Improving the Feasibility of Household and Community Energy Storage: A Techno-Enviro-Economic Study for the UK

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Summary

Rooftop photovoltaics (PV) have become widely adopted by domestic customers in tandem with energy storage systems to generate clean energy and limit import from the grid, however most applications struggle to achieve profitability. The level at which energy storage is deployed, be it household energy storage (HES), or as a community energy storage (CES) system, can potentially increase the economic feasibility. Furthermore, the introduction of a Time-of-Use (TOU) tariff enables households to further reduce their energy costs through demand side management (DSM). Here we investigate and compare the performance of HES and CES with DSM. The results suggest that TOU tariffs can effectively shave peak demand by up to 30% and lower energy bills by at least 20%, but do not improve self-consumption or self-sufficiency rate. This study indicates that all cases considered are environmentally friendly and can pay back the total CO_2 emissions associated with the manufacturing within 8 years. However, the levelised cost of storage (LCOS) is still beyond a household's affordability, ranging from £0.4 to £2.03 kWh^{-1}, though CES is proven more effective at improving self-consumption for consumers and shaving peak demand for network operators. The feasibility 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

Keywords: Photovoltaics, Community energy storage, Agent-based modelling, Time-of-Use Tariff, Distributed Energy Resources, Demand side management

(Word Count: 7930)

List of Abbreviations

FIT	Feed-In Tariff	*TOU*	Time-of-Use
HES	Household Energy Storage	*CES*	Community Energy Storage
DER	Distributed Energy Resource	*DSM*	Demand Side Management
DNO	Distribution Network Operator	*TDCV*	Typical Domestic Consumption Values
HESM	Household Energy Storage Management	*CESM*	Community Energy Storage Management
HES-Flat	Household Energy Storage Self-Consumption Mode under Flat Tariff	*CES-Flat*	Community Energy Storage Self-Consumption Mode under Flat Tariff
HES-SC	Household Energy Storage Self-Consumption Mode under Time-of-Use Tariff	*CES-SC*	Community Energy Storage Self-Consumption Mode under Time-of-Use Tariff
HES-GC	Household Energy Storage Grid-Charging Mode under Time-of-Use Tariff	*CES-GC*	Community Energy Storage Grid-Charging Mode under Time-of-Use Tariff
KPI	Key Performance Indicator	*SCR*	Self-Consumption Rate
SSR	Self-Sufficiency Rate	*LCOE*	Levelised Cost of Energy (£.kWh^{-1})
LCOS	Levelised Cost of Storage (£.kWh^{-1})	*SPBT*	Simple Payback Time of System (years)
PBT_{CO2}	Carbon Payback Time of System (years)	*EFC*	Equivalent Full Cycle
SOC	State of Charge (%)	*DOD*	Depth of Discharge (%)
C_e	Effective Battery Capacity (kWh)	C_0	Nominal Battery Capacity (kWh)
Q_{loss}	Battery Capacity Loss (%)	E_{ah}	Total Energy Throughput (ah)
E_{PV}	Energy Generated by PV (kWh)	E_{export}	Total Exported Energy (kWh)
E_{import}	Energy Imported Energy from Gird (kWh)	E_{demand}	Total Household Energy Demand (kWh)
$E_{discharge}$	Total Energy Discharged from Battery (kWh)	E_{toCES}	Energy Export to CES Network (kWh)
$E_{fromCES}$	Energy Import from CES Network (kWh)	p_{grid}	Energy Supplier Tariff (£.kWh^{-1})
$p_{standing}$	Standing Charge (£.day^{-1})	p_{gen}	Feed-In Tariff for Generation (£.kWh^{-1})
p_{export}	Feed-In Tariff for Export (£.kWh^{-1})	p_{CES}	Inter-House Trading Tariff within CES (£.kWh^{-1})
I_t	Investment Expenditures in Year t (£)	M_t	Maintenance Expenditures in year t (£)
EM_{total}	Total System Carbon Emissions (kg)	EM_{PV}	Total Carbon Emissions from PV Manufacture (kq)
$EM_{battery}$	Total Carbon Emissions from Battery Manufacture (kg)	q_{grid}	Grid Carbon Intensity (kg.kWh^{-1})

1. Introduction

The amount of electricity generated in the UK fell to its lowest level in a quarter century in 2018 to around 335 TWh [1] and output from renewable sources rose to another record high, estimated to be 33% of the UK's total generation [2]. Reduced electricity consumption and increasing adoption of renewables reduced CO_2 emissions from the power sector by 37% since 1990 [3]. 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 [4] as the relevant subsidies were recently removed [5]. Self-consumption has therefore become increasingly popular in domestic applications at household level, as the consumers can localise their energy demand by using on-site PV generation. Energy storage, especially via Li-ion batteries, has become an increasingly popular supplement to PV as it can further enhance household self-consumption [6], due to the high energy density, power density and conversion efficiency [7]. PV coupled with energy storage has been widely adopted and investigated in many countries, such as the UK [8], Germany [9], and Switzerland [10].

The increasing deployment of distributed energy resources (DERs) 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 community energy storage (CES). CES can act as an energy management system in the energy community and may be co-owned by the participants in the energy community [11]. Compared to household energy storage (HES), a CES system has significant advantages [12], including: 1) a higher and more stable power supply; 2) lower power ratings; and 3) cheaper upfront investment. Our previous study [13] conducted a multi-criteria assessment of HES and CES in the UK. Although the results suggest that both applications are yet to be economically feasible, the energy trading within the CES network is found to have the potential to improve profitability. It is therefore important to find more options to diversify the revenue sources and enhance the feasibility, such as providing multiple services [14] and demand side management (DSM).

Demand side management refers to initiatives and technologies that encourage consumers to optimise their energy use and a common method is via financial incentives [15]. In the UK, the plan to upgrade to a smart energy system [16] along with the regulator's desire to mandate half-hourly settlement of all electricity users [17], 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 [18]. Their introduction aims to enhance the flexibility and sustainability of the electricity system, and also benefits the consumers by lowering energy prices [18]. Although TOU tariffs can potentially ease the burden of network reinforcement resulting from growing demand [19] and greater renewable energy penetration in the future [20], there have not been many studies carried out to investigate its potential benefits.

Talent and Du [21] 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 $4260. Although the energy import under the two tariffs were similar, the demand tariff showed better peak shaving capability compared to the TOU tariff. Under the demand tariff, the energy costs were based on the total amount of imported energy and peak power demand. For the network operators, time-dependent tariffs were unlikely to be helpful in reducing the total energy consumption, but the authors addressed their potential to contribute to a more level grid profile and therefore to enhance grid stability. Gitzadeh and Fakharzadegan [22] used a mixed integer programming model to investigate the optimal storage sizing on pre-existing PV installations and the impacts of different tariffs. The lead-acid battery used in their research was found to financially benefit the consumers under TOU tariff, as the battery managed to use surplus PV power and off-peak electricity. The optimal battery capacity was found to be 30 kWh, which reduced the annual energy costs from $884.7 to $632.7. However, the authors claimed the economic profitability was questionable when battery degradation was considered and the improvement in system cost-effectiveness required more financial incentives. Lam et al. [23] proposed an economic analysis on the potential of energy arbitrage by using PV with a grid connected HES through peak load shifting under TOU tariff. The annual saving achieved was at least $1000 year^{-1} for both large and medium homes. Pimm et al. [24] investigated the performance of a 100-houehold community with various levels of PV penetration, battery storage and heat pump usage. Although the TOU tariff could effectively lower the energy costs of households, it failed to shave the peak demand for the local substation and conversely caused an increased demand overnight. A few measures of incentivising the deployment of energy storage were recommended to shave peak demand at low voltage level, such as capacity charges based on the maximum import and export capacity, and storage rental or sharing between the households and aggregators.

CES has drawn considerable attention from the industry and academia and has been extensively investigated in the past few years. Parra et al. [12] proposed a model to investigate the optimal CES for renewable energy and demand load management. In a projected 2020 scenario, CES could provide demand load-shifting and PV self-consumption at the same time under the chosen Economy 7 Tariff. The results showed that the LCOS of the Li-ion battery could effectively be reduced by 37% compared to a single-household storage system. The benefits were found to become greater with the increase in community size. Van Der Stelt et al. [25] compared the techno-economic performance of HES and CES for residential prosumers. The results showed that both HES and CES can significantly improve the use of on-site generation by at least 22% compared to the baseline households without a storage system. Both systems can 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). CES is widely considered beneficial for the community [26] and lower voltage networks [27]. However, most existing research analyses the performance from the perspective of the overall system. Given the fact that the installation location is near end-users, CES can also be operated to optimise energy costs of households. Alskaif et al. [28] developed a centralised reputation-based energy management system that controlled the allocation of available energy in a centralised storage system to connected households. The proposed framework was found able to reduce household energy cost by up to 68%. Mediwaththe et al. [29] proposed a dynamic game for electricity load management in a neighbourhood area with a communal battery. By aggregating the information from users and electricity markets, the CES was found to be capable of flattening the overall electricity demand on the grid across the day and of also reducing users' energy cost by 27%. Similar results can also be found from other studies [13], both HES and CES still struggled to be profitable within their lifetime.

The author suggested that the revenue of inter-house power exchange needed to be realised, which could potentially improve the economic performance.

To summarise, it is widely recognised that CES can significantly enhance PV self-consumption and energy saving, but such systems still struggle to be financially profitable. It is therefore essential to investigate alternative reimbursement schemes, different pricing schemes, better allocation of CES capacity and the provision of different services to improve overall sustainability. The main contributions of this paper are 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 rest of this work is arranged as follows: Section 2 describes the system configuration and the scenarios considered in this article, section 3 introduces the parameters used for analysis on three different perspectives, the simulation results are presented and analysed in Section 4, and the current barriers and issues hindering the applications are discussed in Section 5. Finally, Section 6 addresses the main findings and conclusions.

2. System Model Setup

2.1. System Setup

To simulate the interaction between households and the power grid, the agent-based model proposed in our previous study [13] is extended. Pertinent details of the original model are given in sections 2.1-2.3. The original agent-based model included three communities: i) where the households were installed with PV, ii) household PV was coupled with HES, and iii) household was PV coupled with CES; in each case the management of HES and CES was based on a greedy algorithm. In this model, only the HES and CES communities are considered and several more complicated storage system management strategies are introduced. Additionally, to simulate battery operation more accurately, a battery degradation model is also incorporated. Each agent represents a household that consists of a rooftop PV panel, a demand profile and a HES or a CES system according to the needs and capacities. Several rules are proposed for the agents to follow while they are interacting with each other. This study investigates a neighbourhood consisting of 10 households with either HES or CES, which is a good replication of a residential apartment building or a small community to install a large collectively owned storage system.

For the HES community, each house is equipped with a 3kWp rooftop PV panel. The electricity generated from the PV is transferred through an AC/DC converter to meet the demand and the remainder is used to charge the storage system. The HES, ranging from 1.5 to 4.5 kWh, can store the electricity from the PV and grid according to the operation modes. The PV and storage models are described in our previous study [30]. The HES is managed by an HES management (HESM) unit that can operate in three different modes, Self-Consumption Mode under flat (HES-Flat) and TOU tariff (HES-SC), and Grid-Charging Mode (HES-GC) under TOU tariff. The HESM manages the power flows and varies the management strategies with different tariffs and operation requirements. More details are presented in section 2.4.

For the CES community, all the households in the community connect to a larger CES through a private network managed by a central CES management (CESM) unit. Within the community, the CESM prioritises the surplus self-consumed power to be supplied to those households needing power, then to charge the CES and finally to export to the grid. Households within the community collectively purchase and own the CES. There is no set limit on the use of the CES, and therefore all of the households within the community can act as prosumers to maximise the value of the CES network, within its capability. Additionally, the CES can operate in three modes similar to the HES: Self-Consumption Mode under flat (CES-Flat) and TOU tariff (CES-SC), and Grid-Charging Mode (CES-GC) under TOU tariff. More details of the management strategies of the CES are described in section 2.4.

2.2. Household Demand and PV System

Energy consumption data of households is obtained from the CREST demand model [31]. It is based on the results of UK Time Use Survey, which uses thousands of domestic homes occupancy profiles along with a list of appliances to generate a synthetic demand profile. Five different households are chosen in this study and their annual consumptions range from low to high consumption classes according to Ofgem's Typical Domestic Consumption Values (TDCVs) [32].

A 3kWp PV panel is installed in every household, regardless of any influential factors such as tilt angle and rooftop installation area. The PV generation is simulated as a function of the irradiance and outdoor temperature as presented in previous work [13]. The Solar irradiance data is obtained from the Microgen Database developed by Sheffield Solar [33]. Both demand profile and PV generation data used are at 1-minute resolution.

2.3. Energy Storage Model

The Li-ion battery model used in this work was presented in our previous study [13], it is further assumed to operate under 80% depth of discharge (DOD) with a minimum state of charge (SOC) of 20%. The battery is set to have a maximum charge/discharge rate of 0.5C. One of the key gaps preventing a full understanding of the business case of battery storage is the lack of parameters describing their performance and durability. Therefore, a simple energy storage degradation model is introduced into our study.

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, 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 calculates the aging effects by mathematically simulating the electrochemical reactions inside the batteries [34,35] or correlates the experimental data into an empirical [36] or a semi-empirical model [37,38].

The degradation model is adapted from an empirical degradation model developed by Wang et al. [38]. 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).

$$E_{ah} = EFC \times DOD \times C_0 \qquad (1)$$

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:

$$EFC = E_{dischage}/C_e \qquad (2)$$

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:

$$Q_{loss} = 30330 \times \exp\left(\frac{-31500}{RT}\right) \times E_{ah}{}^{0.552} \qquad (3)$$

2.4. Management Strategies of HES and CES

In this study, both HES and CES can operate under three different operational strategies: HES/CES-Flat, HES/CES-SC and HES/CES-GC Modes. Both HES-Flat and CES-Flat modes are fully described in previous studies [30][13]. In this work, two new operational strategies are proposed to enable the operation of HES and CES under a TOU tariff.

2.4.1. Tariffs Adopted in The Study

The TOU tariff adopted in this research is the TIDE tariff from GreenEnergy [39]. During weekdays, there are three prices for peak, off-peak and shoulder periods, while the weekends only have two price rates. In comparison, the flat tariff rate is £0.186 kWh^{-1} based on the TDCVs of a dual-fuel user whose annual electricity consumption is ca. 3100 kWh and electricity bill is £577, according to Ofgem [20]. The flat tariff also includes £0.2 day^{-1} as the standing charge [40]. More details of the two tariffs are presented in Table 1.

Table 1 Tariff Information Used in The Study

Tariff Name	**Day**	**Time**	**Electricity Price (£.kWh^{-1})**	**Standing Charge (£.day^{-1})**
TIDE Tariff [39]	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 [20,40]	All-time		0.186	0.20

2.4.2. Forecast Function

When the system operates under the TOU tariff, a forecast function shown in Figure 1 is introduced to maximise cost savings. When there is surplus PV generation, the battery will charge continuously without any energy output. The hourly net energy demand is calculated and then combined with the electricity price, at a given time, to determine the potential savings if the battery discharges the available energy. Therefore, the forecast function can generate two outputs: the SOC corresponding to the daily maximum amount of energy that can be stored ($SOC_{reserve}$) and at what time the discharge of battery electricity can achieve the most bill reduction (ES Discharging Point). The former one can be used in HES/CES-GC mode, while the latter can be used for both HES/CES-GC and HES/CES-SC modes.

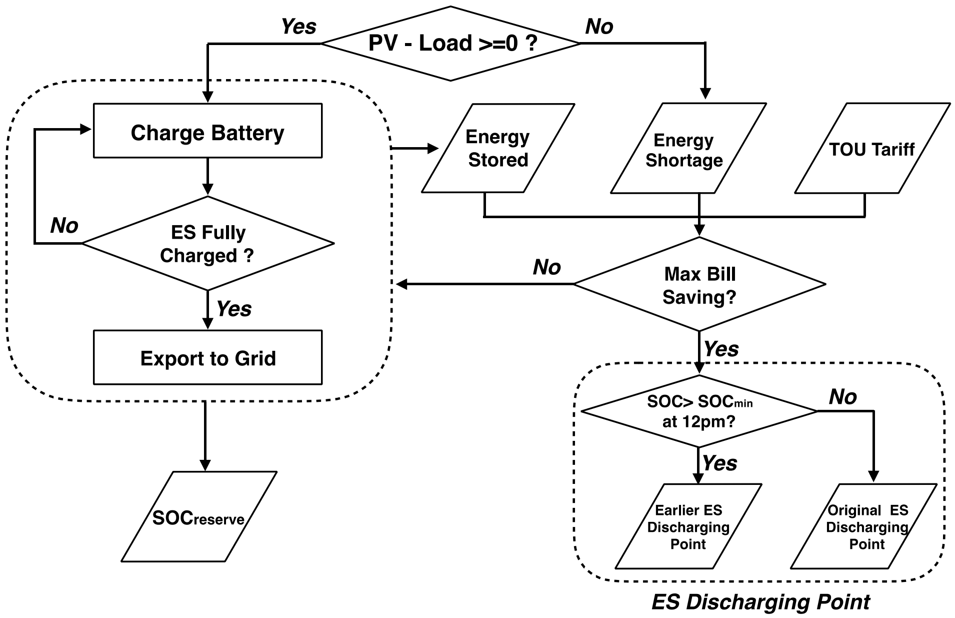


Figure 1 Forecast Function of Control Unit

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

The HES/CES-SC Modes are adapted from the HES/CES-Flat, which use the ES Discharging Point to control the discharge process instead of discharging battery power whenever the PV is not sufficient to meet the demand. This is to minimise the grid power import during the peak price period and hence maximise the bill savings. The HES-SC and CES-SC are shown in Figure 2 and Figure 3 respectively.

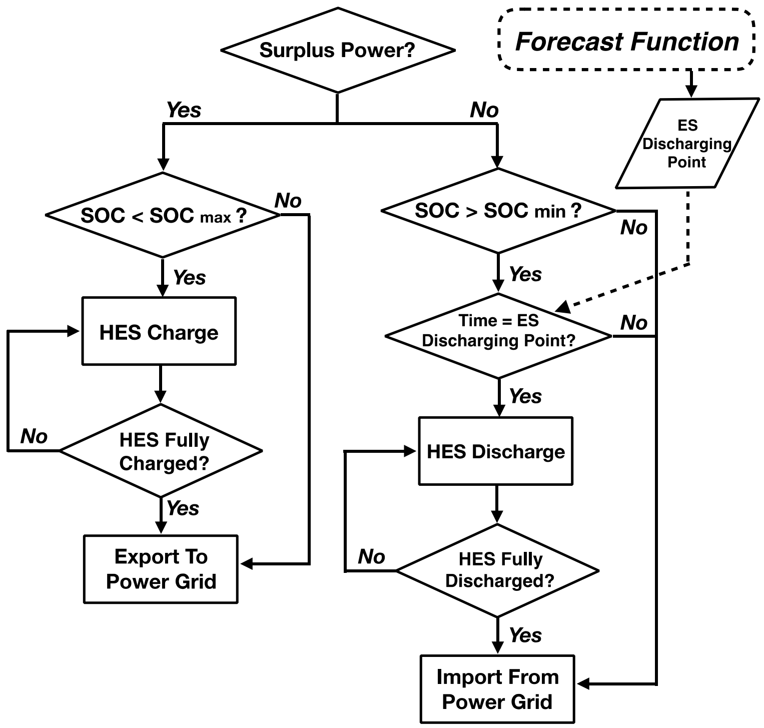


Figure 2 Flowchart of HES-SC Mode

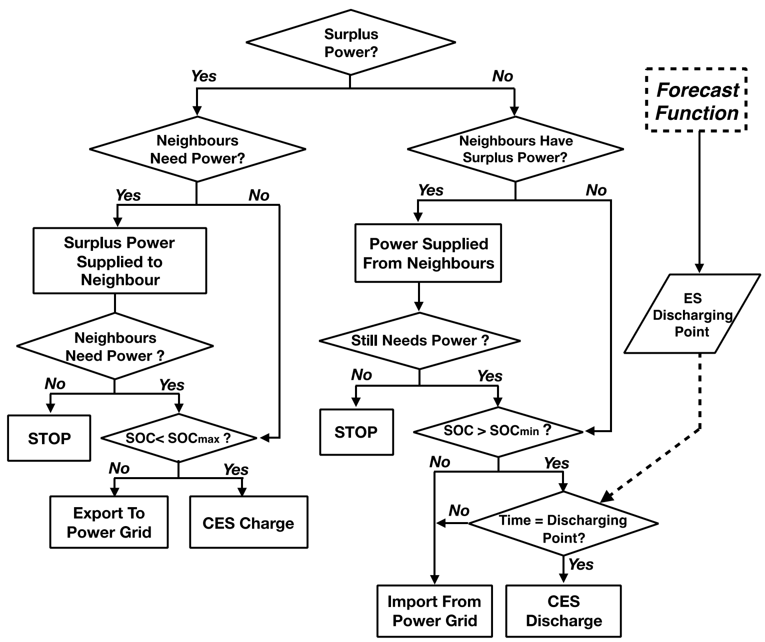


Figure 3 Flowchart of CES-SC Mode

2.4.4. Grid-Charging Mode Under TOU (HES-GC and CES-GC)

The HES/CES-GC Modes aim to improve the use of storage system, especially for times without sufficient PV production. Two outputs from the Forecast Function are used to control the storage systems. The HES/CES-GC is based on the HES/CES-SC with the additional function that enables the battery to charge from the power grid. The $SOC_{reserve}$ is the SOC after battery charging from the grid during the off-peak time and the battery is then expected to be fully charged with the addition of PV electricity. The battery discharges when it comes to the predicted discharging point, and the remaining operation works the same as the HES/CES-SC. The flowcharts describing HES-GC and CES-GC Modes are presented in Figure 4 and Figure 5 respectively.

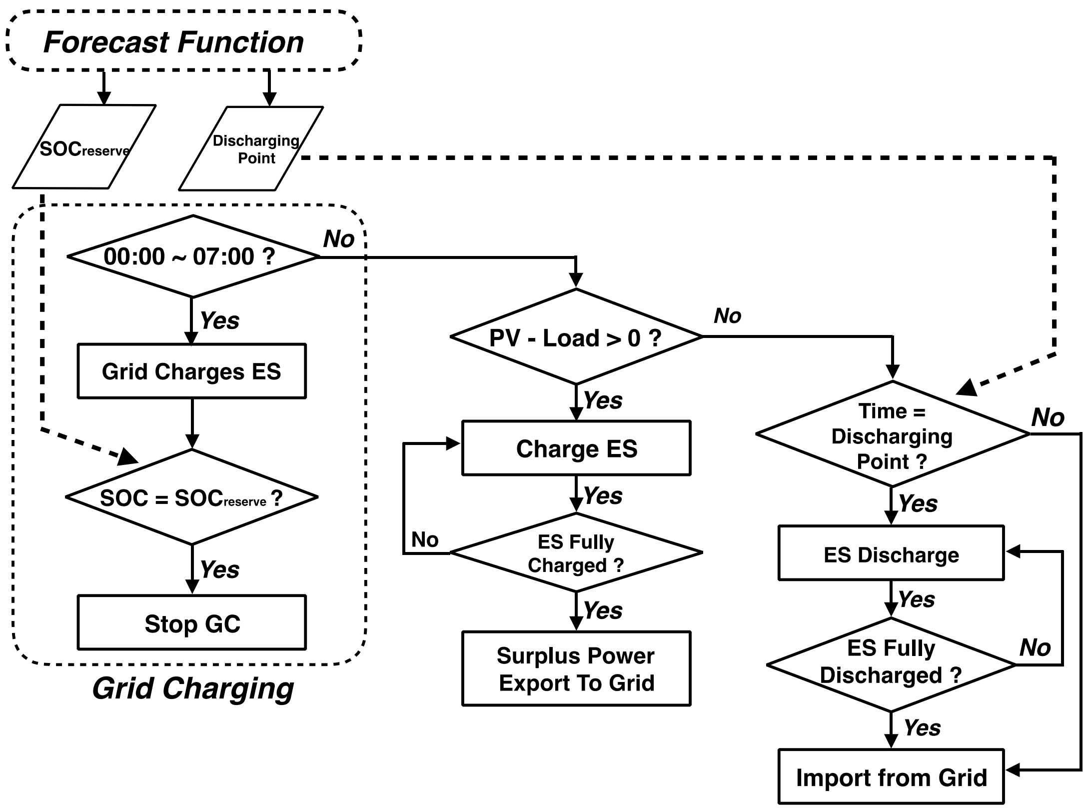


Figure 4 Flowchart of HES-GC Mode

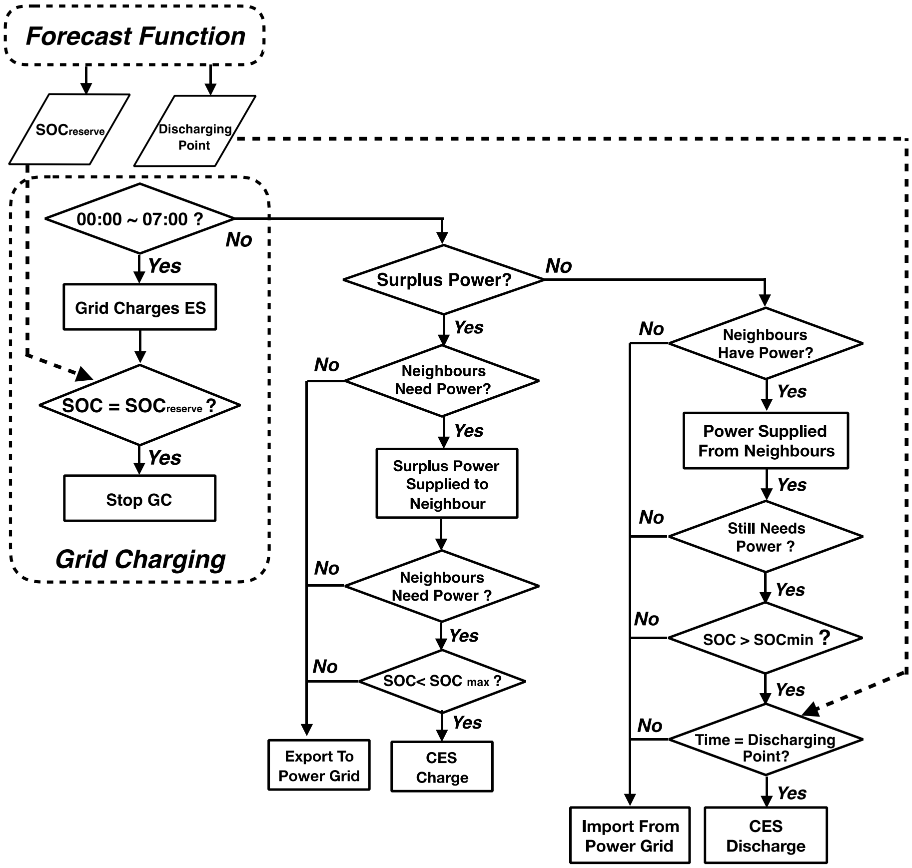


Figure 5 Flowchart of CES-GC Mode

3. Evaluation Criteria

To understand the impact of different storage options and operation modes, several technical and economic key performance indicators (KPIs) developed previously [13] are adopted in this study. The analysis is undertaken at both community and household levels to identify the most suitable system setup and operation for the community.

3.1. Technical Analysis

SCR and SSR proposed in our previous study [13] are used to calculate the system performance. The SCR and SSR used differ from the traditional definitions to take into account energy trading/sharing, and exclude the discrepancy caused by the difference of residual electricity left in the battery from the beginning. The SCR is defined as self-consumed PV electricity excluding exported electricity over the total amount of PV generated electricity, i.e. it is the proportion of PV that is self-consumed:

$$SCR = (E_{PV} - E_{export})/E_{PV} \tag{4}$$

where the total on-site generated PV electricity is E_{PV} and the amount of surplus electricity injected to the grid is E_{expor}. The SSR is defined as the ratio of total energy demand met locally except the grid imported electricity over the total energy demand:

$$SSR = (E_{demand} - E_{import})/E_{demand} \quad (5)$$

where E_{demand} represents the total amount of energy consumed by a household or a community and E_{import} is the electricity supplied by the power grid.

3.2. Economic Analysis

In this work, the profitability of a project is assessed by several parameters, including simple payback time (SPBT), Levelised Cost of Energy (LCOE) and LCOS. The SPBT is used to calculate how long a project takes to recover its upfront investments without any influential time-dependent factors, such as inflation ratios or discount rate. To obtain the SPBT, the total investment costs and yearly energy bill savings are needed. As inter-house trading is considered in our study, the energy bill is calculated as:

$$Energy\ Bill = E_{import} \times p_{grid} + d \times p_{standing} - E_{PV} \times p_{generation} - E_{export} \times p_{export} + (E_{toCES} - E_{fromCES}) \times p_{CES} \quad (6)$$

where p_{grid} represents the retail electricity tariff charged by energy suppliers, d is the number of days, $p_{standing}$ is a fixed connection charge by energy suppliers, $p_{generation}$ and p_{export} represent FIT payment rates for generation and export respectively, E_{toCES} and $E_{fromCES}$ represent the amount of energy exported to and imported from the CES network, and p_{CES} is the inter-house trading electricity price. The two tariffs described in Section 2.4.1 are adopted to calculate the minimum result of Equation (6). Once the Energy Bill is obtained, the yearly saving is the difference between the current energy bill and the energy bill fully supplied by the grid. If the SPBT is within the system's lifespan, the system is taken to be profitable :

$$SPBT_{system} = Total\ System\ Cost/Yearly\ Savings \quad (7)$$

All the households within the communities are assumed to two main methods to recover the upfront costs, subsidies and yearly energy savings. As stated earlier, the CES is a collectively owned property and purchased by all the households. The total capital investment of the system with the additional distribution network modification charge [41] is split between all the participating households. The value of electricity traded between neighbours and a sensitivity analysis on $SPBT_{system}$ are investigated respectively in Section 4.2. The pertinent economic parameters adopted are shown in Table 2.

The Levelised Costs of Energy (LCOE) is widely used to determine the economic feasibility of generation alternatives. It is the net present value of the unit-cost of electrical energy over the lifetime of an asset. The LCOE includes all the costs occurring during the project's lifespan and associated energy production. In this study, the LCOE of PV is calculated as:

$$LCOE = \sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t} \Big/ \sum_{t=1}^{n} \frac{E_t}{(1+r)^t} \quad (8)$$

Where I_t is investment expenditures in year t; M_t is the operation and maintenance expenditures in 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 LCOS is calculated as formulated in Eq (9), which is converted from LCOE in Eq (8) but uses the total amount of energy discharged from storage and also with the addition of charging cost.

$$LCOS = \sum_{t=1}^{n} \frac{I_t+M_t+C_t}{(1+r)^t} \Big/ \sum_{t=1}^{n} \frac{E_{discharge}}{(1+r)^t} \quad (9)$$

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. All the parameters adopted are shown in Table 2.

Table 2 Economic Values Adopted in This Study

Parameter	**Value**	**Unit**
Li-ion Battery [42]	*570*	£.kWh^{-1}
Battery Inverter [43]	*500*	£.kW^{-1}
Battery Casing [42]	*293*	£
PV inverter [44]	*500*	£.kW^{-1}
Solar Panel [45]	*0.4*	£.Wp^{-1}
Solar Optimiser [45]	*0.25*	£.Wp^{-1}
PV mounter [45]	*328*	£
Accessories [45]	*150*	£
O&M Cost [45]	*50*	£.year^{-1}
Discount Rate [46]	*5*	%.year^{-1}

3.3. Environmental Analysis

One of the main reasons for adopting renewable energy generation technologies is to replace traditional carbon-intensive technologies, because of the zero-marginal carbon-emissions of wind and solar based generation. However, manufacturing technologies such as PV and wind turbines is very carbon-intensive. It is therefore important to include the environmental significance in our study. The same approaches developed previously [13] are used in this study to calculate carbon emission savings and payback time of carbon emissions from manufacturing. The total amount of CO_2 emitted (EM_{total}) during manufacturing only includes CO_2 emissions from manufacturing PV and battery storage. Other emissions, such as emissions from operation and maintenance, are ignored. The EM_{total} can be calculated by:

$$EM_{total} = EM_{PV} + EM_{battery} + E_{import}q_{grid} \quad (10)$$

where the total amount of CO_2 emission from manufacturing PV and battery are represented as EM_{PV} and $EM_{battery}$ respectively (kg), and q_{grid} represents the grid CO_2 intensity in the UK . The values of environmental factors considered are shown in Table 3. This study only adopts the cradle-to-use values for environmental assessment [47–49] and the CO_2 emission are mainly saved by on-site PV generation and reduced grid import.

$$EM_{avoidance} = ((E_{demand} - E_{import}) + E_{PV}) \times q_{grid} \quad (11)$$

The amount of surplus PV injected to the grid cannot markedly influence the grid carbon intensity. Carbon avoidance only therefore includes the carbon savings by the households and the community. The Payback Time of the system's CO_2 (PBT_{CO2}) is defined as:

$$PBT_{CO2} = EM_{total}/EM_{avoidance} \quad (12)$$

Table 3 Carbon Emission Parameters

Parameter	**Value**	**Unit**
Grid Carbon Intensity [50]	*0.256*	kg.kWh^{-1}
CO_2 Emission During Inverter Manufacture [48]	*12.03*	kg.kWh^{-1}
CO_2 Emission During PV Manufacture [49]	*865.44*	kg.kWp^{-1}
CO_2 Emission During Battery Manufacture [48]	*175*	kg.kWh^{-1}

4. Results and Discussion

4.1. Technical Assessment

4.1.1. Impacts on Communities

Figure 6 shows a comparison of the community 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-SC and 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 varies very little 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 the HES and CES operate more frequently under flat tariff and hence to meet more demand locally, because they only aim to maximise the consumption of PV generated electricity. However, the operation under the TOU tariffs rely 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 in Section 4.3.

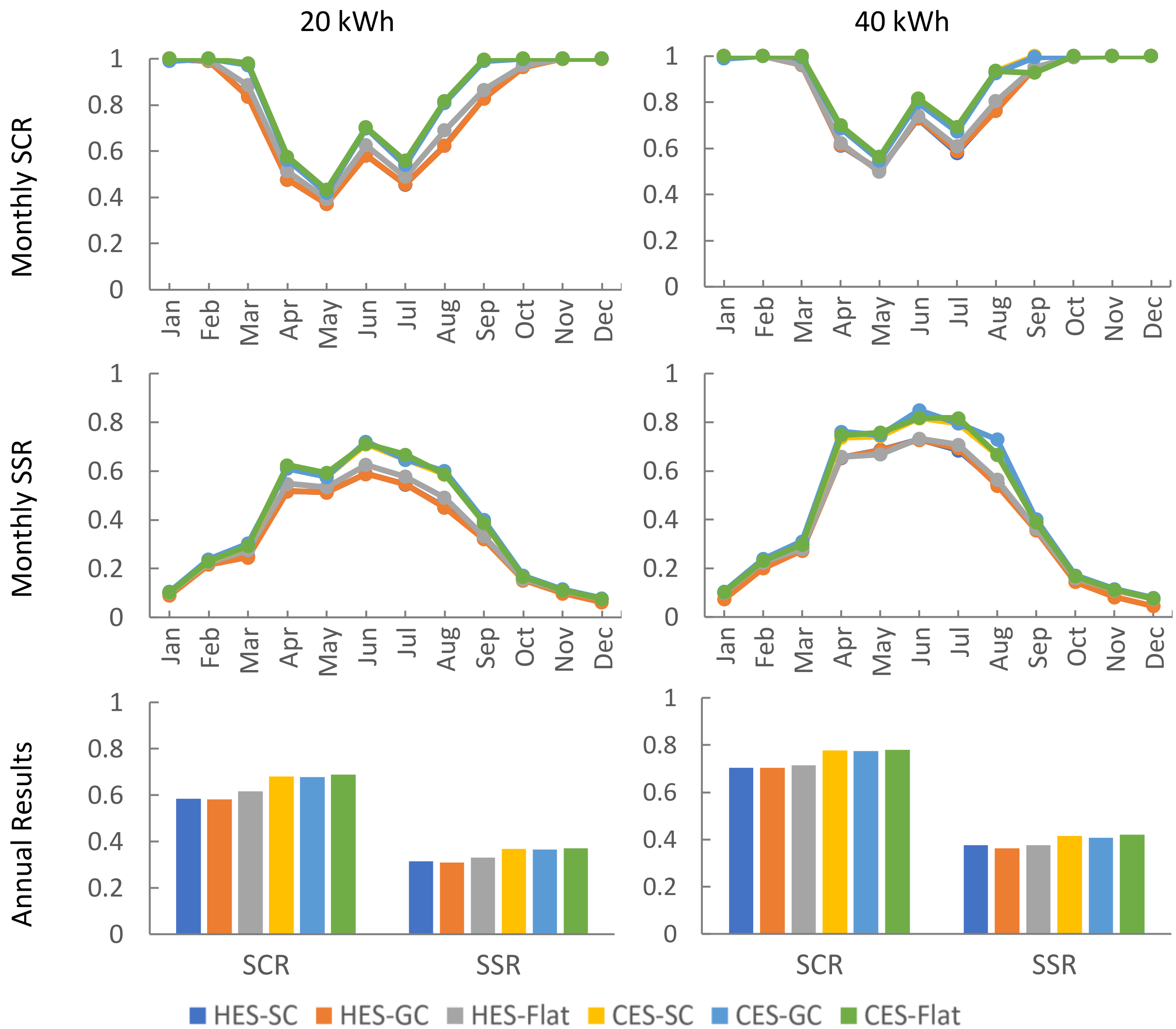


Figure 6 Monthly and Annual SCR and SSR of The Community

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.

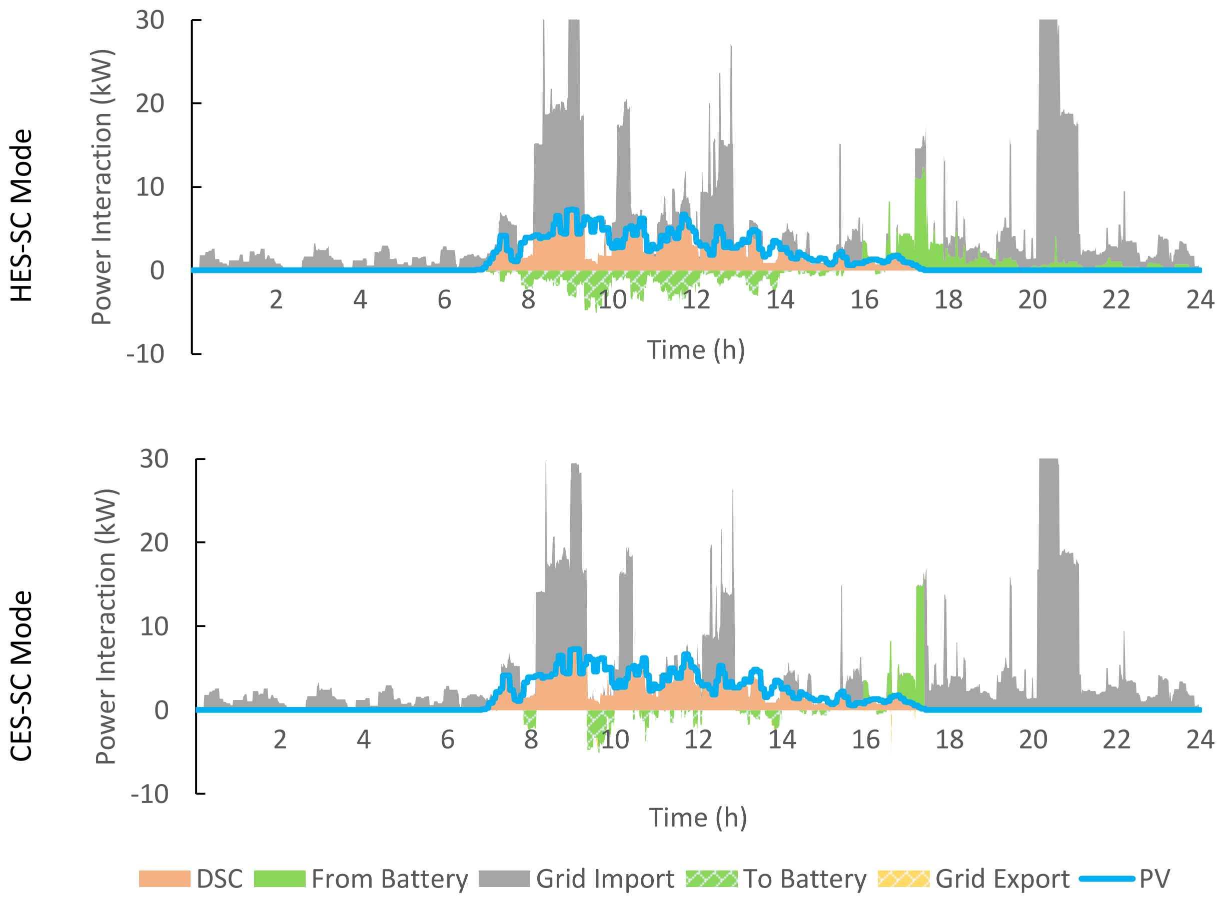
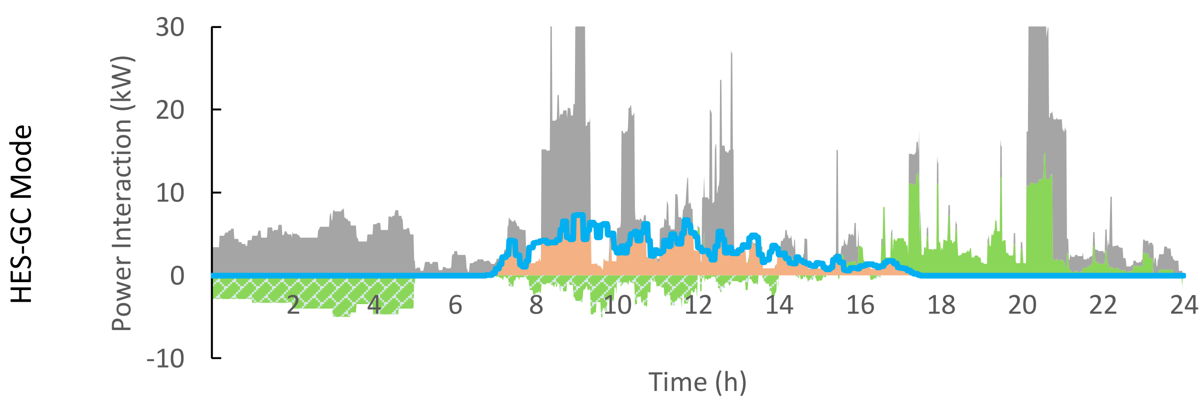


Figure 7 Grid Interaction of Community Operating in HES-SC and CES-SC Modes in March

Figure 7 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 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.



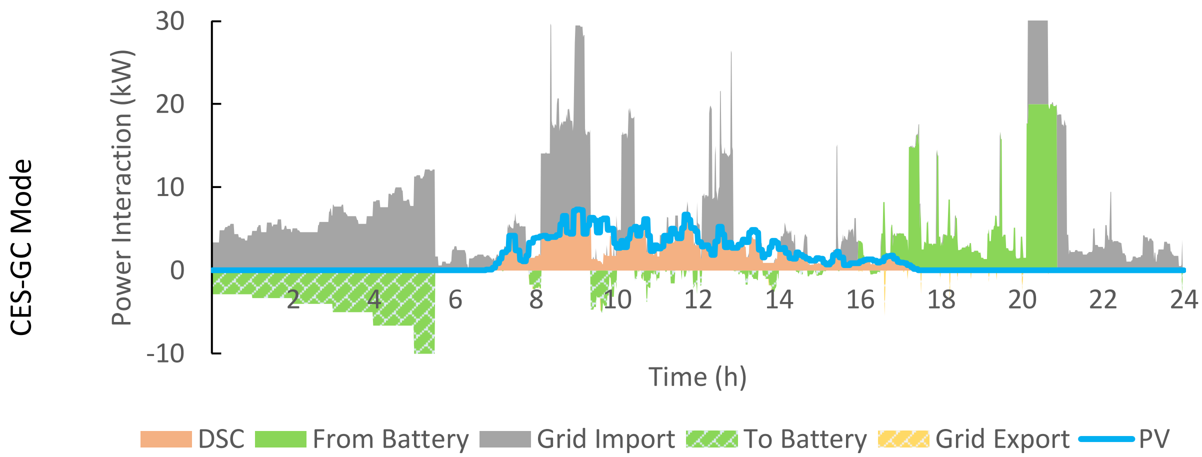


Figure 8 Grid Interaction of Community Operating in HES-GC and CES-GC Modes in March

Figure 8 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. 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 8 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 distribution network operators (DNOs), especially for a community with a high adoption rate of storage systems or electricity vehicles.

4.1.2. Impacts on Households

Figure 9 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 as HH2, the utilisation of PV electricity and supply localisation in CES are found marginally better than HES. Additionally, the change in operational strategy is found to be unlikely to cause significant variation in system performances.

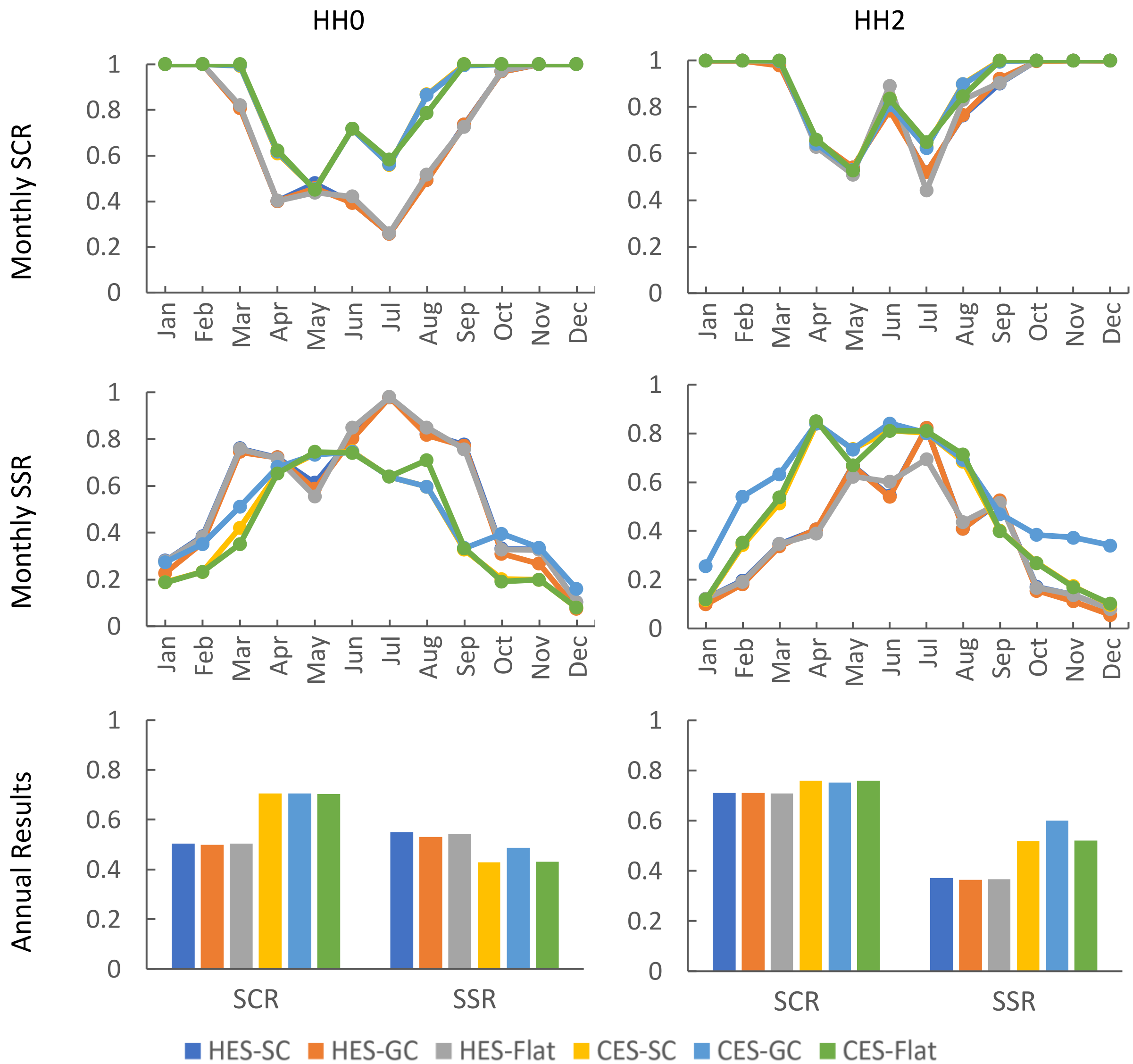


Figure 9 Monthly and Annual SCR and SSR of HH0 and HH2

Figure 10 compares the power flows of HH2 operating in HES/CES-SC Modes. The HH2 with HES struggles to meet the demand locally and hence 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.

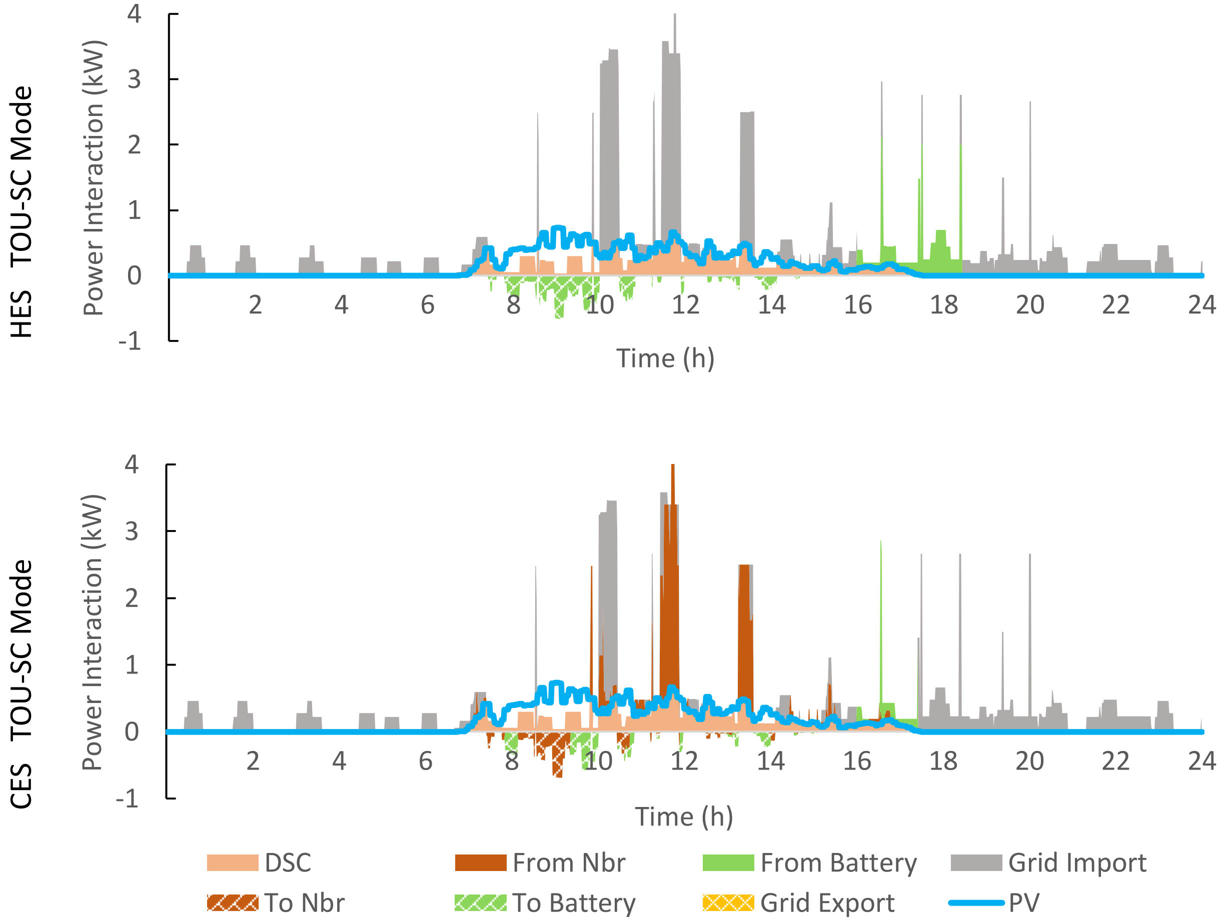
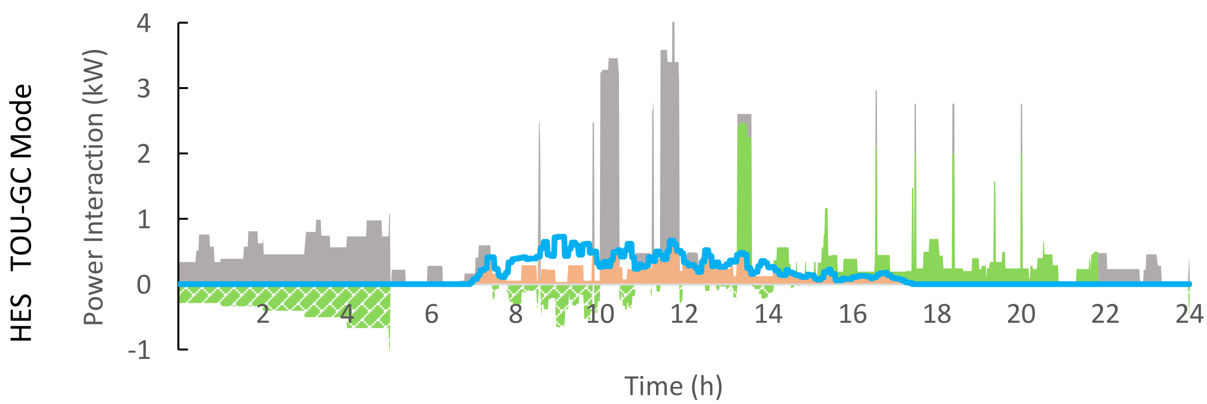


Figure 10 Power Interaction of HH2 in HES-SC and CES-SC Modes in March

Figure 11 shows the power flow of the HH2 operating under HES/CES-GC Modes. Compared to Figure 10, 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 Sections 4.3.



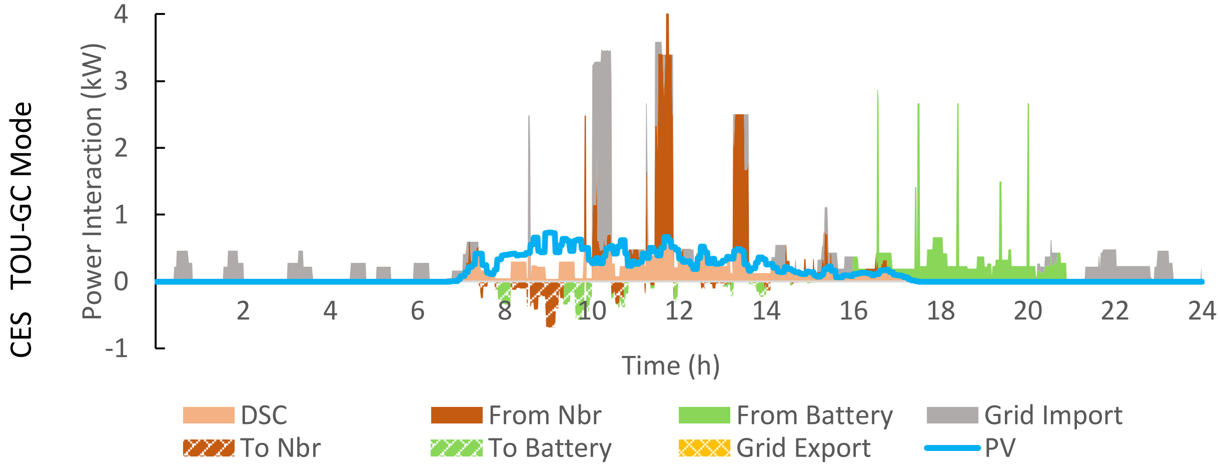
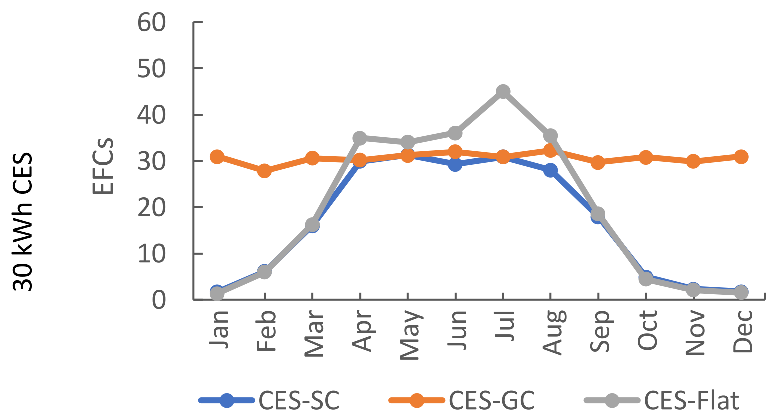


Figure 11 Power Interaction of HH2 in HES-GC and CES-GC Modes in March

4.1.3. Equivalent Full Cycles (EFCs) and Capacity Degradation of Storage Systems

Figure 12 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 an8d 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.



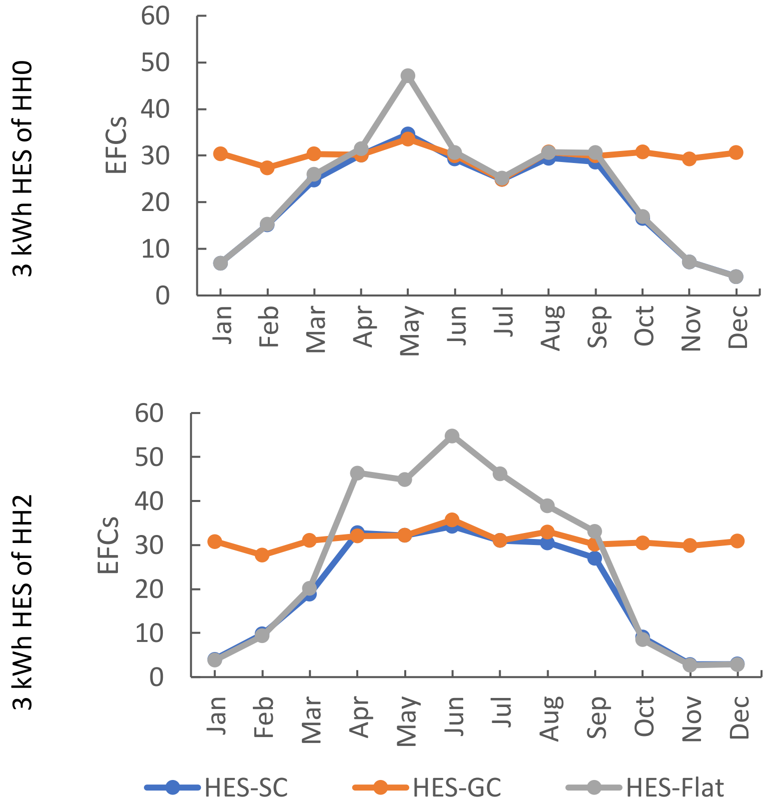
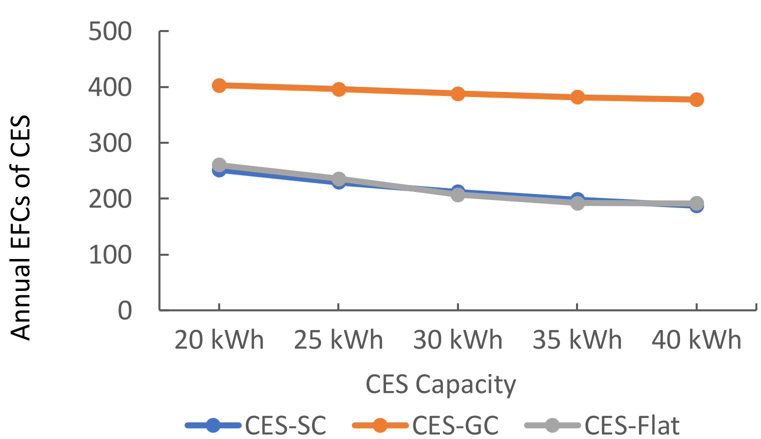


Figure 12 EFCs of HES and CES Operating in Three Modes

Figure 13 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. Additionally, 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}.



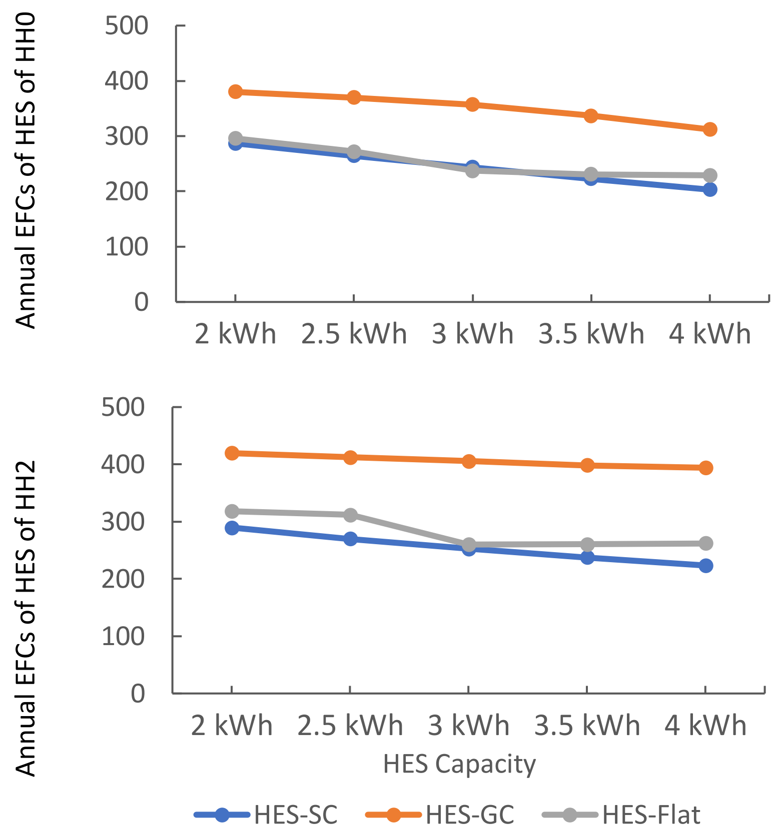


Figure 13 Annual EFCs of HES and CES

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 import during peak usage time and ease the burden of 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 [24]. As the result, both HES and CES can operate more frequently than other modes in winter, which also lead to a faster degradation of storage system around 3-4% $year^{-1}$.

4.2. 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 won't benefit the households environmentally.

Figure 14 shows the annual CO_2 avoidance of two households in 6 different operation modes. For light user HH1, three operations with HES can save approximately 10% more annual CO_2 emission. 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 100kg 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}.

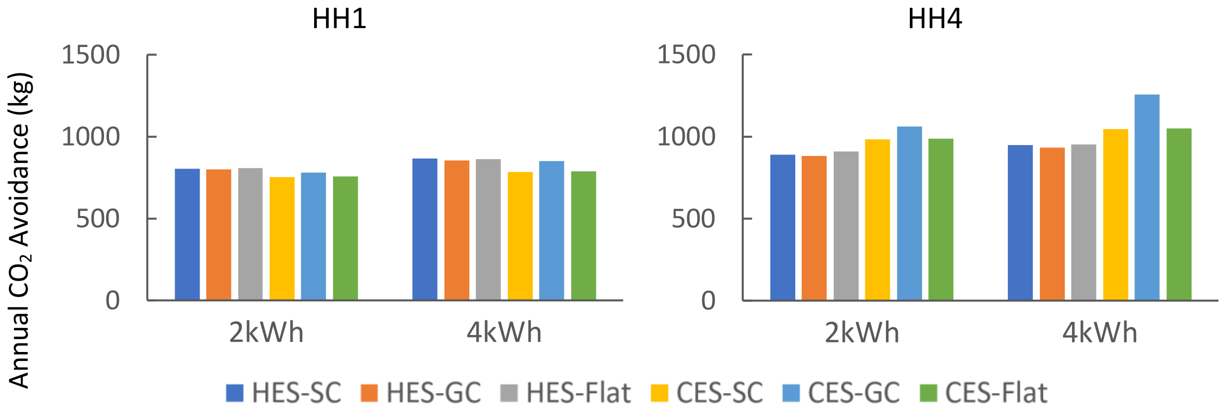


Figure 14 Annual CO_2 Avoidance of HH1 and HH4

Figure 15 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 3 years. In our study, 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 emission. The PBT_{CO2} is at least 6.2 years for CES, and others are taking 7 to 8 years to compensate the total carbon emission.

a)

b)

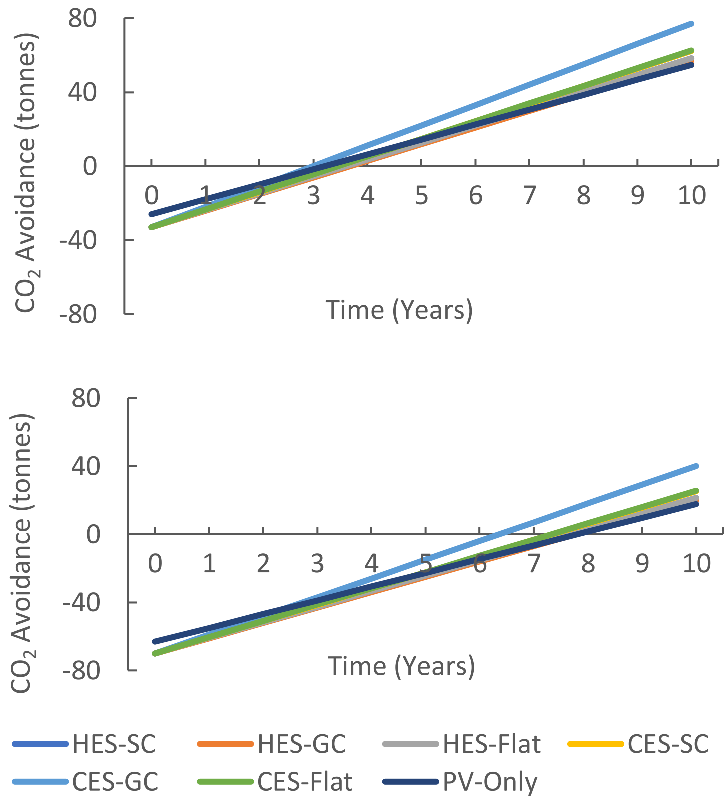


Figure 15 Community's CO_2 Avoidance with 40 kWh Storage Manufactured in a) UK and b) China

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 4 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 in the past decades [51], suggesting that energy sector is undergoing a transition towards a more sustainable and environmental-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.

4.3. Economic Assessment

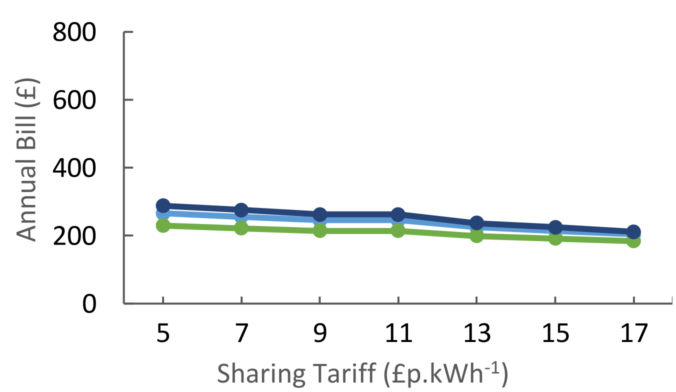
Table 4 shows the results that the annual energy costs of households in different operation modes. When the household demand is fully grid-supplied, the energy bill for HH1 is £599.3 (TOU tariff) and £549.5 (flat tariff), while HH2 spends £1021.1 (TOU tariff) and £957.1 (flat tariff) annually. In comparison, 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 4 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. To investigate its significance, a sensitivity analysis is hence undertaken, and the results are shown in Figure 16.

Table 4 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	599.3	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	1021.1	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 16 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.

HH1



HH4

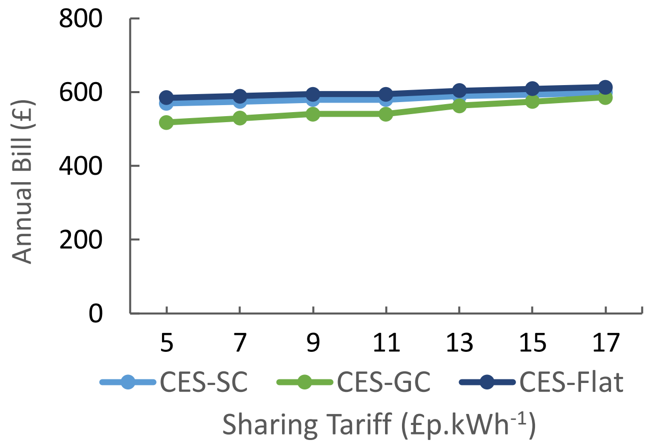
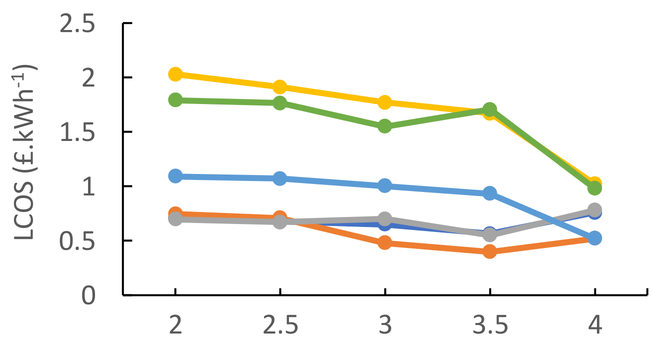


Figure 16 Annual Bill Charges of HH1 and HH4 with Sharing Tariff Connecting to A 20 kWh CES

As stated in Section 2, every household is assumed to have the same PV and an 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 17 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 turn out to have 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.

HH1



HH4

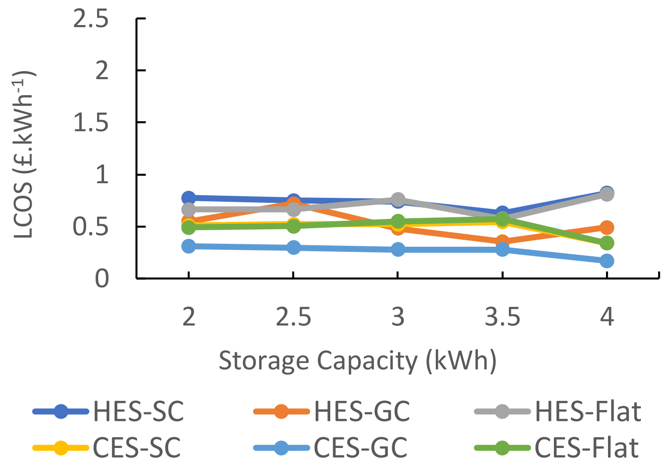
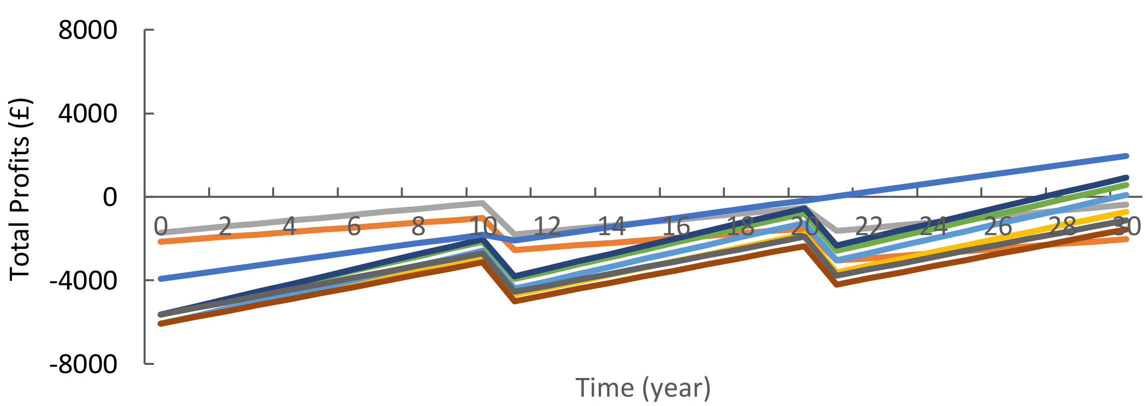


Figure 17 LCOS of Storage in Different Applications

Figure 18 shows the total profits of HH1 over 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 found 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.

20 kWh Storage Capacity



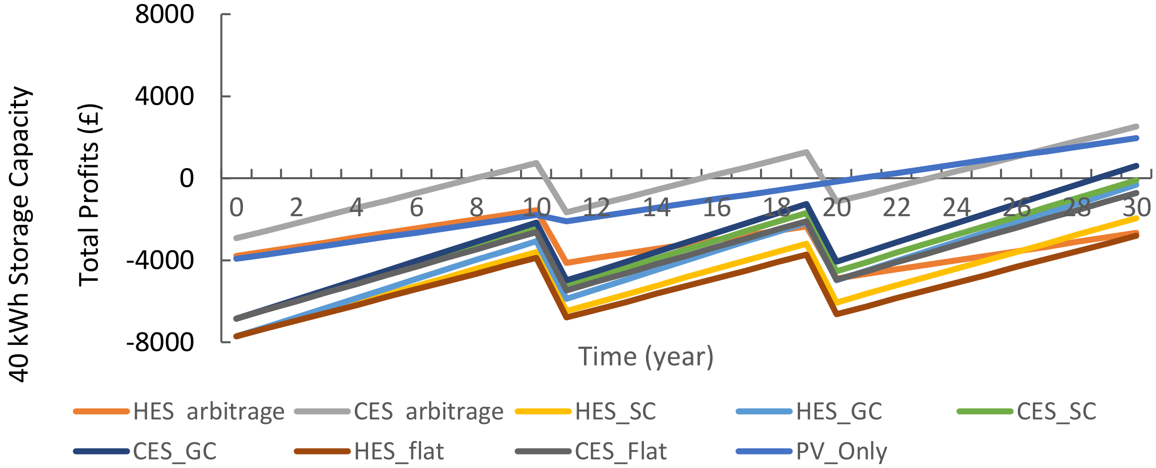
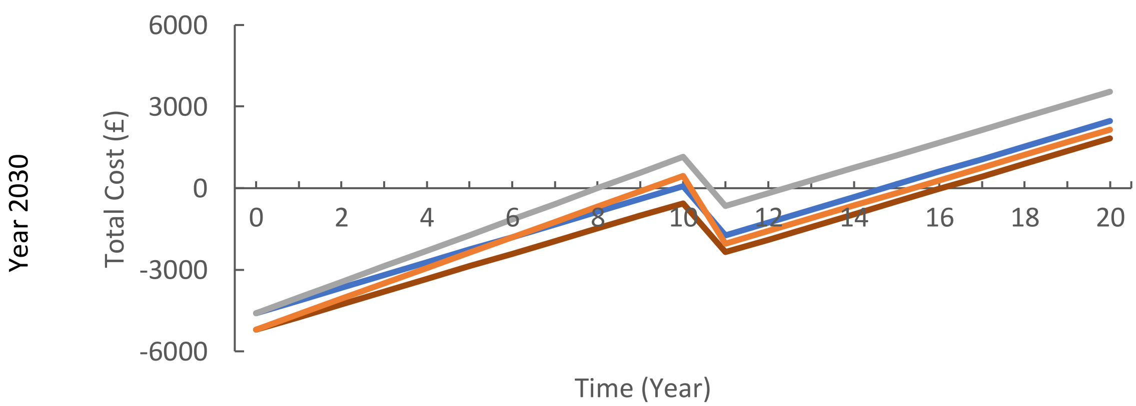


Figure 18 Total Profits of HH1 Over Time

Figure 19 shows a comparison of the $SPBTs_{system}$ of HH1 and HH4 when the PV plus storage system price in 2030 and 2040. The technology advancement and mass production will further facilitate the costs reduction of PV [52] and battery system [53]. 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.

An assessment at community level is also undertaken, suggesting that the PV plus storage can effectively cut down the energy costs, but yet to make the application economically feasible. The current revenues are mainly from the cost savings from reduced import, subsidies for PV generation and export 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 [5] and will be replaced by the Smart Export Guarantee [54] 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.



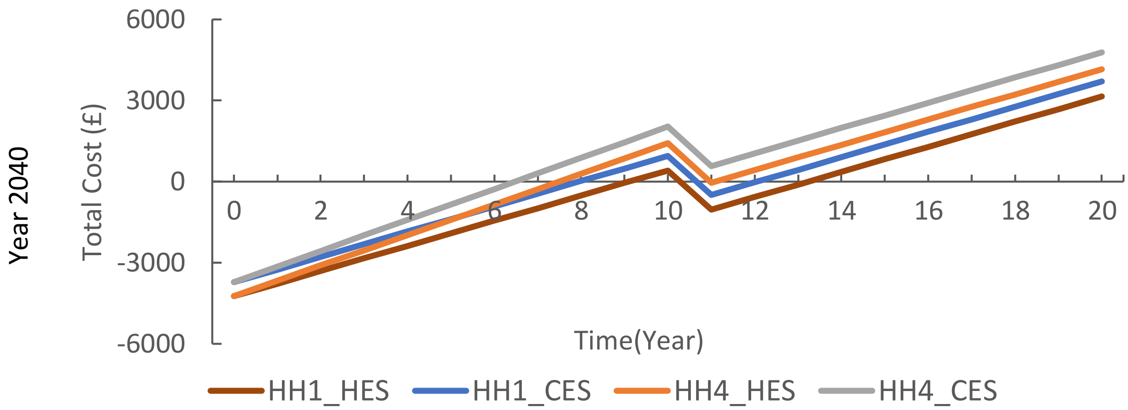


Figure 19 Total Profits of HH4 Over Time with Reduced System Costs

The inter-house trading within the CES seems to be a good opportunity to shorten the $SPBT_{system}$. 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} [55] and the average LCOS of behind-the-meter Li-ion battery is around £0.47 kWh^{-1} shown in Table 5, which are cheaper than most results in our study. Although the future increasing capacity of PV and storage may reduce the manufacture 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 [56].

Another solution is to obtain extra revenues by aggregating HES and CES to provide grid services. According to [57], a household with 4kWp PV coupled with a 4 kWh storage system can harvest £33.24 revenues by peak shaving, 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 our study, the combination of functions of PV and storage will play a more important role in future distributed energy systems.

Table 5 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 [58]	15	398	8	0.05	0.28
Jülch [59]	20	590 - 940	10 - 17	0	0.18 - 0.29
Lazard [60]	10	640 - 1027	0	0.09 - 0.1	0.37 - 0.58
World Energy Council [61]	5 - 20	239 - 2948	5.6 - 59	0	0.12 - 0.56

5. Challenges and Barriers

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 to their feasibility, though the inter-house trading may be a valuable additional revenue source. However, many challenges and barriers need to be solved so that the applications in our study can be applicable.

Traditional DNOs mainly facilitate the power flow towards energy consumers. However, the increasing DERs have imposed new challenges on distribution networks [62], 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. Aggregators 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 [63]. 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 [64], levy exemption [64], ownership[65], and network connection [66]. However, many questions and ambiguities still need to be answered and clarified, such as the role of independent aggregators [67], and the access to the balancing market [15].

In our 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 [68]. 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 [69]. 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 [70], but its capability of tracking all the required data is still unclear.

6. 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 found helpful to shave peak demand, but it also leads to marginal SSR drop 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 found environmentally beneficial, especially for 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 found 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 considerable 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, many legislative and financial supports need to be in place to ensure DERs 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.

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