94	0.41	0.41	0.44	0.69	0.68	0.71
Sep	0.73	0.72	0.81	0.83	0.82	0.81	0.53	0.52	0.52	0.47	0.40	0.40
Oct	0.61	0.60	0.65	0.78	0.68	0.67	0.16	0.17	0.17	0.38	0.27	0.27
Nov	0.20	0.22	0.23	0.60	0.36	0.36	0.11	0.14	0.14	0.37	0.17	0.17
Dec	0.07	0.09	0.09	0.66	0.35	0.36	0.06	0.08	0.08	0.34	0.10	0.10


SSR of Heavy User (DE)


SSR of Heavy (UK)

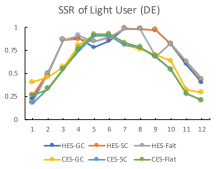
SCR	DE						UK					
Jan	HES-GC	HES-SC	HES-Falt	CES-GC	CES-SC	CES-Flat	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat
Feb	0.92	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Mar	0.81	0.82	0.83	0.97	0.96	0.97	1.00	1.00	1.00	1.00	1.00	1.00
Apr	0.42	0.42	0.42	0.56	0.56	0.56	0.81	0.81	0.82	0.99	0.99	1.00
May	0.33	0.33	0.34	0.48	0.47	0.49	0.40	0.40	0.40	0.62	0.61	0.62
Jun	0.26	0.29	0.29	0.45	0.44	0.45	0.46	0.48	0.44	0.45	0.45	0.45
Jul	0.31	0.32	0.32	0.39	0.37	0.40	0.39	0.39	0.42	0.72	0.72	0.72
Aug	0.27	0.27	0.27	0.41	0.40	0.43	0.26	0.26	0.26	0.56	0.56	0.58
Sep	0.25	0.25	0.25	0.56	0.56	0.58	0.49	0.49	0.52	0.87	0.87	0.79
Oct	0.40	0.40	0.70	0.65	0.65	0.70	0.74	0.74	0.73	0.99	1.00	1.00
Nov	0.65	0.64	0.66	0.92	0.93	0.93	0.97	0.97	0.97	1.00	1.00	1.00
Dec	0.83	0.83	0.84	0.98	0.98	0.98	1.00	1.00	1.00	1.00	1.00	1.00
12	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

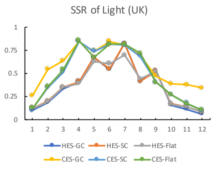

SCR of Light User (DE)


SCR of Light (UK)

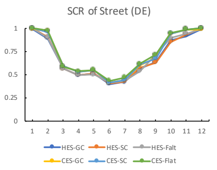
Light Users

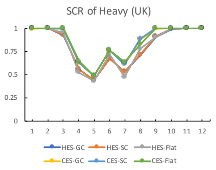
	DE						UK					
SSR	HES-GC	HES-SC	HES-Falt	CES-GC	CES-SC	CES-Flat	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat
Jan	0.22	0.26	0.19	0.40	0.17	0.26	0.10	0.12	0.12	0.26	0.12	0.12
Feb	0.48	0.50	0.49	0.45	0.34	0.32	0.18	0.20	0.19	0.54	0.34	0.35
Mar	0.85	0.86	0.86	0.57	0.55	0.54	0.34	0.35	0.35	0.63	0.51	0.54
Apr	0.87	0.86	0.90	0.80	0.75	0.77	0.41	0.41	0.39	0.84	0.84	0.85
May	0.78	0.84	0.84	0.91	0.90	0.92	0.67	0.67	0.62	0.73	0.74	0.67
Jun	0.85	0.88	0.89	0.91	0.90	0.92	0.54	0.55	0.60	0.84	0.81	0.81
Jul	0.98	0.98	0.98	0.80	0.81	0.83	0.82	0.82	0.69	0.80	0.80	0.81
Aug	0.98	0.98	0.98	0.76	0.78	0.78	0.41	0.41	0.44	0.69	0.68	0.71
Sep	0.96	0.97	0.68	0.70	0.67	0.68	0.53	0.52	0.52	0.47	0.40	0.40
Oct	0.81	0.81	0.82	0.63	0.54	0.54	0.16	0.17	0.17	0.38	0.27	0.27
Nov	0.59	0.62	0.62	0.32	0.28	0.28	0.11	0.14	0.14	0.37	0.17	0.17
Dec	0.40	0.43	0.44	0.29	0.20	0.20	0.06	0.08	0.08	0.34	0.10	0.10


SSR of Light User (DE)


SSR of Light (UK)

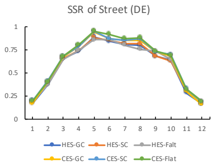
	DE						UK					
SCR	HES-GC	HES-SC	HES-Falt	CES-GC	CES-SC	CES-Flat	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat
Jan	0.99	1.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00	0.99	1.00	1.00
Feb	0.89	0.90	0.90	0.97	0.96	0.97	1.00	1.00	1.00	1.00	1.00	1.00
Mar	0.57	0.56	0.56	0.59	0.59	0.59	0.92	0.93	0.95	1.00	0.99	1.00
Apr	0.49	0.50	0.50	0.53	0.53	0.54	0.56	0.55	0.52	0.63	0.63	0.64
May	0.51	0.51	0.50	0.54	0.55	0.55	0.44	0.44	0.43	0.48	0.49	0.48
Jun	0.40	0.41	0.41	0.41	0.41	0.43	0.67	0.67	0.72	0.76	0.76	0.76
Jul	0.42	0.42	0.43	0.44	0.44	0.47	0.53	0.53	0.47	0.61	0.61	0.63
Aug	0.56	0.57	0.54	0.60	0.61	0.62	0.71	0.71	0.78	0.88	0.88	0.82
Sep	0.63	0.63	0.71	0.68	0.67	0.71	0.91	0.91	0.90	0.99	1.00	1.00
Oct	0.87	0.85	0.89	0.94	0.94	0.94	0.99	0.99	0.99	1.00	1.00	1.00
Nov	0.91	0.93	0.94	0.98	0.98	0.98	1.00	1.00	1.00	1.00	1.00	1.00
Dec	0.99	1.00	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

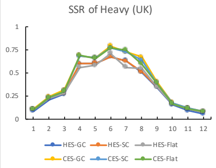

SCR of Street (DE)


SCR of Heavy (UK)

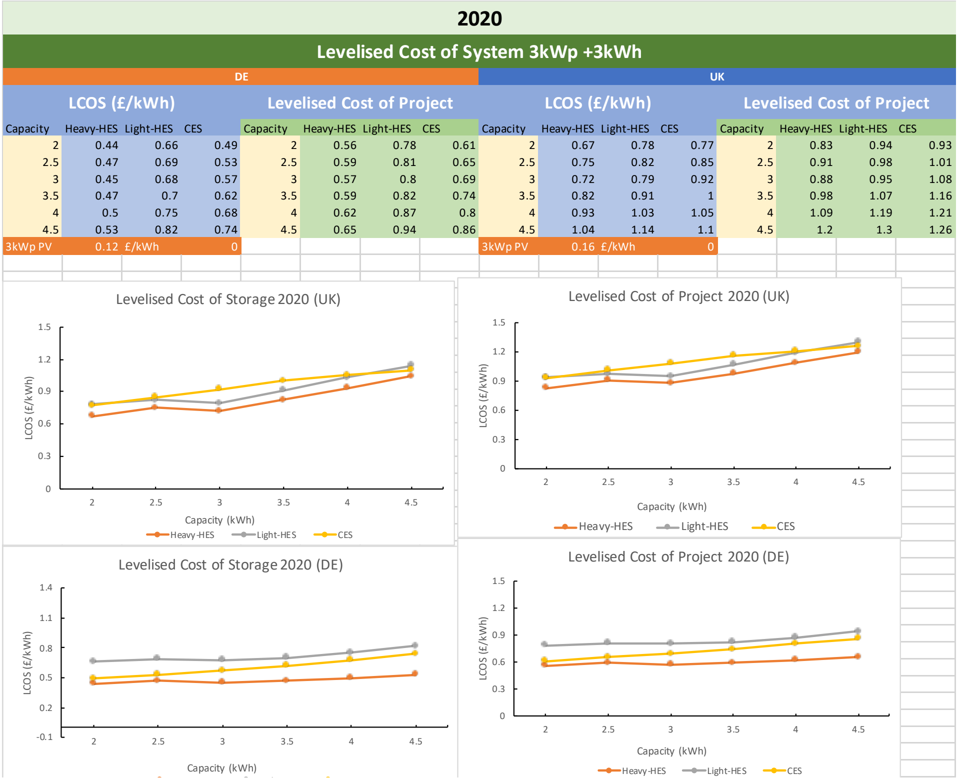
Ccmmunity

	DE						UK					
SSR	HES-GC	HES-SC	HES-Falt	CES-GC	CES-SC	CES-Flat	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat
Jan	0.17	0.20	0.19	0.17	0.20	0.19	0.08	0.10	0.10	0.10	0.10	0.10
Feb	0.37	0.39	0.37	0.40	0.41	0.40	0.21	0.23	0.22	0.24	0.23	0.23
Mar	0.65	0.65	0.65	0.67	0.68	0.68	0.27	0.28	0.28	0.31	0.30	0.30
Apr	0.73	0.74	0.74	0.79	0.79	0.81	0.60	0.60	0.56	0.69	0.68	0.69
May	0.89	0.88	0.86	0.95	0.95	0.95	0.60	0.60	0.58	0.66	0.66	0.66
Jun	0.84	0.86	0.86	0.87	0.87	0.92	0.67	0.67	0.71	0.79	0.77	0.77
Jul	0.81	0.82	0.80	0.86	0.86	0.87	0.63	0.62	0.56	0.72	0.72	0.75
Aug	0.80	0.81	0.75	0.86	0.87	0.88	0.51	0.51	0.55	0.67	0.63	0.59
Sep	0.68	0.68	0.73	0.72	0.72	0.73	0.35	0.35	0.35	0.40	0.39	0.39
Oct	0.64	0.63	0.64	0.68	0.70	0.69	0.15	0.16	0.16	0.17	0.17	0.17
Nov	0.28	0.31	0.30	0.30	0.32	0.32	0.09	0.11	0.11	0.12	0.11	0.11
Dec	0.16	0.18	0.18	0.15	0.19	0.18	0.05	0.08	0.07	0.08	0.08	0.08


SSR of Street (DE)

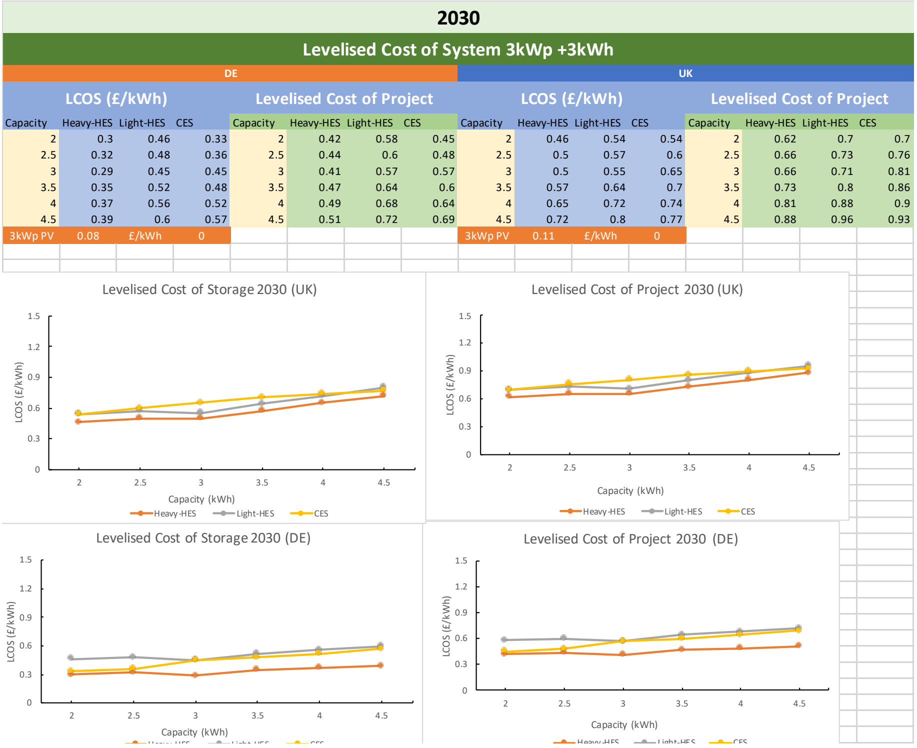

SSR of Heavy (UK)

LCOE of System 3kWp + 3kWh for 2020



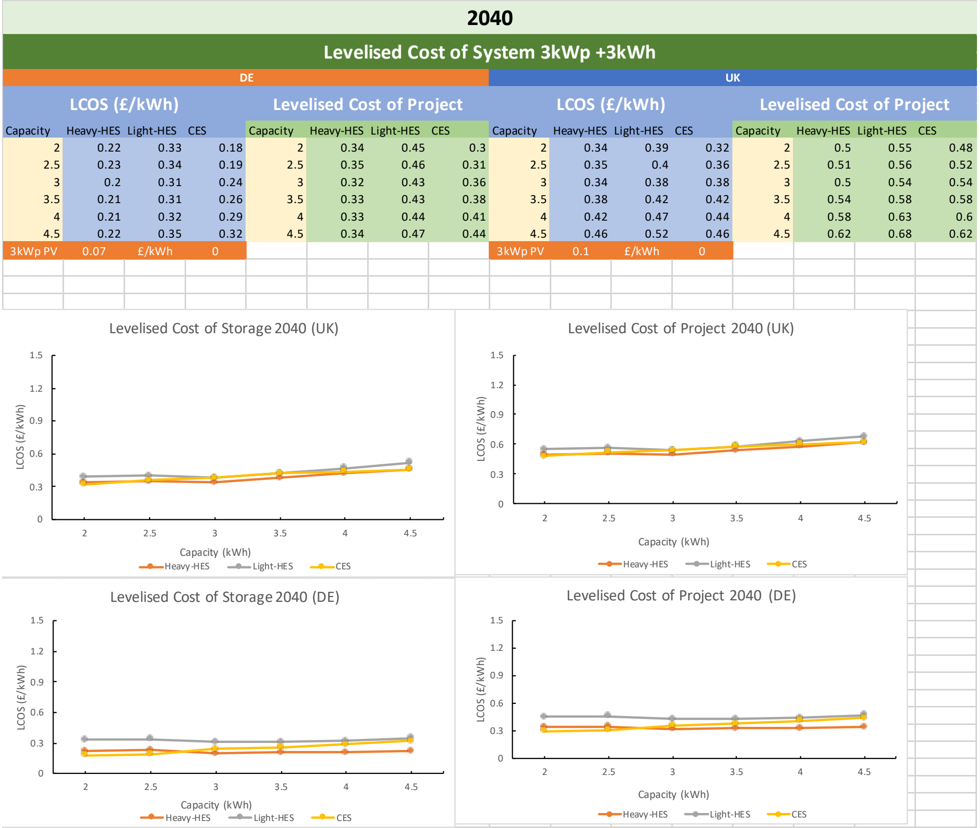
2020															
Levelised Cost of System 3kWp +3kWh															
DE								UK							
LCOS (£/kWh)				Levelised Cost of Project				LCOS (£/kWh)				Levelised Cost of Project			
Capacity	Heavy-HES	Light-HES	CES	Capacity	Heavy-HES	Light-HES	CES	Capacity	Heavy-HES	Light-HES	CES	Capacity	Heavy-HES	Light-HES	CES
2	0.44	0.66	0.49	2	0.56	0.78	0.61	2	0.67	0.78	0.77	2	0.83	0.94	0.93
2.5	0.47	0.69	0.53	2.5	0.59	0.81	0.65	2.5	0.75	0.82	0.85	2.5	0.91	0.98	1.01
3	0.45	0.68	0.57	3	0.57	0.8	0.69	3	0.72	0.79	0.92	3	0.88	0.95	1.08
3.5	0.47	0.7	0.62	3.5	0.59	0.82	0.74	3.5	0.82	0.91	1	3.5	0.98	1.07	1.16
4	0.5	0.75	0.68	4	0.62	0.87	0.8	4	0.93	1.03	1.05	4	1.09	1.19	1.21
4.5	0.53	0.82	0.74	4.5	0.65	0.94	0.86	4.5	1.04	1.14	1.1	4.5	1.2	1.3	1.26
3kWp PV	0.12	£/kWh	0					3kWp PV	0.16	£/kWh	0				

LCOE of System 3kWp + 3kWh for 2030



2030															
Levelised Cost of System 3kWp +3kWh															
DE								UK							
LCOS (£/kWh)				Levelised Cost of Project				LCOS (£/kWh)				Levelised Cost of Project			
Capacity	Heavy-HES	Light-HES	CES	Capacity	Heavy-HES	Light-HES	CES	Capacity	Heavy-HES	Light-HES	CES	Capacity	Heavy-HES	Light-HES	CES
2	0.3	0.46	0.33	2	0.42	0.58	0.45	2	0.46	0.54	0.54	2	0.62	0.7	0.7
2.5	0.32	0.48	0.36	2.5	0.44	0.6	0.48	2.5	0.5	0.57	0.6	2.5	0.66	0.73	0.76
3	0.29	0.45	0.45	3	0.41	0.57	0.57	3	0.5	0.55	0.65	3	0.66	0.71	0.81
3.5	0.35	0.52	0.48	3.5	0.47	0.64	0.6	3.5	0.57	0.64	0.7	3.5	0.73	0.8	0.86
4	0.37	0.56	0.52	4	0.49	0.68	0.64	4	0.65	0.72	0.74	4	0.81	0.88	0.9
4.5	0.39	0.6	0.57	4.5	0.51	0.72	0.69	4.5	0.72	0.8	0.77	4.5	0.88	0.96	0.93
3kWp PV	0.08	£/kWh	0					3kWp PV	0.11	£/kWh	0				

LCOE of System 3kWp + 3kWh for 2040



2040															
Levelised Cost of System 3kWp +3kWh															
DE								UK							
LCOS (£/kWh)				Levelised Cost of Project				LCOS (£/kWh)				Levelised Cost of Project			
Capacity	Heavy-HES	Light-HES	CES	Capacity	Heavy-HES	Light-HES	CES	Capacity	Heavy-HES	Light-HES	CES	Capacity	Heavy-HES	Light-HES	CES
2	0.22	0.33	0.18	2	0.34	0.45	0.3	2	0.34	0.39	0.32	2	0.5	0.55	0.48
2.5	0.23	0.34	0.19	2.5	0.35	0.46	0.31	2.5	0.35	0.4	0.36	2.5	0.51	0.56	0.52
3	0.2	0.31	0.24	3	0.32	0.43	0.36	3	0.34	0.38	0.38	3	0.5	0.54	0.54
3.5	0.21	0.31	0.26	3.5	0.33	0.43	0.38	3.5	0.38	0.42	0.42	3.5	0.54	0.58	0.58
4	0.21	0.32	0.29	4	0.33	0.44	0.41	4	0.42	0.47	0.44	4	0.58	0.63	0.6
4.5	0.22	0.35	0.32	4.5	0.34	0.47	0.44	4.5	0.46	0.52	0.46	4.5	0.62	0.68	0.62
3kWp PV	0.07	£/kWh	0					3kWp PV	0.1	£/kWh	0				

Levelised Cost of Storage 2040 (UK)

Levelised Cost of Project 2040 (UK)

Levelised Cost of Storage 2040 (DE)

Levelised Cost of Project 2040 (DE)

LCOE of 3kWp + 3kWh System In Different Modes

DE									
LCOS (£/kWh)									
HES							CES		
	Heavy			Light					
	HES-GC	HES-SC	HES-Flat	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat
2	0.45	0.52	0.44	0.62	0.66	0.49	0.42	0.52	0.49
2.5	0.46	0.54	0.47	0.62	0.69	0.69	0.43	0.56	0.53
3	0.41	0.50	0.45	0.56	0.65	0.68	0.44	0.60	0.57
3.5	0.38	0.47	0.47	0.53	0.63	0.70	0.47	0.65	0.62
4	0.43	0.54	0.50	0.63	0.76	0.75	0.50	0.72	0.68
4.5	0.45	0.58	0.53	0.69	0.84	0.82	0.54	0.78	0.74
3kWp PV	0.12 £/kWh								

UK									
LCOS (£/kWh)									
HES							CES		
	Heavy			Light					
	HES-GC	HES-SC	HES-Flat	HES-GC	HES-SC	HES-Flat	CES-GC	CES-SC	CES-Flat
2.00	0.52	0.76	0.65	0.58	0.77	0.74	0.46	0.75	0.77
2.50	0.52	0.79	0.68	0.57	0.80	0.78	0.48	0.82	0.85
3.00	0.51	0.82	0.86	0.58	0.85	0.87	0.48	0.89	0.92
3.50	0.51	0.86	0.78	0.61	0.92	0.88	0.49	0.95	1.00
4.00	0.51	0.91	0.85	0.64	0.99	0.98	0.50	1.00	1.05
4.50	0.51	0.94	0.91	0.67	1.03	1.02	0.52	1.01	1.10
3kWp PV	0.16 £/kWh								