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Techno-Enviro-Economic Assessment of Household and Community Energy Storage in the UK

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Abstract

Residential electricity demand is expected to rise in the next few decades due to the electrification of heating and transport. 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 PV, in partnership with energy storage systems in the residential sector. The scale of the energy storage system is important, i.e. in individual properties or as a community resource. Many advantages of community energy storage (CES) over household energy storage (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. 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 and export, improve the community self-consumption rate (SCR) and self-sufficiency rate (SSR), and contribute to much higher energy saving. Furthermore, optimising the CES capacity leads to more effective use of PV power and better demand localisation during high PV-generation periods. It is found that an important challenge for CES systems is to realise the value of the shared electricity equitably amongst the participants and potentially to seek other revenue streams.

Keywords: Agent-based modelling, Community energy storage, Self-consumption, Photovoltaics, Distributed generation, Battery management

1. Introduction

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]. In order to mitigate climate change [2], both European [3] and UK [4] national policies suggest that efforts should be made to ensure sustainable development in future. One effective measure is to replace traditional carbon-intensive resources with renewable energy, due to the environmental benefits [5]. This has led to the rapid development and application of renewable energy technologies in residential sectors and also encouraged the transition of electrifying transport and heating, for example through electric vehicles and heat pumps [6].

An issue that arises with greater deployment of power generation using intermittent renewable energy sources (RESs) and increasing energy demand is the maintenance of grid stability [7] and flexibility [8]. Energy storage is considered an essential compensation tool to improve dispatchability [9]. Electrical [10] and thermal storage [11] are the two main forms of storage and are expected to play an important role in future to make residential or commercial buildings more self-sufficient [12]. The selection of storage technology still needs, however, to consider several factors, such as energy/power density, efficiencies, costs and technological maturity, amongst others [13]. Lithium-ion batteries are becoming increasingly affordable and popular due to the rapid development and mass production of electric vehicles. Although the battery cell cost may continue to reduce in the future, the complete system cost is unlikely to reduce much as non-battery costs still account for nearly 60% of total installation cost [14]. Researchers from the UK [15], Germany [16] and the US [17] find the current systems struggle to recover the upfront investment in home PV plus battery storage systems. In recent years, some countries, such as the UK [18] and Germany [19], have reduced subsidies for electricity generated from RESs, such as Feed-in Tariffs (FITs), whilst the retail electricity price still remains much higher than selling price. This further reduces the incentive for residential customers to export renewable sourced electricity to the grid to recover investment costs. Instead, self-consumption is becoming increasingly attractive to households in order to maximise the economic value of their distributed energy resources (DERs) [20].

With the rapid development of decentralised energy systems, communities are expected to play a more significant role along with the wider energy system, especially for energy storage. In the UK, most energy storage is either distribution grid connected or installed in a single household, namely household energy storage (HES). Community energy storage (CES) is an emerging alternative to provide services for both grid-scale [21] and single household scale [22]. 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' [21]. Many advantages of CES over HES have been identified [23] including: 1) better performance of the battery system due to smoother aggregated demand compared to single home demand; 2) lower requirement on power ratings of batteries and 3) potential cost reduction of components. Research indicates CES has the capability of offering additional benefits for energy trading [24] and enhancing grid balance [25], whilst other research shows that the design and operation of CES is more interesting at consumer level [26,27]. Parra et al [21] used a simulation-based optimisation method to compare the performance of Pb-acid and Li-ion batteries for a 100-home community under different pricing cases and different PV and heat pump penetration. Their results indicate that batteries are more attractive for communities than individual homes for all cases, while Li-ion batteries are more suitable for higher PV production. The current time-shifting strategy is beneficial to network operators by shaving peak demand, but it is found to be less economic for households when the peak demand is not very long. Al Skaif et al [22] proposed a reputation-based framework to manage the use of CES by households within the CES network to avoid insufficient utilisation of surplus energy. It enables the households who contribute more energy to the community to be rewarded with better and easier access to the CES. The power dispatch strategy of CES is formulated as a Mixed Integer Linear Programming (MILP) function to minimise the amount and price of energy absorbed from the grid. The proposed reputation-based framework tracks and reviews the historical amount of renewable energy the entities shared with the community and allocates energy across the community fairly. Together with load shifting, CES can help households achieve a demand cost saving of up to 68%. Marczinkowski and Ostergaard [28] used EnergyPLAN to simulate HES and CES integrated with PV and wind turbines. Their results show that both HES and CES can contribute towards lower electricity imports and higher self-consumption, while the annual full capacity cycles of HES systems are much higher than CES (157 and 68 cycles respectively). CES is found to be beneficial to the distribution network in terms of reducing peak power exchange, while HES is suitable for consumers. Barbour et al. [29] suggest that CES has a number of advantages over HES, which can decrease total storage deployed, decrease surplus PV generation and hence improve the self-sufficiency of a community. They also raise questions regarding storage ownership and operation, such as which parties can benefit from storage financially. They also suggest some specific market mechanisms should be developed in favour of CES, such as a more complicated tariff structure involving all the stakeholders on a case-by-case basis.

It is therefore clear that CES has the potential to reduce the costs of and generate more localised energy consumption. However, 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]). There has been a limited number of studies that explore the behaviour of individual households within a network connecting to CES. In contrast to the optimisation-based approaches employed in the literature, agent-based modelling (ABM) 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 [32]. ABM therefore represents a powerful tool to help to understand not only the action of household agents, but also the interaction of households with the external environment, namely the community and the power grid.

The technical assessment of HES and CES systems is presented using a variety of typical indicators. Luthander et al. [10] identify the Self Consumption Rate (SCR) and Self Sufficiency Rate (SSR) as two effective parameters to evaluate the PV system and emphasize the importance of storage and demand side management to improve system operation. The Maximum Demand [33], or Peak Import/Export [34] is also used to measure the potential of load shifting and peak shaving. Cost of Electricity and Payback Time are commonly used in economic analysis [30] to show the cost savings attributed to the addition of a storage system and load scheduling. Net Present Value [35] and Internal Rate of Revenue [36] are also used to indicate the system profitability within a systems' lifetime. The Simple Payback Time (SPBT) is defined as the time taken for a project to pay for itself [37] and is not sensitive to financing parameters or the relative timing of system costs and revenues.

The increasing awareness of environmental issues necessitates reporting of environmental impacts in addition to economic analysis. There are numerous methods to evaluate environmental impact and that chosen must be based on the system in question and the comparison being made. Hou et al. [38] evaluate the life cycle energy consumption and greenhouse gas emission of grid-connected Crystalline silicon photovoltaic systems via Life Cycle Assessment (LCA). LCA can also be used to analyse other parameters, including ozone layer depletion potential, human toxicity potential, acidification potential, eutrophication [39] and ecological scarcity [40]. The different storage technologies and applications have also been assessed via LCA, such as household Lead-acid batteries [41] and household Li-ion batteries [42]. The environmental contributions of CES are yet to be further explored.

In order to meet future carbon budgets and the UK's 2050 target to decrease greenhouse gas emissions by at least 80% of 1990 levels, the Committee on Climate Change suggests more challenging and low-cost measures are needed to supplement current carbon reduction progress [43]. There is some evidence to suggest that grid-scale [44] and behind-the-meter [45] storage may increase CO_2 emissions in historic power systems. 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. A full life cycle assessment of CES would be the topic of a whole paper, therefore here CO_2 emissions is chosen as the environmental indicator as it is the most pertinent to the system.

The contributions of this paper are summarised as follows:

- an agent-based model is proposed to simulate HES and CES in a small community;
- an operational strategy of a community with rooftop PV and CES is proposed, which distributes available surplus energy to neighbours, CES and the grid;
- modified definitions of SCR and SSR are introduced as the KPIs for HES and CES;
- technical, economic and basic environmental evaluations are undertaken to quantify and compare three different cases.

The paper is organised as follows: The methodology adopted in this study is presented in Section 2, including the set-up of model and data input. Section 3 describes three different evaluation criteria used for technical, economic and environmental analysis respectively. Results from the simulations, including self-consumption rate, self-sufficiency rate, energy savings, carbon avoidance and payback time, are discussed in Section 4 and conclusions of this study are presented in Section 5.

2. System Model Design

2.1. Cases Considered in Study

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 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 households and its installation of DERs. Three cases are considered, PV-only, HES and CES, which contribute to the different sequences of energy supply to each household; in each case the system is assumed to be made up of 10 households. More details of the cases considered in the study are described in the following sub-sections.

2.1.1. Case 1: PV-only

In this case, each household is installed with a 3 kWp 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. The system architecture of Case 1 is shown in Figure 1.

2.1.2. 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 HBMS 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 2.

2.1.3. Case 3: CES

In Case 3, the CES consists of a large battery and a communal battery 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 CBMS 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.

2.2. Household Demand

In order to quantify and compare different influences on households due to the addition of PV and an energy storage system, five different types of load profiles are used in this study. Household power demand is represented by a load profile that is adapted from Richardson et al [46] with 1-min resolution and used as the model input. Five synthetic demands range from Electricity Profile Class 1 Low to High band according to Ofgem [47] (

Table *1*).

2.3. 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 [48].

The solar radiation received by an inclined surface of a PV panel can be obtained by:

$$I_r = I_b R_b + I_d R_d + (I_b + I_d) R_r \quad (1)$$

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:

$$P_{si} = I_{Ti} \eta A_{PV} \quad (2)$$

Where system efficiency is given by:

$$\eta = \eta_m \eta_{pc} P_f \quad (3)$$

And the module efficiency η_m is given by:

$$\eta_m = \eta_r [1 - \beta (T_c - T_r)] \quad (4)$$

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:

$$T_c = T_a + \alpha\tau / U_L \quad (5)$$

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 $I_{T,NOCT}$ = 800W/m^2. The specification of PV used in the study is shown in Table 2. The Solar radiance data is obtained from the Microgen Database developed by Sheffield Solar [49]. Each household owns a PV system with the same specification, in order to eliminate the discrepancies of electricity production from PV.

2.4. Battery Storage Model

Pb-acid and Li-ion batteries are widely used in real-life application of PV-battery systems. A lithium-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 [50].

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 [48]:

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

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.

2.5. HES Management (HESM) and CES Management (CESM) Strategy

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. For this study, the household energy storage management (HESM) can operate with several management strategies to control charging and discharging [51].

For Case 3, a different management strategy for the CES 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 4 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, then it is used to charge the CES and any surplus power is exported to the power grid.

Battery charging and discharging from/to the grid from the CES is not considered in this study, as the addition of an energy storage system primarily aims to improve the use of local PV generation. Power that charges the battery thus can only be from the PV system. The proposed storage system operational management aims to meet the demand of households by optimising the use of the available energy generated from PV. In this way, there are several battery operational limits to be established according to the SOC of the battery. During operation, when the SOC is between 20% and 100%, the battery storage is able to supply household demand and any remaining energy required is imported from the grid. When the battery reaches either its minimum or maximum SOC, the battery stops supplying energy and power flux within a household works as described in Case 1.

3. Evaluation Criteria

To quantify and evaluate the performance of Cases 1-3, this section provides several evaluation criteria of 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 system payback time and energy bill reduction, is then measured. Finally, the carbon avoidance and payback time in the three Cases are used as KPIs to represent the environmental influence.

3.1. 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 [10]. 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 community with CES. Therefore, the new definitions take into account 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:

$$SCR = (E_{PV} - E_{export})/E_{PV} \tag{9}$$

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.

$$SSR = (E_{demand} - E_{import})/E_{demand} \tag{10}$$

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

3.2. 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.

$$Energy\ Cost = E_{import}p_{grid} + dp_{standing} - E_{PV}p_{generation} - E_{export}p_{export} \quad (11)$$

where p_{grid} is the electricity unit cost charged by energy suppliers, d is the number of days, $p_{standing}$ is the standing charge, $p_{generation}$ is the FIT generation rate and p_{export} is the FIT export rate. This function is specifically proposed as the predominant interest for domestic consumers to install batteries is to reduce energy costs [52]; similarly, it is also the primary reason for the adoption of renewable energy communities [53]. In the UK, residential users are offered a wide range of retail electricity tariffs by energy suppliers, including both fixed-rate and time-dependent tariffs. In this study, only fixed-rate tariffs are considered and three exemplary values representing low, medium and high prices from those offered in 2018 are used for p_{grid}.

In our study, a simple payback time is adopted as a metric to indicate economic feasibility. Simple Payback Time (SPBT) 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 [37]. When the SPBT is larger than the systems' lifetime, the project is considered as economically infeasible.

$$SPBT_{system} = Total\ Net\ Cost/Annual\ Energy\ Cost\ Savings \quad (12)$$

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 charge 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 [54] 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 adopted in the study are shown in Table 4. Different 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 hence identify the suitable energy storage installation objectives.

3.3. 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 technology, e.g. centralised coal power plants. However, manufacturing renewable technologies is usually an energy intensive process, therefore, it is of great importance to quantify the environmental benefits of renewable technologies. Life Cycle Assessment and Carbon Footprint Analysis are two common methods to investigate the environmental impacts of an application, which corresponds to two most used environmental performance indicators, energy payback time and savings of carbon emission. In this study, the environmental analysis is undertaken by calculating the CO_2 avoidance by PV and storage system and the payback time of total carbon emission. The total carbon emission in the study only includes the CO_2 emission produced during PV and battery manufacture process, and electricity generation. It excludes the emissions generated from other processes such as system operation and maintenance. The Total Carbon Emission is determined as:

$$Total\ Carbon\ Emission = Q_{PV} + Q_{battery} + E_{import}q_{grid} \quad (13)$$

where the Q_{PV} is the total amount of CO_2 produced during PV production (kg), $Q_{battery}$ is the total amount of CO_2 produced during Li-ion battery production and q_{grid} is the CO_2 emission for every kWh electricity from power grid. The values used in this study for the environmental parameters are shown in Table 5. The carbon emissions used in our study represent the cradle-to-use values from literature. The avoided CO_2 emission ($EM_{avoidance}$) is due to reduction of energy import from the power grid.

$$EM_{avoidance} = ((E_{demand} - E_{import}) + E_{PV}) * q_{grid} \tag{14}$$

The export of surplus PV to the grid can only lead to a marginal reduction in grid carbon factor as it is a negligible amount compared to the capacity of the grid. Therefore the carbon avoidance here only focuses on household and community level. The CO_2 Payback Time is calculated via following equation:

$$PBT_{CO2} = Total\ Carbon\ Emission/EM_{avoidance} \tag{15}$$

4. Results

4.1. Technical Assessment

In this section, the criteria proposed in the previous section are used to evaluate the practice of installation of CES compared to HES and PV-only and also to quantify the impact of increasing capacity of CES. 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.

4.1.1. 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 5 and Figure 6 shows the monthly and annual energy import savings of the community through 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 cold months. Throughout the whole year, Case 3 is able to contribute to slightly more energy saving than Case 2, approximately 500 kWh.

Figure 7 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 [10]. 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 on SSR of Case 3 can be understood as the role that shared electricity plays in the system, which is further analysed in Figure 8.

Figure 8 illustrates the power flux going through and out of a community. The power export and import of a community from power grid are shown by the negative and positive shapes respectively. For Case 1, when PV generation is appreciable, the majority of 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 8 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.

4.1.2. Value of Energy Storage to Households

The results in the previous section 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 three Cases are now analysed from the perspective of households. Two types of households are used to demonstrate the impacts, a household with low demand (HH0) and a household with high demand (HH2).

In Figure 9, 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 harvest 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 10 shows the SCR, SSR and energy savings of HH0 and HH2 over a year, illustrating a similar trend to Figure 9. 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 amount of surplus PV power from its neighbours. In some month, although the monthly results might be against the tendency, it is not significant enough to influence the overall results, however it is of great importance for system planning.

Figure 11 illustrates a set of exemplary daily power interaction profiles of HH0 and HH2 in September, showing a similar trend to that of a community in Figure 8. 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 priority, which might lead to a questionable fairness issue.

4.1.3. CES Capacity Comparison

The previous section has demonstrated that the installation of CES is beneficial to the community. Therefore, to extend this, we investigate the value of CES and find out how the performance varies with the CES capacity. 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 12 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 13 shows how the monthly SCR and SSR varies with the capacity of CES, which reflects a similar tendency to that described in the previous section. Through the whole year, Figure 14 suggests that an extra 25 kWh contribute to a 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.

The daily SOC charts of CES with different capacities in four different months are shown in Figure 15. 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. 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 [55,56] and different tariff structures.

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.

4.2. 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 costs savings and subsidy via FIT. The ownership of CES and operation charges are therefore excluded from the study.

Table 6 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 shorter period of time when the system adopts higher tariff. Case 1 has the shortest payback time, suggesting that expensive storage system costs are the main barrier to 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.

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 7 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.

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 the 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. 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 16 shows the CO_2 avoidance of a community with three cases over 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, 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.

Table 8 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 using 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, in line with the results of Uddin et al. [15] who showed a reduction of 0.8 - 1.4 tonnes/year for a 4kWp panel. It is therefore clear that household heterogeneity is unlikely to be the most influential factor in CO_2 avoidance.

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 our study, the estimation of the total amount of emitted CO_2 is based on reference values (see Table 5) 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 should result in shorter PBT_{CO2} for Case 3 than predicted here.

In our research, we assume both manufacture and installation of solar panel and battery storage are in the UK. Arcos-Vargas et al. [57] emphasize the importance of installation and manufacture location, suggesting that the carbon emission can reach the lowest around 7g/kWh 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) [58] is found to be much higher than the UK (323 g/kWh), regardless of the ambition of China aiming to reduce it to 600 g/kWh by 2020 [59]. If we use the grid carbon intensity of China to calculate total carbon emission during manufacture, the PBT_{CO2}s of the three cases are almost double (5 – 5.5 years) that shown in Figure 17. 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 in Morocco [60], and 0.48 tonnes/kWp in Malaysia [61].

Across the three cases presented in this section, we investigate both HES and CES in addition to PV and identify the value of these applications. 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 [62]. For grid operators, this is obviously a better and cheaper alternative compared to expensive distribution and transmission network expansion [63]. 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 [64]. 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 [65].

5. Conclusion

In this study, 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. A CES power dispatch strategy is proposed, aiming to localise consumption and minimise the costs of energy import from external power grid.

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 hinder 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. Our 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. 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 [66].

The economic analysis above shows that both HES and CES system are yet to be economically feasible to consumers. More innovative solutions are yet to be proposed and deployed. The storage system could also be used to participate in more services to benefit other objectives, such as DNOs. CES can potentially help mitigate grid congestion and prevent grid reinforcement. The investment costs will be significantly reduced if the batteries are used for multiple sides and hence improve the feasibility of CES system. In this way, in order to enhance economic feasibility, future work will focus on a combination of battery services and different operating strategies. However, the question is how the revenue is generated and distributed within the neighbourhood, how the shared electricity meters are installed and who owns the CES. These are very problematic regulation issues that are yet to be solved. The financial outcome of a system is determined by several factors: the sensitivity analysis of system specification, and temporal distribution of load demand. A reliable and accurate modelling approach is essential to identify the opportunities for a particular site.

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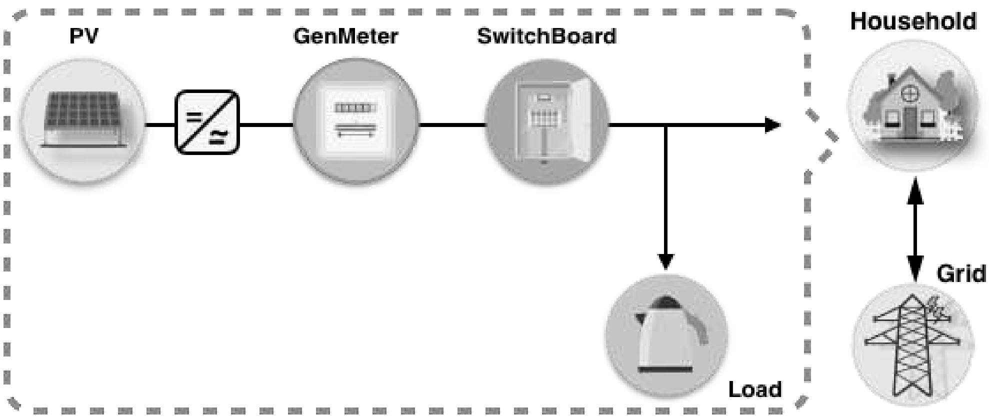

Figure 1 System Set-up of Case 1: PV-only

883

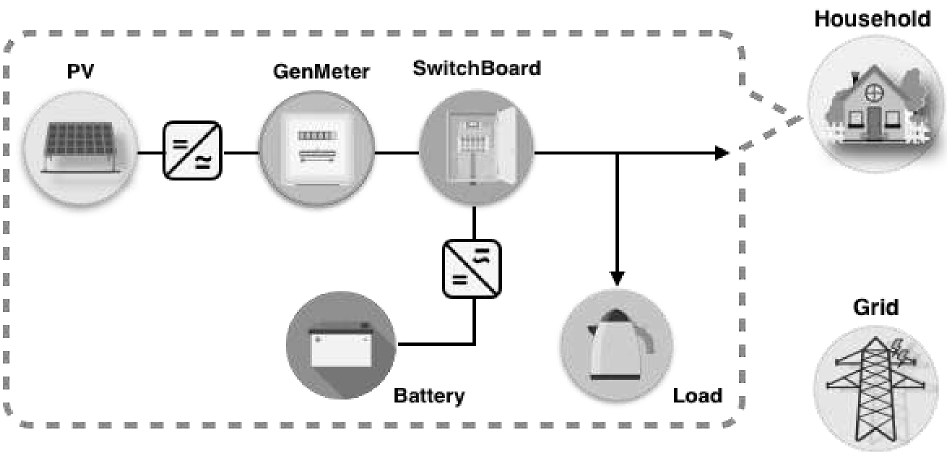

Figure 2 System Set-up of Case 2: PV+HES

884

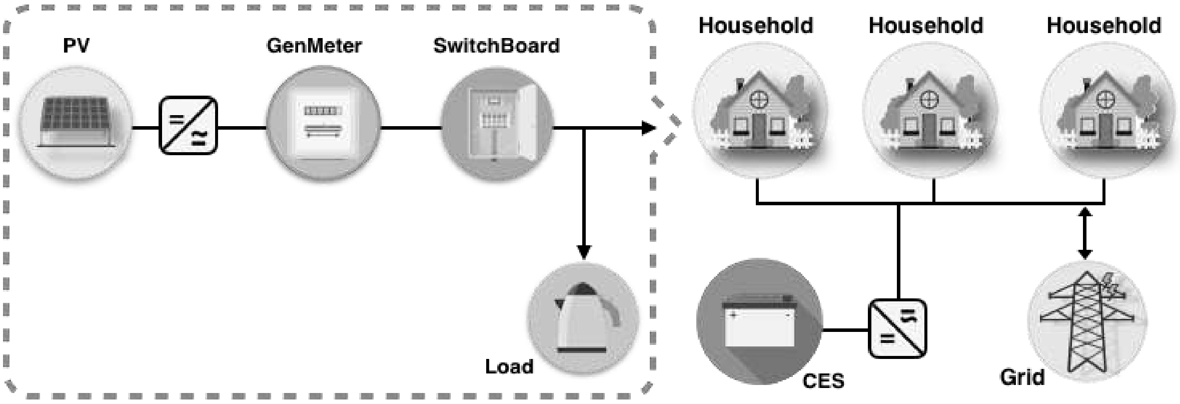

Figure 3 System Set-up of Case 3: PV+CES

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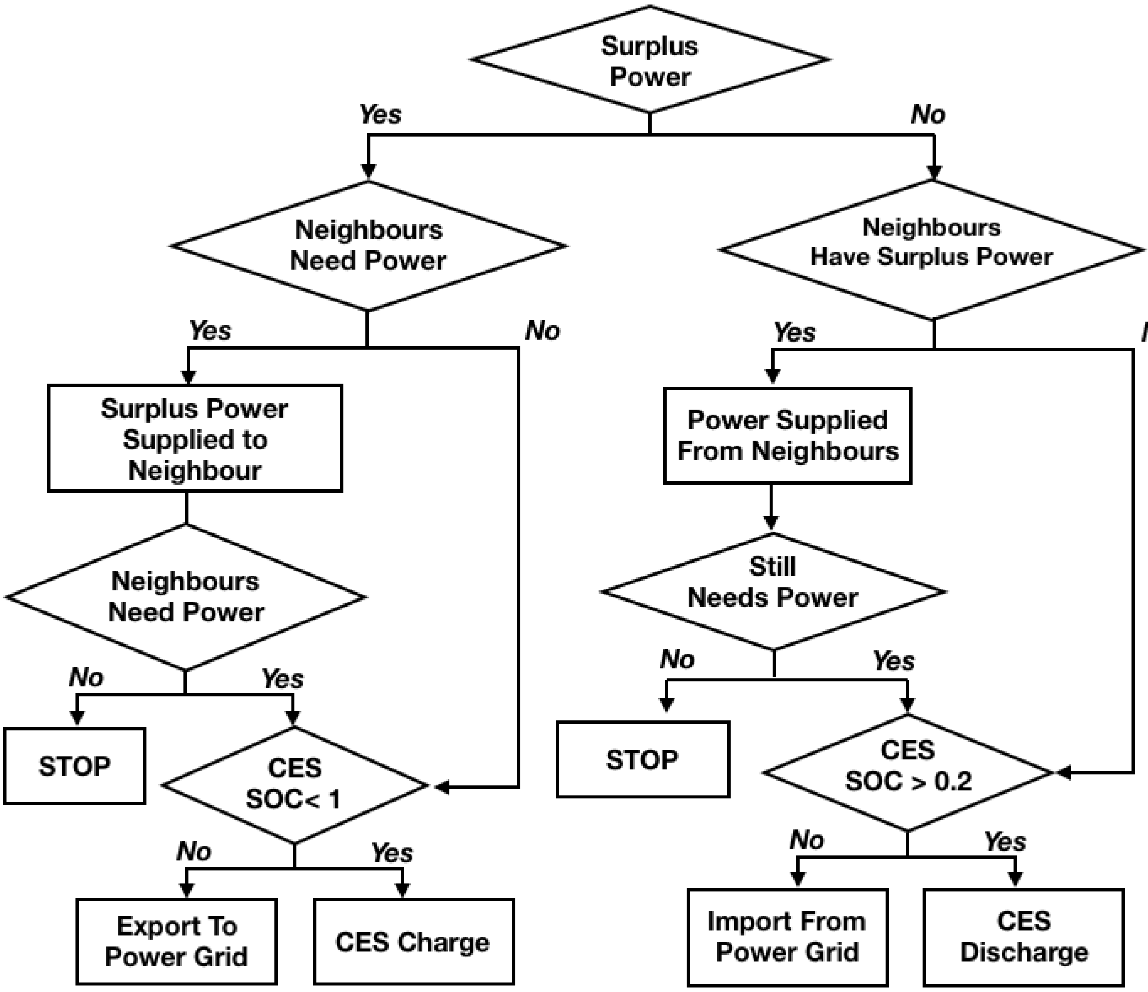


Figure 4 CESM Flowchart

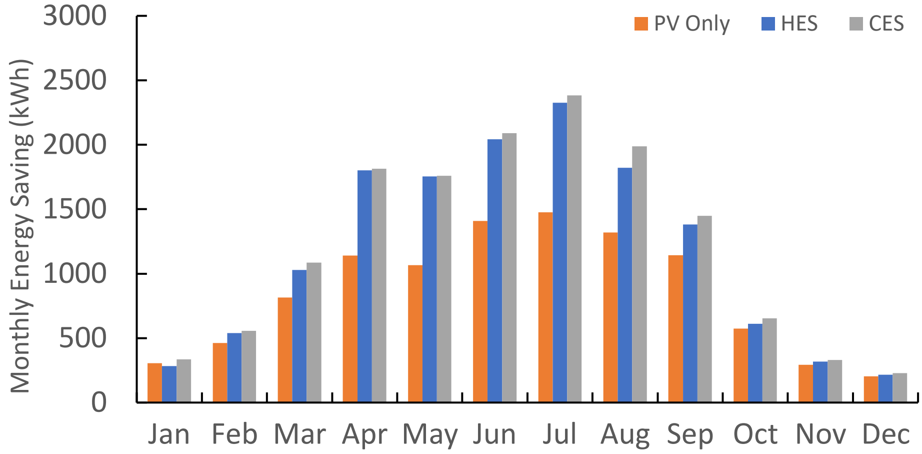


Figure 5 Monthly Energy Savings for A Community in Three Cases

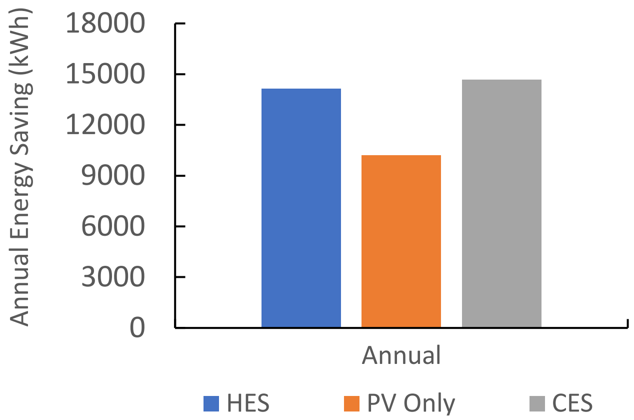


Figure 6 Annual Energy Savings for A Community in Three Cases

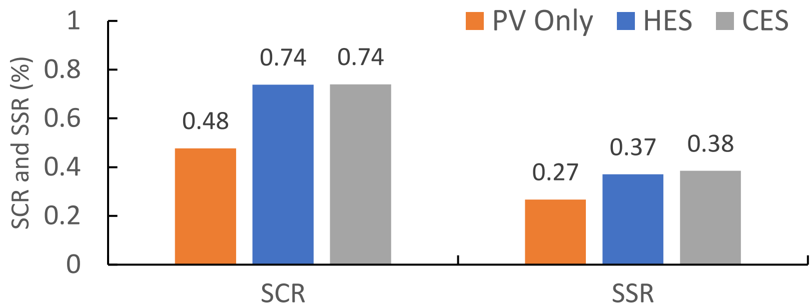


Figure 7 Annual SCR and SSR for A Community in Three Cases

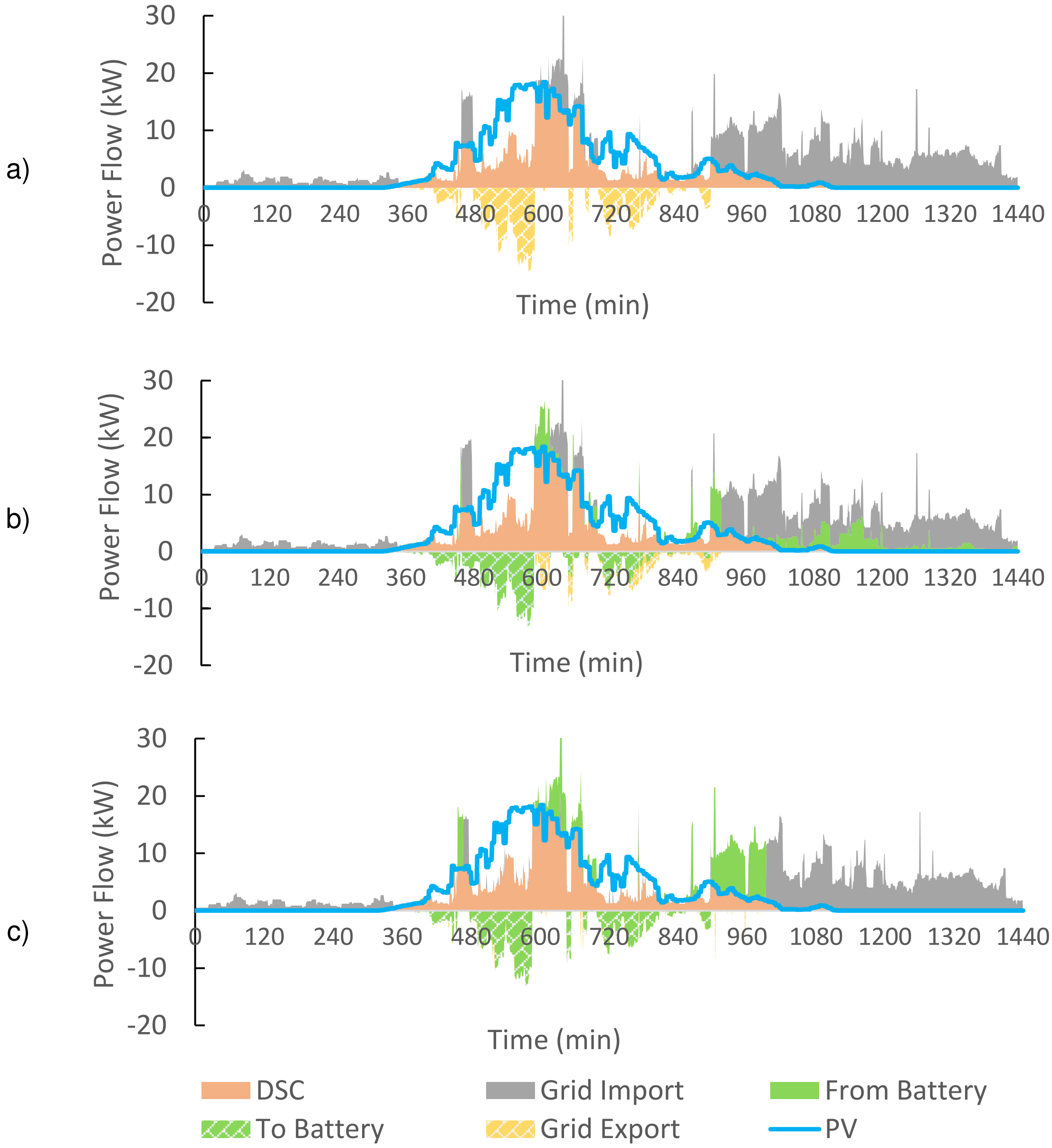
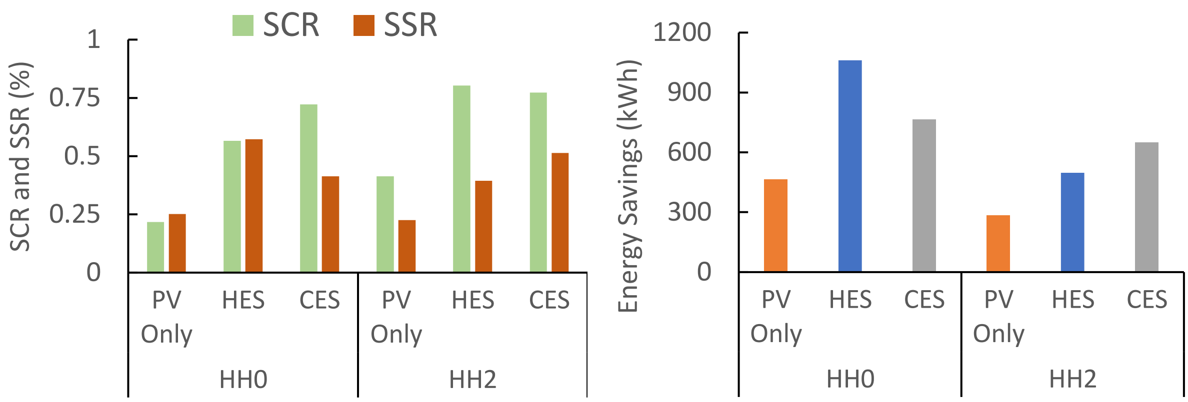


Figure 8 Power Injection of a Community in September with a) PV-only b) HES and c) CES



a) b)

Figure 9 Annual a) SCR, SSR and b) Energy Savings of HH0 and HH2

891

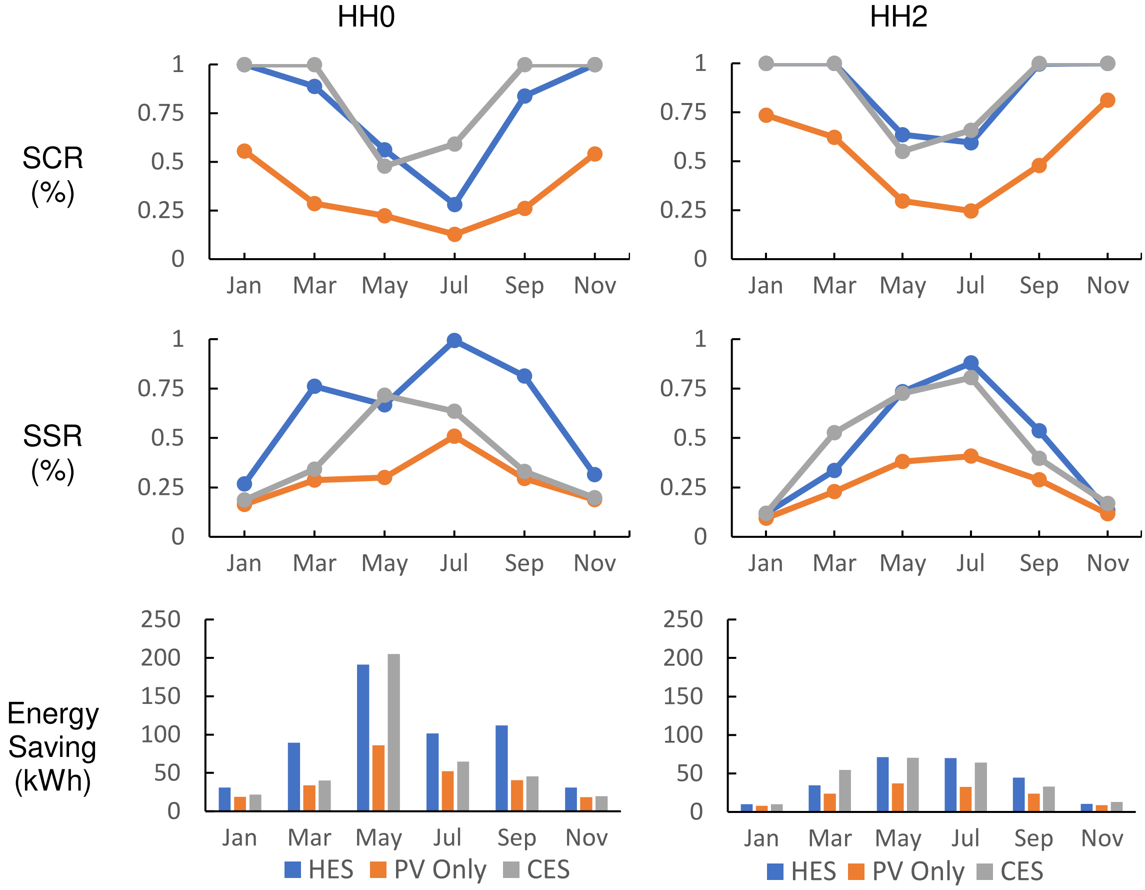


Figure 10 Monthly SCR, SSR and Energy Savings of HH0 (left) and HH2 (right)

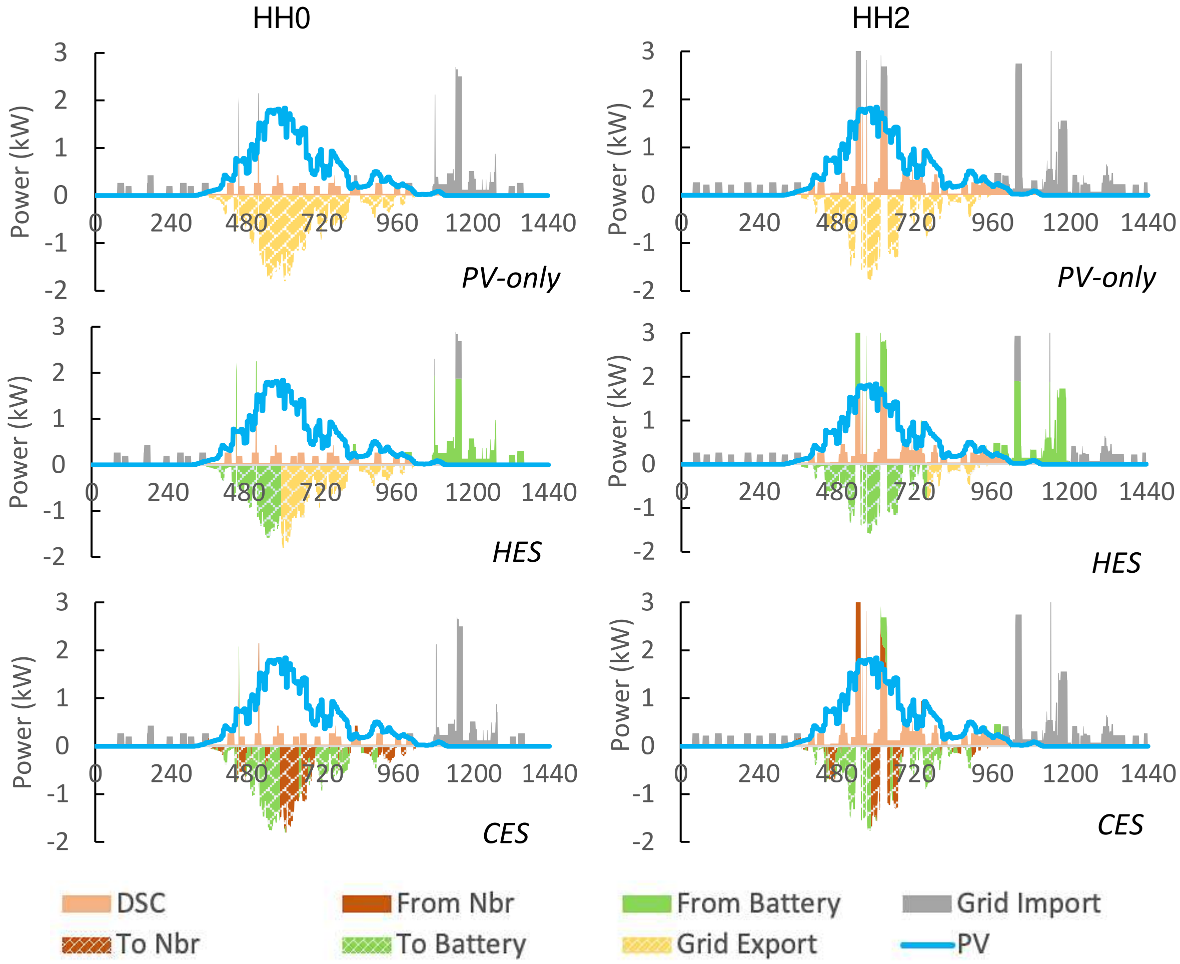


Figure 11 Daily Grid Interaction of HH0 (left) and HH2 (right) in September

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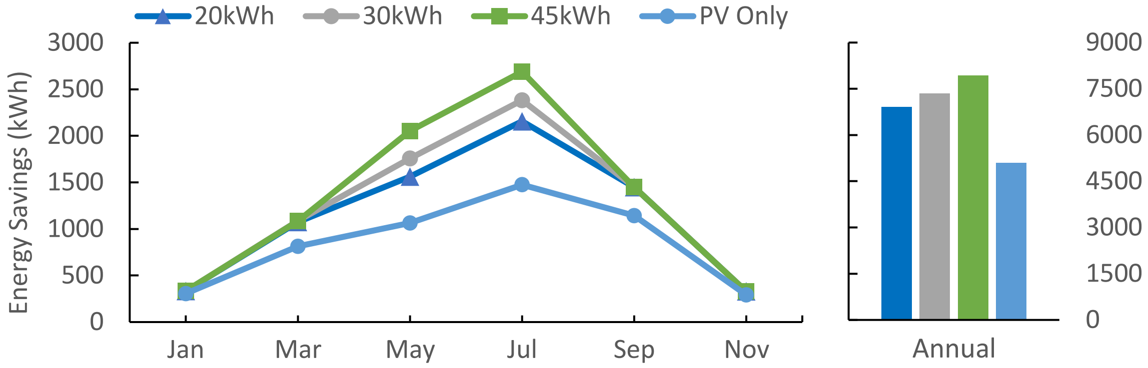

Figure 12 Energy Saving of a Street with Different Capacities of CES

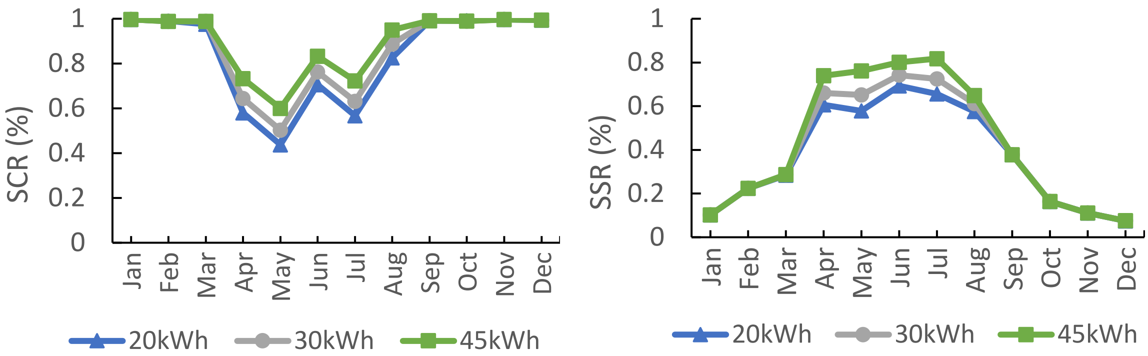

Figure 13 SCR (left) and SSR (right) of A Street with CES in Different Sizes

895

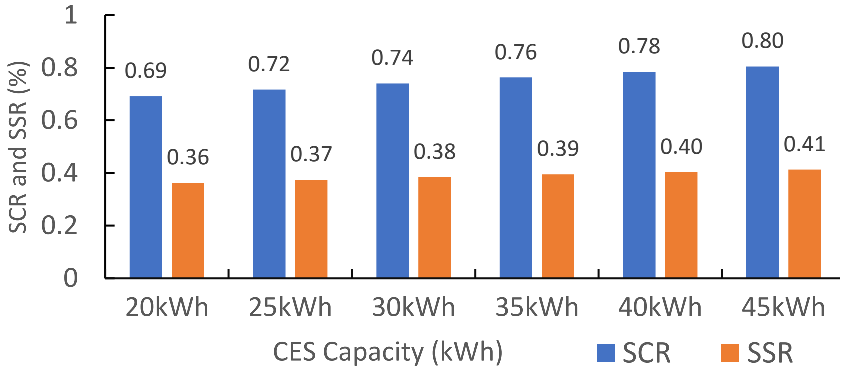

Figure 14 Annual SCR and SSR of A Community with CES

896

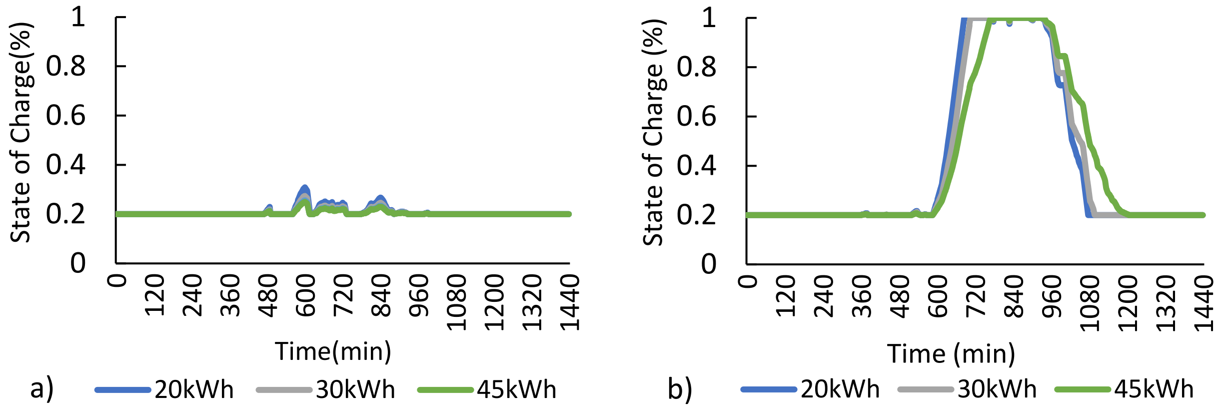

Figure 15 The SOC of CES with Different Capacities in a) March and b) May

897

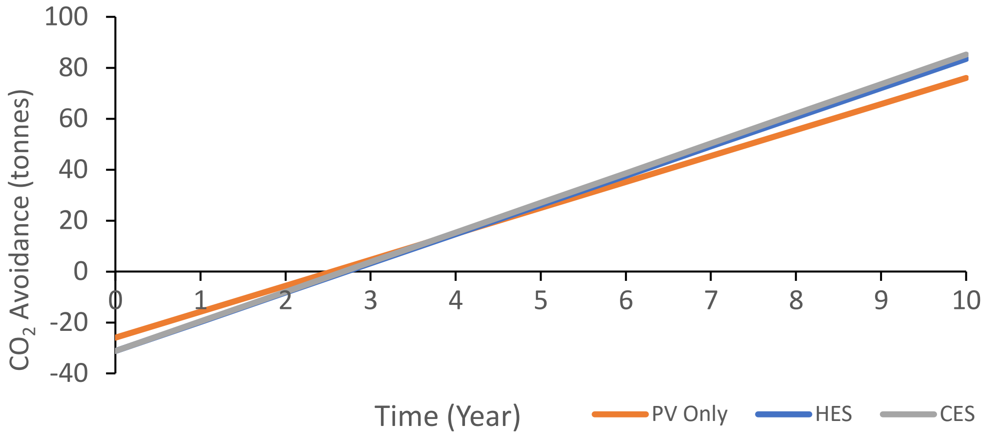

Figure 16 CO_2 Avoidance of a Community with 30 kWh Storage Over Years When Manufacture in UK

898

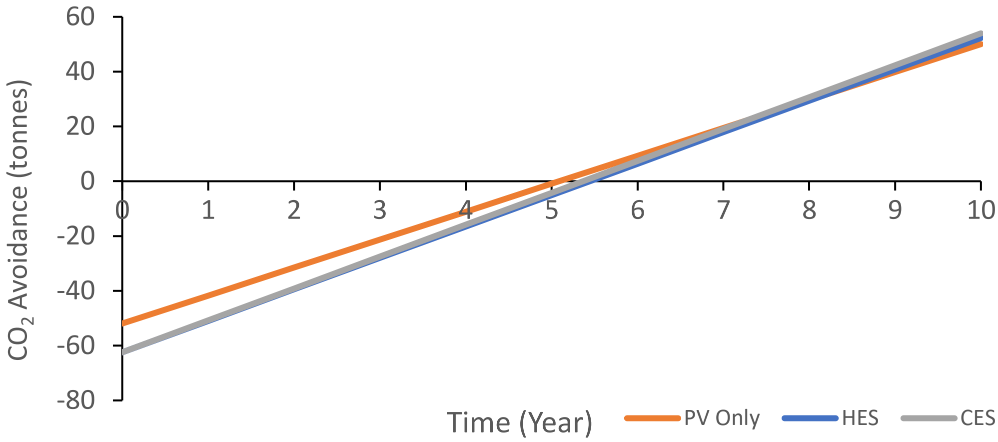

Figure 17 CO_2 Avoidance of a Community with 30 kWh Storage Over Years When Manufacture in China

Table 1 Overview of Electrical Load Profiles of Five Exemplary Households

Household Type	Type of Occupants	Occupants	Annual Electricity Consumption (kWh)	Ofgem TDCV Classification
HH0	Adult-Single	*1*	*1975*	Class1 Low
HH1	Adult-Couple	*2*	*2737*	Class1 Low
HH2	Adult-Couple with a Child	*3*	*4180*	Class1 Medium
HH3	Adult Couple and two Children	*4*	*2993*	Class 1 Low
HH4	Retired Couple	*2*	*4453*	Class 1 Medium

Table 2 Summary of PV parameters assumed for this purpose of this study [67]

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

Table 3 Parameters for the Li-ion battery [68]

Parameter	Value	Unit
Maximum Battery SOC	*100*	*%*
Minimum Battery SOC	*20*	*%*
Roundtrip Efficiency	*92*	*%*
Cycle Lifetime	*3000*	*Cycles*
Battery Degradation	*0.4*	*%/a*

Table 4 Economic Parameters Adopted in This Study

Parameter	**Value**	**Unit**
3 kWp PV Cost [68]	*2700*	£
2.5 kWh Battery Unit Cost [68]	*1108*	£
Feed-In Generation Tariff [69]	*0.0381*	£* kWh^{-1}
Feed-In Export Tariff [69]	*0.0524*	£* kWh^{-1}
Electricity Retail Price [70]	0.*1323*; 0.*1504*; 0.*1801*	£* kWh^{-1}
Retail Standing Charge [70]	*0.2044*	£* day^{-1}

Table 5 Environmental Parameters Adopted in This Study

Parameter	Value	Unit
Carbon Factor of Grid Electricity [71]	*0.323*	kg.kWh^{-1}
CO_2 Emission During Inverter Manufacture [72]	*12.03*	kg.kW^{-1}
CO_2 Emission During PV Manufacture [73]	*865.44*	kg.kWp^{-1}
CO_2 Emission During Battery Manufacture [72]	*175*	kg.kWh^{-1}

Table 6 Payback Time (years) of a Street with Three Different System

Storage Capacity	Low Tariff (£0.1323/kWh)		Medium Tariff (£0.1504/kWh)		High Tariff (£0.1801/kWh)	
	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*

Table 7 CES Payback Time of HH0 and HH2 with High Supplier Tariff

Storage Capacity	HH0 Payback Time (Years)		HH2 Payback Time (Years)	
	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*

Table 8 Annual CO_2 Avoidance and CO_2 Payback Time

CES Capacity	CO_2 Avoidance (tonnes*Year^{-1})			CO_2 Payback Time (Years)		
	Community	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*