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Environmental and economic impact of household energy systems with storage in the UK

Yuzhou Tang, Tim T Cockerill, Andrew J Pimm, Xueliang Yuan

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Yuzhou Tang[a,b], Tim T Cockerill[b,c], Andrew J Pimm[c], Xueliang Yuan*[a]

[a] *School of Energy and Power Engineering, Shandong University, Jinan 250061, China*

[b] *School of Mechanical Engineering, University of Leeds, Leeds, LS2 9JT, UK*

[c] *School of Chemical and Process Engineering, University of Leeds, Leeds, LS2 9JT, UK*

**Email: yuanxl@sdu.edu.cn. Tel.: +86 531 88399372. fax: +86 531 88395877*

Abstract: Households accounted for 35% of total UK electricity consumption in 2019 and have considerable potential to support the target of net-zero CO_2 emissions by 2050. However, there is little understanding of the potential to reduce emissions from household energy systems using emissions-responsive battery charging, and existing investigations use average emissions factors rather than marginal. To understand the overall carbon reduction potential of household energy systems, a life cycle assessment has been conducted for a typical house in the UK, with annual electricity consumption of 3960 kWh. Household energy systems comprising solar photovoltaics arrays and battery energy storage systems are assessed using time-series consumption and generation data, determined by combining a validated demand model, marginal emissions factor calculations, storage system models, and assumptions regarding the future grid. Marginal emissions factors are used to calculate the life cycle carbon emissions of electricity consumption. The carbon emissions and financial costs of household electricity consumption have been estimated for different combinations of battery storage, photovoltaics arrays, and smart battery charging systems. Results show that the deployment of a rooftop photovoltaics array and lithium nickel-manganese-cobalt battery operating in response to grid emissions factors could achieve 14 tons of CO_2 savings through the system's life span, though total electricity costs would be increased considerably. The household with just a photovoltaics array and no battery storage could increase total electricity costs by £2,170 and achieve 12 tons of CO_2 savings through the system's life span, providing much improved marginal abatement costs over systems with battery storage. The battery operation mode and the characteristics of batteries and photovoltaics systems in carbon emissions reduction are discussed. High cost is the main factor limiting the deployment of household battery systems.

Keywords: Energy storage household, PV panel system, Marginal emissions factors, Future grid assumption, Life cycle assessment

1. Introduction

In 2019, households accounted for roughly 35% of the UK's total electricity consumption [1] and around 9% [2] of carbon emissions. Households have considerable potential to support the realisation of the net-zero emissions target through strategies such as decentralised electricity production at domestic scales, in addition to reductions in electricity consumption [3].

Fitting domestic properties with PV panels could facilitate an effective reduction in electricity import from the grid [4]. However, the potential is limited by intermittency effects [5]. In particular, during daytime, the sufficiency of a rooftop PV system depends upon the capacity of the system compared with the household demand. Obviously, there is no PV generation overnight when the sun has set. PV certainly has a low-capacity factor. [6]. Thus, introducing an integrated PV-battery system could help balance unpredictable outputs [7] and increase self-consumption via deferring the use of the electricity produced from PV, known as load shifting [8]. In principle, a detached house with a PV-battery system [9] should be able to reach grid independence with net-zero external electricity consumption [10] despite many challenges [11].

Considering the battery storage part of the PV-battery system, the storage system increases self-consumption of local generation and hence reduces electricity bills, the use of fossil generation and the stress on electricity distribution infrastructure [12]. A "smart battery charging" strategy is proposed in this paper based on marginal emissions factors (MEFs) [13]. MEFs is defined as the metric to measure the CO_2 intensity of the demand change, which could represent the impact on emissions of changes in consumption relative to current conditions [14]. Average emission factors (AEFs) are the ratio of CO_2 emission to electricity generation which describe the average $kgCO_2/kWh$ of the electricity consumption [15]. MEFs are suitable and applied to the energy sector because the AEFs underestimate the impact of policies on electricity consumption [16,17]. MEFs have also been applied to the electricity consumption sector in the study of carbon emissions [18]. Braeuer et al. applied MEFs to assess the carbon emissions of grid storage system and found that MEFs can better reflect changes in grid carbon emissions than AEFs [19]. Bettle et al. applied MEFs to calculate the carbon emissions of electricity from the UK grid [20]. Pinel et al. analysed the impact of grid structure on MEFs and highlighted the importance of fully accounting for electricity imports and exports [21]. The proposed smart battery charging strategy facilitates charging at low MEFs when electricity is mainly generated from low carbon sources and discharges at high MEFs when power comes from high carbon sources, thus resulting in a reduction in carbon emissions [22].

Economic and environmental benefits are the two main motivations for households to adopt the proposed strategies [23,24]. The priority of the two is different in each study [25–27]. The infrastructure construction, manufacture, the maintenance of the system and the battery efficiency all affect the carbon emissions and financial burden for the households and the government. Life cycle assessment (LCA) and life cycle cost (LCC) have been widely applied to household PV and battery systems to evaluate the environmental and economic impacts, respectively [6,28–33]. Hoppmann et al. studied how PV-battery system sizing affects environmental and economic benefits and found that smaller systems have better environmental and economic performance than larger systems based on existing technology [34]. Chatzisideris et al. analysed the impact of electricity generation mix characteristics and found that under current electricity prices in Greece and Denmark, it is not financially viable to add storage to a PV system, and the generation mix greatly affects the environmental benefits of the system [35]. Analysing the environmental and economic benefits of PV generation, Espinosa et al. focused on standalone PV systems, where all generation is exported to the grid [36]. In contrast, others such as Chatzisideris et al. consider PV generation mainly for self-consumption [37]. The effect of different battery chemistries has also been assessed in studies of PV-battery systems, with common examples being Lead-acid batteries [38] and Li-ion batteries [11].

However, most research into household PV-battery systems and demand response has only focused on annual average values of electricity production and consumption [6,29,31–33,39]. Studies using high-resolution household demand and generation data according to the features of the research area or considering possible future changes in the structure of the energy system are unavailable. Although a few studies on estimation according to questionnaires or some experimental cases are available [28,30], they do not involve widely recognised data on household electricity consumption and future grid assumptions. Additionally, there is no integrated evaluation that takes into account temporal variations in electricity grid emissions factors to assess the environmental impacts and economic costs of implementing these facilities. Most research has calculated the carbon emissions of electricity demand and generation using temporally- and spatially-averaged values of electricity generation mix and emissions factor [6,28–30,33]. The assessment of carbon emissions based on marginal emissions factors has not previously been included in studies using an LCA approach.

Therefore, the major challenges and contributions of the current research are summarised as follows:

- The influence mechanisms of battery, PV and smart charging systems on carbon emissions and economic performance are comprehensively investigated using time-series household electricity consumption and generation data, through comparison of LCA and LCC analyses in different scenarios. This comparison considers a range of combinations of PV and battery systems.

- Marginal emissions factors are used to calculate the life cycle carbon emission of electricity consumption. The smart charging system is developed for further decarbonisation in household PV-battery systems.

This research not only highlights opportunities to further reduce the UK's carbon emissions and the cost of household electricity, but also provides insights for other countries looking to meet green commitments and tackle climate change.

2. Aims and approach

This study compares three combinations of domestic PV, battery, and smart battery charging systems to identify which scenario is associated with the highest CO_2 saving and the lowest marginal abatement cost compared to the scenario without a PV or battery system, as illustrated in Table 1. A further goal is to determine the effect of the following parameters:

- different storage system operation modes;
- three battery types (lead acid battery (LAB), lithium-ion phosphate battery (LIB) and lithium nickel-manganese-cobalt battery (LNB));
- PV and battery characteristics.

Table 1: Four scenarios of the household electricity consumption

Scenarios	**Details**
Basic (no PV or battery, NPB)	The houses in this scenario just use electricity from the grid.
PV only (P)	The houses in this scenario use electricity from the grid and PV, without the battery system.
PV + battery (PB)	The houses in this scenario use electricity from grid and PV, with a battery system. The battery is charged from the grid and PV in the low tariff time and discharged in the high tariff time.
PV + smart-charging battery (PSB)	The houses in this scenario use electricity from the grid and PV, with a smart battery charging system. The battery is charged from the grid and PV in the low MEFs time and discharged in the high MEFs time.

This study uses LCA and LCC to analyse the environmental and economic impact of different strategies applied to the UK, with complete consideration of the characteristics of batteries, PV panels, and the source of electricity. The semi-detached house is considered to represent a typical British house, accounting for 31.9% of homes in the UK [40]. The electricity consumption of a typical household energy system for 25 years from 2018 to 2043 (excluding energy for travel) is selected as the functional unit for quantitative analysis of the energy input, material consumption and environmental impact of the entire system. As shown in Fig.1, the system boundary of '**cradle to grave**', including extraction, manufacture, operation and maintenance, disposal and recycling of all components (excluding transportation), is selected.

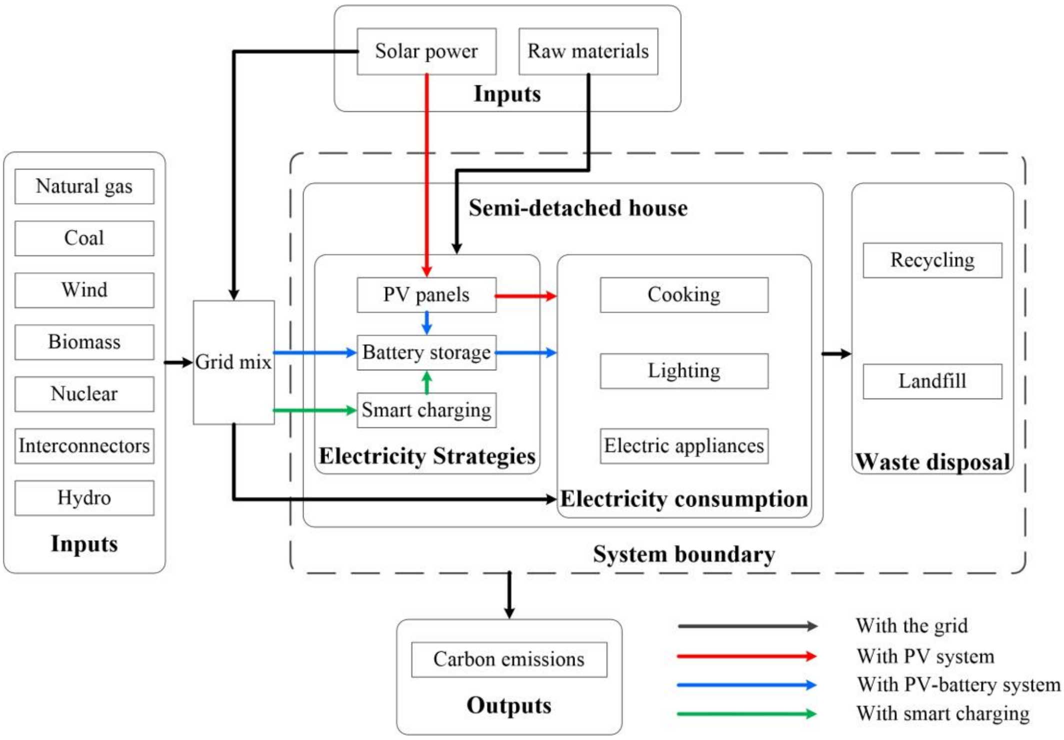

Fig. 1. System boundary of household electricity consumption

For our analysis, the inventory is divided into two parts: facilities (battery system, PV system) and the usage stage, as shown in Fig.2. The inventory of facilities is mainly taken from the literature and the Ecoinvent Database. The inventory of the usage stage is determined by combining the CREST Demand Model [41], MEF calculations, a storage system model, and assumptions regarding the future grid.

In detail, half-hour resolution household electricity demand and generation data are obtained for the simulation period using the CREST Demand Model. The half-hour resolution marginal carbon emissions of the unit grid electricity in the year a ($M_{t,a}$) is obtained through the MEFs simulation. Then, the amount of grid electricity consumption ($G_{t,i,a}$) and export ($E_{t,i,a}$) of scenario i in the year a could be calculated based on the storage model. The CO_2 saving of the optimised scenario i in the year a ($C_{i,a}$) could then be calculated (Eq. 1). The life cycle CO_2 saving of scenario i in the usage stage could be estimated using the $C_{i,a}$ in 2018, 2030 and 2050 as reference years. 2018 is assumed as the starting year for the 25-year period and the results in other years are found using linear interpolation between the 3 reference years.

$$C_{i,a} = \sum_{t=1}^{n}(E_{t,i,a} - G_{t,i,a}) * M_{t,a} - C_{basic,a} \tag{1}$$

In Eq. 1, $C_{i,a}$ is the CO_2 saving of scenario *i* in the year a; *n* is the total number of all half-hours in the year a; $E_{t,i,a}$ is the grid electricity consumption of scenario *i* in the year a at time t; $G_{t,i,a}$ is the export of scenario *i* at time *t* in the year a; $M_{t,a}$ is constant MEF at time *t* in the year a; $C_{basic,a}$ is the total carbon emissions from electricity consumption in the basic scenario in the year a.

The 100-year global warming potential (GWP100) values of the ReCiPe midpoint model and the EcoInvent Database are used to determine the life cycle carbon emissions of the facilities (battery system and PV system). The ReCiPe midpoint model is the most widely used life cycle impact assessment method and includes 17 midpoint impact categories [42-44]. The GWP100 for a greenhouse gas can be defined as the heat absorbed by that gas in the atmosphere over a 100-year period, as a multiple of the heat that would be absorbed by the same mass of CO_2 over the same period [45].

The LCC is used to calculate the present value of financial cost of each strategy through the life span. The time-of-use tariff is the same as the one used in the Bethesda Energy Local Club community energy scheme [46] in the UK and is used to calculate the financial burden and economic benefits of the scenarios. Cash flow is determined for each year from 2018. This takes into account all potential costs and revenues including installation cost, O&M cost, replacement cost of battery system and PV system, as well as electricity bills and electricity export benefits. Electricity prices and capital costs are assumed to remain the same throughout the lifetime. The study calculates the discounted costs by multiplying the cash flow of each year by the discount factor cited in HOMER Pro 3.14 [47]. The LCC of the system is calculated by summing the discounted costs for each year through the lifecycle.

The influence mechanisms of the battery and PV characteristics are detailed through the sensitivity analysis of smart battery charging condition, battery C-rate and PV capacity.

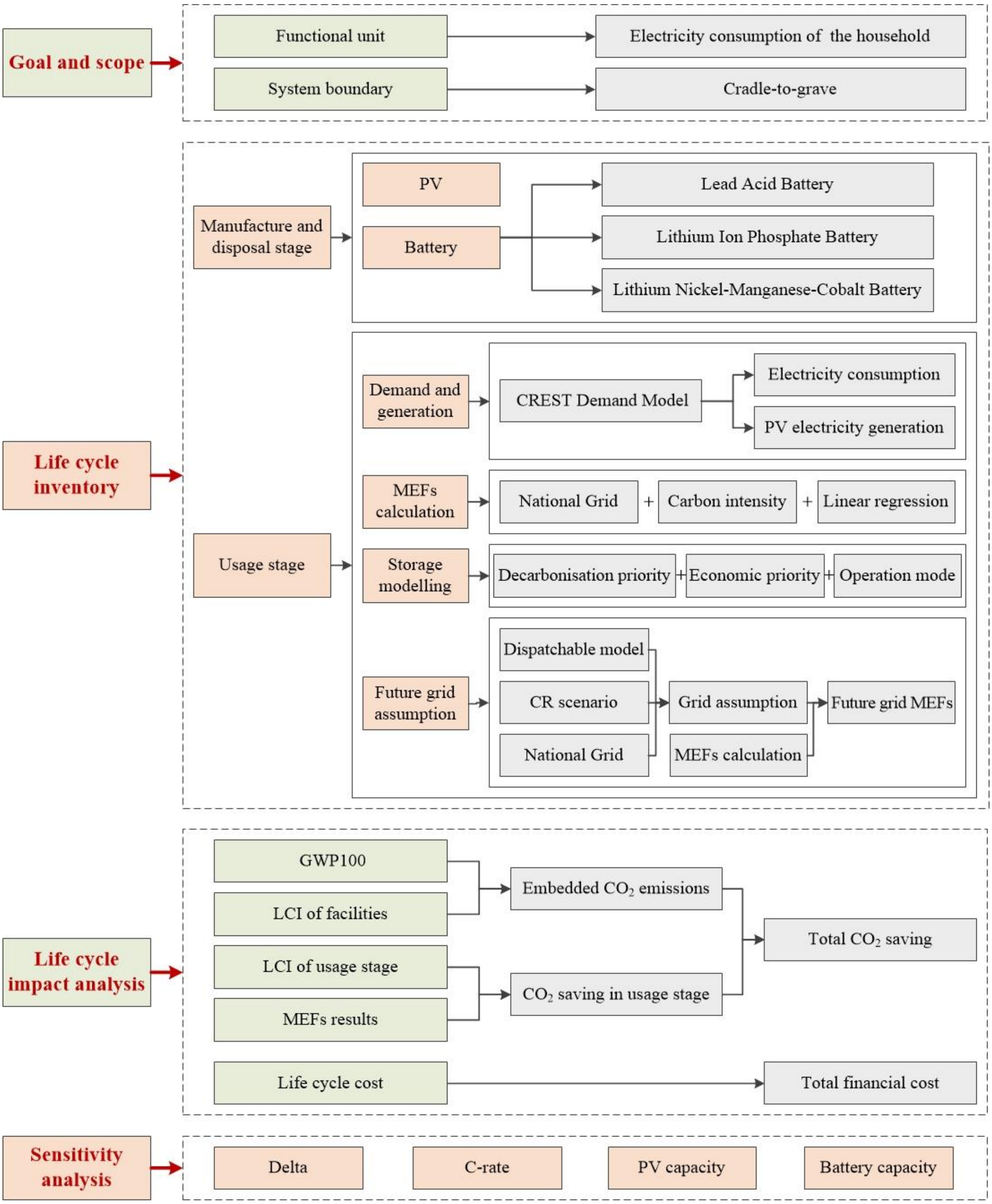

Fig. 2. Flow chart of the approach

3. Inventory of manufacture and disposal

Concerning the inventory in the manufacture and disposal stage, three kinds of batteries are considered in this paper: the LAB as the most common battery [5], the LIB as the battery of Moixa Smart Battery [48], and the LNB as the battery of Tesla Powerwall 2 [49]. The life cycle inventory (LCI) data of PV and batteries are obtained from the Ecoinvent database [50] and other studies [51,52].

3.1 PV panel inventory

The panel size of 2.6 kWp is chosen in accordance with the roof area of an average semi-detached house [53]. The effect of different panel sizes (0−10 kWp) is examined in the sensitivity analysis. The lifespan of the PV system is assumed to be 25 years because most manufacturers offer a 25-year warranty for solar systems [54,48]. The life cycle inventory (LCI) data of PV panel manufacture is based on the research of Balcombe et al. [11]. At the end of life, all valuable materials are assumed to be recycled and the recycled materials displace the raw materials from manufacture. All other components are assumed to be landfilled. The inverter efficiency of the PV panel is assumed at 97% [55]. Further details are given in Table 2.

3.2 Battery inventory

The battery size is assumed to be 4.8 kWh, equal to that of the Moixa Smart Battery [48], and the influence of varying the battery capacity between 4.8 kWh (Moixa Smart Battery) [48] and 13.5 kWh (Tesla Powerwall 2) [54] is shown in the sensitivity analysis. Referring to Sun's battery storage modelling [13], a charge/discharge rate limit (C-rate) of 0.25 C (1.2 kW for a 4.8 kWh battery) is used for the simulation, and the effect of varying C-rate from 0.1 C to 0.5 C (0.48–2.4 kW for a 4.8 kWh battery) is assessed in the sensitivity analysis. The charge/discharge and AC-DC/DC-DC each-way converter efficiencies are assumed at 98.5% and 97%, respectively [13]. The lifespan of the lead acid battery (LAB) is assumed at five years based on previous research [56]. The life spans of lithium-ion phosphate battery (LIB) and lithium nickel-manganese-cobalt battery (LNB) are assumed at 10 years according to the warranties offered by Moixa [48] and Tesla [54]. As battery recycling is a legal requirement in the UK [57], valuable materials are assumed to be recovered. All other components are assumed to be landfilled. The details of the three types of battery are shown in Table 2. The realisation of the smart battery charging mainly relies on the control component integrated in the battery's supporting hardware. The annual real discount rate of 6% from HOMER Pro 3.14 is used to calculate the life cycle cost of the system [47]. Hardware cost and material input are not associated with the implementation of the smart battery charging.

Table 2: Inventory data and the cost of strategy components for household electricity consumption

Components	Description	Data source for LCA	Capital cost (£)	O & M cost (£)
PV panel	2.6kWp	Balcombe et al. [11]	4251 [58]	42.12/yr [56]
LAB	4.8 kWh	Wang et al. 2018 [51]	1134 [59]	13.88/yr [59]
LIB	4.8 kWh	Wang et al. 2018 [51]	4450 [48]	0 [48]
LNB	4.8 kWh	Berg and Zackrisson 2019 [52]	2350 [54]	0 [54]

4. Inventory of usage stage

The semi-detached house with four residents is selected to create the household electricity demand and generation through the CREST Demand Model. The carbon footprint of electricity is calculated using the regression method with the generation and demand data from the G.B. National Grid for two weeks before and after a specific half-hour and the carbon intensity data from the Carbon Intensity API. The economic effect is calculated using the electricity tariff of the Bethesda Energy Local Club community energy scheme. The storage systems of different strategies are modelled separately based on the time-varying MEFs and electricity tariffs. The MEFs in 2030 and 2050 are estimated by a dispatch model built on the basis of the capacity of different generation types in the CR Scenario. The electricity consumption and generation data of each scenario in the usage stage could then be assumed.

4.1 Estimation of the household demand and generation

The use of the CREST Demand Model offers comprehensive, high-resolution data on domestic energy demand and rooftop PV generation for households in the UK [60]. This is a widely recognised model to simulate minute-resolution household electricity consumption and PV generation based on a bottom-up activity-based structure, using Markov chain programming to analyse time-use data [41,60]. For the simulation preset of the CREST Demand Model, the gross electricity demand, PV output, and net electricity demand data are collected from 1 January to 31 December for a semi-detached house at latitude 53.8, longitude −1.5 in the UK with household size of 4 and annual consumption of 3960.31 kWh. The average UK household electricity consumption in 2017 was 3760 kWh per household [61]. It is assumed that the annual household electricity consumption and PV generation are consistent through the lifecycle. This research selects the average of five simulation results to reduce the uncertainty of the household demand and generation data. The LCI data for grid electricity are those published by the G.B. electricity system operator, National Grid [62].

4.2 Determining MEFs

The MEFs of the UK in 2018 are determined to calculate the carbon footprint of electricity consumption in each half-hour. MEFs are calculated using the regression approach for different fuel types, as developed by Hawkes [63]. The half-hourly time series of MEFs for 2018 is calculated using systematic, detailed, five-minute resolution monitoring data from the G.B. National Grid [62], and carbon intensity factors (Table 3) determined by Staffell [64] and GridCarbon [65], to estimate nationwide, type-based, time-varying emissions factors. The fuel types of CCGT, nuclear, wind, pumped storage, hydro (non-pumped storage hydro), other (mainly biomass CHP), intfr (French interconnector), intirl (Moyle interconnector), intned

(Dutch interconnector), intew (East-West interconnector), dedicated biomass, and solar are included to calculate the MEFs. Pimm et al. [22] obtained the MEFs in the simulation based on the entire year, which disregarded the impact of the demand variation and the grid mix structure in different months. Sun et al. [13] calculated the MEFs separately for each month, which resulted in discontinuous MEFs between months. Pinel et al. found that yearly marginal factors ignore the seasonal variation of electricity [21]. Hawkes' method is applied to the generation and demand data for two weeks before and after a specific half-hour to calculate the MEFs for the given time and address the aforementioned problems.

Table 3: The carbon intensity factors

Fuel Type	Carbon Intensity (gCO_2/kWh)
Biomass	120
Coal	937
Dutch Imports	474
French Imports	53
Gas (Combined Cycle)	394
Gas (Open Cycle)	651
Hydro	0
Irish Imports	458
Nuclear	0
Oil	935
Other	300
Pumped Storage	0
Solar	0
Wind	0

The data is binned by system net demand and the MEFs are calculated by two-dimensional linear regression, with a line of best fit in the form of $y = m_i x$, which is fitted to a plot of change in emissions (ΔC_i) against change in net demand (ΔD_i). Fig.3 shows an example of the linear regression approach results. In the example, the generation and demand data from 00:00 on January 1, 2018 to 00:30 on January 29, 2018 are used to calculate the MEF result at 00:30 on January 15, and the same method will be used throughout the year. The MEF time series in 2018 is shown in Fig.4. It is observed that MEFs are higher in winter than in summer because of the increased use of fossil generation.

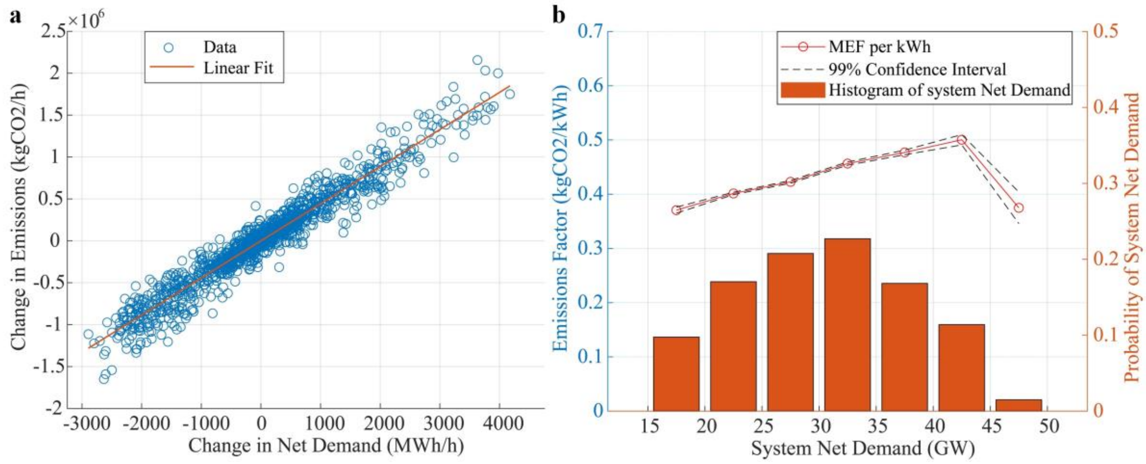

Fig. 3. MEF results of two-dimensional linear regression for the UK from 00:00 on January 1, 2018 to 00:30 on January 29

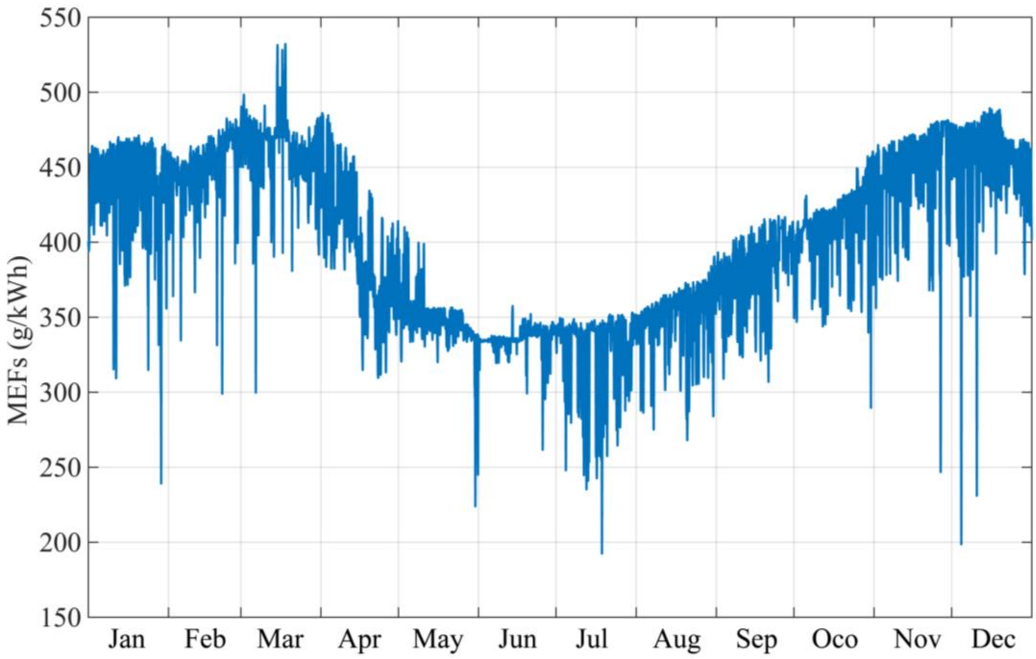

Fig. 4. MEF results in 2018

4.3 Modelling the storage system

The charging and discharging condition is simulated to fully understand the effect of the battery operation on economics and carbon emissions. The life cycle environmental impact and economic cost of the four household energy scenarios are analysed based on the household demand and generation, the MEFs in 2018, the electricity tariff and the modelled storage system.

The storage system operation in the PB scenario depends on the electricity tariff, with the time-of-use tariff from the Bethesda Energy Local Club used here, as shown in Table 4 [46]. The battery is charged when the tariff is low (11:00–16:00 and 20:00–06:00) and discharged when the tariff is high (06:00–11:00 and 16:00–20:00).

Table 4: Electricity tariff seen by the Bethesda Energy Local Club community energy scheme.

Tariff Component	Period	Price
Morning	06:00-11:00	12 p/kWh
Midday	11:00-16:00	10 p/kWh
Evening	16:00-20:00	14 p/kWh
Overnight	20:00-06:00	7.25 p/kWh
Export	All the time	6 p/kWh

The PSB scenario uses MEFs as the standard for charging and discharging. The battery discharges whenever the instantaneous MEF(t) is above a given limit L+, and charges whenever MEF(t) is below limit L− [13]. The limits L− and L+ are continuously updated and set at a fixed delta below and above the mean of the previous 30-day MEF(t). This delta is set at 20 gCO_2/kWh [13] and the effect of varying delta from 0 gCO_2/kWh to 100 gCO_2/kWh in each year is analysed in the sensitivity analysis.

In both the PB and PSB scenarios, the charge/discharge rate of the battery is fixed as the maximum C-rate until full/empty. When discharging, all excess energy (from both PV generation and battery) above the household demand is exported. If there is no excess then electricity from the grid is imported to serve the demand. When charging, the PV generation is prioritized as the source of battery charging and the rest is supplemented by the grid. All excess energy from PV generation is exported. The system structure is shown in Fig.5.

The conditions used to determine charging and discharging have a considerable impact on battery operation, which affects carbon emissions and financial cost results. Therefore, the influence of the charging source and the discharging rate is simulated.

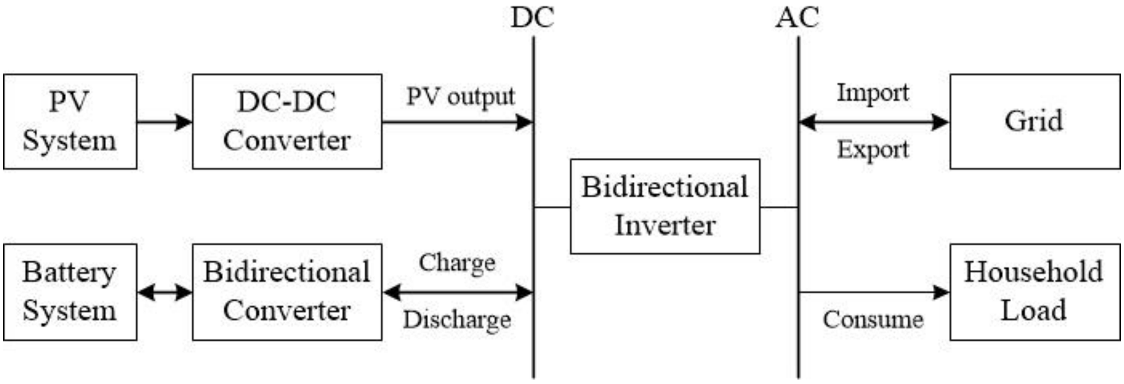

Fig. 5. System structure of the household energy network

4.4 Future energy scenarios

A dispatch model is built to estimate the energy supply in 2030 and 2050, based on the Community Renewables (CR) scenario from the *Future Energy Scenarios 2019 Data Workbook* [66] (published by Great Britain's electricity system operator) and GB grid data [62].

This model is then coupled with the MEFs module to calculate the future MEFs. Within the four scenarios of the *Future Energy Scenarios 2019 Data Workbook* [66], the Community Renewables (CR) and Two Degrees (TD) scenarios are the only ones that meet the 2050 carbon reduction target of the UK [67]. Of these, the CR scenario is the one with the highest deployment of decentralised energy technologies, therefore the CR scenario is used to develop the model framework, along with data from the GB system in 2018 [62]. A dispatch model is built for 2030 and 2050 based on historical data. The dispatch model is used to allocate power generation shares and utilise various types of power resources [68]. As a simplification, the energy supply data for nuclear, wind, solar and other renewables are assumed to maintain the same trend as the data for 2018 and are only positively correlated with changes in their capacity. Storage is used to balance variable wind and solar energy and is dispatched ahead of CCGT and interconnectors, which are used to meet the remainder of total demand.

The installed generation capacity of the CR scenario is shown in Table 5. Some simplifications are made to the grid composition because the CR scheme does not have the installed generation capacity for specific types of interconnectors and other renewables. The four interconnectors in 2018 are treated as one type in the future, and hydro, biomass and others are combined as other renewables [69] and then divided in accordance with their energy supply proportion in 2018 for MEF calculation. The UK government is committed to phasing out coal-fired power generation by 2025 [70]. Therefore, the thermal fuel type is assumed to be CCGT in 2030 and 2050.

Table 5: Installed generation capacity of different generation types and peak demand assumption in the CR scenario

	2018	2030	2050
Interconnectors	3.585	16.505	16.505
Nuclear	9.229	4.556	7.896
Thermal	48.487	22.824	16.636
Solar	12.719	29.715	52.215
Wind	20.977	53.282	86.885
Other renewables	9.27	14.096	14.396
Storage	3.59	12.3	28.063
Peak demand	59.6	57.4	72.4

To simplify the assumption, the dispatch model in this study followed the trend of energy supply by generation types of nuclear, wind, solar and other renewables and the total generation requirement in every half hour in 2018. The storage system is used to compensate for the volatility inherent to renewable energy because of the significant increase in installed wind and solar generation capacity in future [71,72]. CCGTs and interconnectors are used to meet the remainder of the total generation requirement.

Firstly, the total electricity demand for every period t is calculated on the basis of the change in peak demand (Eq. 2).

$$\forall t: \quad D_{y,t} = \frac{PD_y}{PD_{2018}} * D_{2018,t} \tag{2}$$

$t, tt \in T$ is the set of all time periods in a modelling horizon T; $D_{y,t}$ is the total electricity demand for every period t in year y; PD_y is the peak demand in year y; PD_{2018} is the peak demand in 2018; $D_{2018,t}$ is the total electricity demand for every period t in 2018.

Secondly, the future energy supply by technology types of nuclear, wind, solar and other renewables for every period t is determined by the energy supply in 2018 and the multiple of the installed generation capacity change by technology types (Eq. 3).

$$\forall j \in J(f), t: \quad p_{y,j,t} = \frac{C_{y,j}}{C_{2018,j}} * p_{2018,j,t} \tag{3}$$

$j \in J$ is the set by generation types of nuclear, wind, solar and other renewables in the model; $p_{y,j,t}$ is the electrical energy flow from generation type $j \in J$ at time t in year y; $C_{y,j}$ is the generation capacity of generation type $j \in J$ in year y; $C_{2018,j}$ is the generation capacity of generation type $j \in J$ in 2018; $p_{2018,j,t}$ is the electrical energy flow from generation type $j \in J$ at time t in 2018.

Thirdly, the generation types of storage, CCGT and interconnectors are modelled to complete the energy supply. The energy in the storage system is used preferentially to meet the remaining electricity demand. Considering the energy storage constraints, charging (Eq. 4) and discharging (Eq. 5) should follow the generation capacity limitation, and the total stored energy cannot be more than the storage volume capacity (Eq. 6). The storage system charges when the total electrical energy output of wind, solar, nuclear and other renewables is higher than the electricity demand at time t. The generation type of CCGT is then used to meet electricity demand. Two constraints ensure that CCGT generation operates within allowable limits for output and ramp rate (Eqs. 7 and 8). Lastly, interconnectors provide any remaining load balancing that is necessary. The flows of interconnectors are limited by installed generation capacity (Eq. 9).

$$\forall t: \quad cha_{y,t} \le C_{y,s} \tag{4}$$

$$\forall t: \quad dis_{y,t} \le C_{y,s} \tag{5}$$

$$\forall t: \quad \sum\nolimits_{tt|tt<t} (SE \times cha_{y,t} - dis_{y,t}) \le \overline{S}_y \tag{6}$$

$$\forall t: \quad p_{y,ccgt,t} \le C_{y,CCGT} \tag{7}$$

$$\forall t: \quad |p_{y,ccgt,t} - p_{y,ccgt,t-1}| \le RC_y \times C_{y,CCGT} \tag{8}$$

$$\forall t: \quad |p_{y,in,t}| \le C_{y,in} \tag{9}$$

$cha_{y,t}$ is the charge of storage at time t in year y; $C_{y,s}$ is the installed charge/discharge capacity of storage in year y; $dis_{y,t}$ is the discharge of storage at time t in year y; SE is the charging efficiency; $\overline{S}_y$ is the maximum storage level; $p_{y,ccgt,t}$ is the electrical energy output of CCGT at time t in year y; RC_y is the maximum ramp rate of CCGT when committed in year y; $C_{y,CCGT}$ is the installed generation capacity of CCGT in year y; $p_{y,in,t}$ is the electrical energy flow of interconnectors at time t in year y; $C_{y,in}$ is the installed generation capacity of interconnectors in year y.

Finally, the electricity balance for every period t must be satisfied (Eq. 10). The deficiency is filled by the generation type of other renewables under the constraint (Eq. 11) when the total generation output is less than the energy demand at time t.

$$\forall t: \sum_{j \in J} p_{y,j,t} + dis_{y,t} - cha_{y,t}/SE = D_{y,t} \tag{10}$$

$$\forall t: \; p_{y,oth,t} \le C_{y,oth} \tag{11}$$

$p_{y,oth,t}$ is the electrical energy flow of other renewables at time t in year y, and $C_{y,oth}$ is the installed generation capacity of other renewables in year y.

The charging efficiency of the storage system is 75% for the modelling [73]. According to the energy capacity and power of operational pumped hydro storage stations in 2016 [74], the maximum storage power of the storage system is assumed to be one-tenth of the energy storage capacity. Inspection of the output of CCGT generation in 2018 reveals that the variation of the CCGT output between two consecutive times is always less than 15%. Therefore, the maximum ramp rate of CCGT is assumed to be 15% in the modelling. The energy supply in 2030 and 2050 are calculated using the approach that has just been presented, and the MEF results for the generation mix in 2030 and 2050 are calculated in accordance with the future energy supply, given in the Supplementary Materials.

5. Results and discussion

5.1 Detailed effects of strategies

Two characteristics (CO_2 saving and financial cost) of the four scenarios are mainly analysed using the demand and generation results and the MEF results in 2018 to explore the substantial carbon reduction effect of each scenario in the use phase. In terms of the export from PV and battery systems, Sun et al. considered the CO_2 saving from this export power in their research [13]. This saving from export electricity is discussed in the current research. Because a certain amount of electricity consumption in the scenarios with battery system does not serve the household demand, but for grid output, the system carbon emissions are disregarded in this research. The total CO_2 saving and cost of the usage stage for each scenario in 2018 is shown in Table 6. Fig.6 and Fig.7 show the results to explain the function of the battery system and PV system. The total carbon emission of the original scenario (NPB scenario) is 1.6 tons.

The results suggest encouraging news regarding the installation of PV, and the related strategies could effectively reduce carbon emissions and financial costs caused by household electricity consumption. Over 650kg CO_2 saving and £170 cost reduction of the P, PB and PSB scenarios can be observed. These benefits are significant from March to August (the months around the summer solstice); specifically, the CO_2 saving reaches around 60kg per month and the cost reduction reaches around 45%. By contrast, the benefits in the months around the winter solstice are relatively lower. Around 60kg monthly CO_2 saving after the application of PV panels would lead to effective progress in the net-zero emission goal. The benefits of the battery (in non-smart charging mode) are insignificant because of the energy losses when the battery is charged and discharged.

In detail, around 29% of the annual household demand is satisfied by solar power in the P scenario, which has no operating cost or carbon emissions. This scenario has the lowest annual electricity bill, of £208. In addition to the positive effect of meeting almost a third of the household demand, approximately 690 kWh of excess electricity from the PV is exported to the grid. Significant CO_2 and cost savings could be realised by further deployment of PV technologies.

The PB scenario conducts load shifting based on the P scenario, and the improvement is mainly focused on the use of batteries to store power in the low tariff periods. The power is then consumed during high tariff periods. However, compared with the P scenario, 138kg less CO_2 saving and £26 cost increase could be observed. This is because 1.89×10^3 kWh extra electricity is exported, energy is lost in the battery operation, and the export tariff shown in Table 4 is relatively low.

The PSB scenario achieves the highest CO_2 saving of 825 kg. This scenario has the same proportion of the PV energy used for demand as the P scenario (29%). Meanwhile, the percentage of battery energy used for demand increases to 8%, of which 4% of the charging energy comes from the PV panel. Most of the extra PV energy in this scenario is exported in high and mid-MEF (t) times, and a certain amount of electricity from the grid in the low-MEF(t) period is exported in the high-MEF(t) period.

Table 6

CO_2 saving and cost of the electricity consumption for the scenarios in 2018

	NPB	P	PB	PSB
CO_2 saving (kg)	*	807	669	825
Cost (£)	406	208	234	222

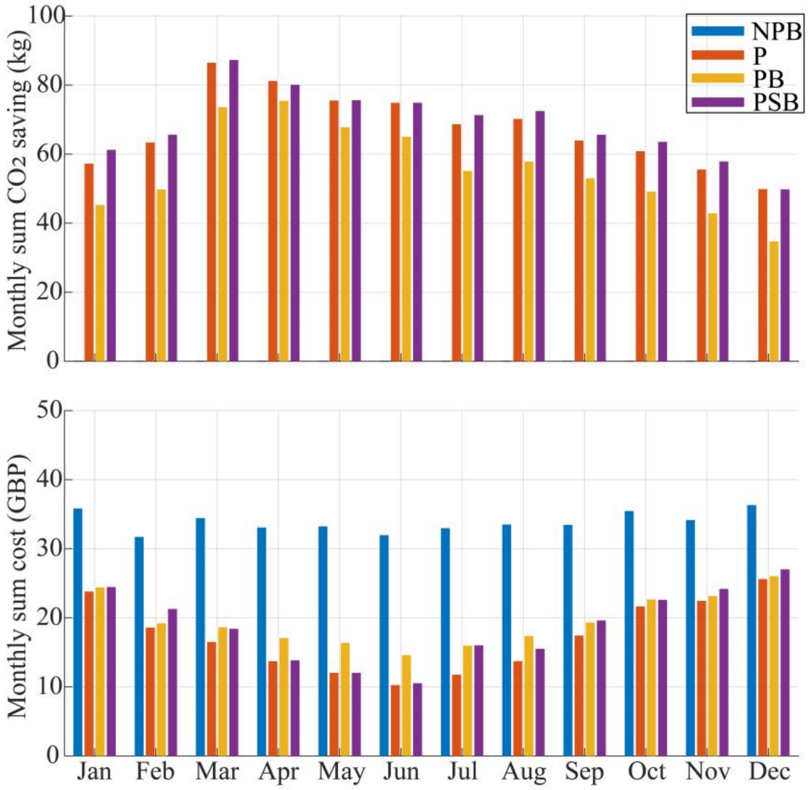

Fig. 6. CO_2 saving and the cost of each scenario in 2018**. a.** The CO_2 saving of the household electricity consumption for four scenarios in 2018. **b.** The cost of the household electricity consumption for four scenarios in 2018.

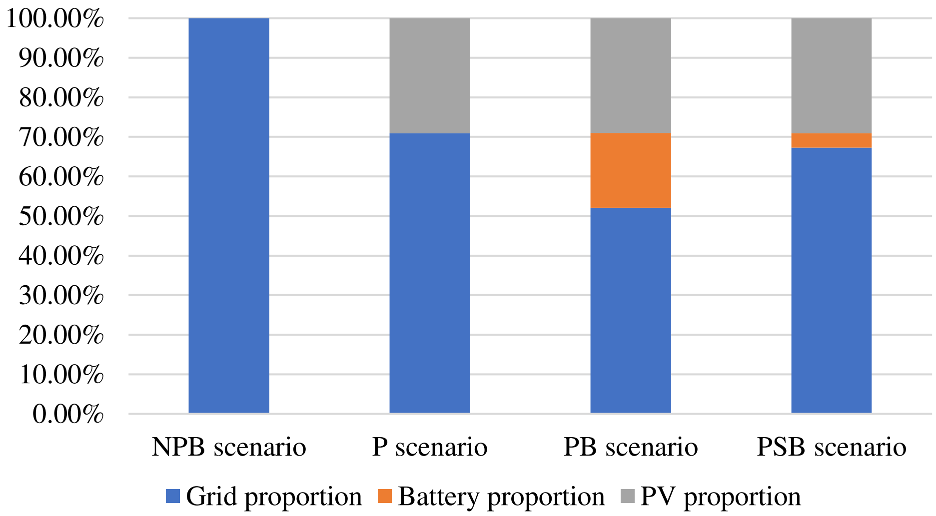

Fig. 7. Proportion of the annual household demand met from the grid, battery and PV panel in each scenario in 2018.

5.2 Effects of battery operation mode

The effects of the source of charging energy and different discharging rates are analysed. Fig.8 shows the estimated variation in environmental and economic impacts in four scenarios in 2018, and the contribution of household electricity demand met from the grid, the battery, and the PV panels. The modes for battery operation have significant effects on scenarios, especially on the PB scenario.

When the battery is only charged from excess PV energy, both the PB and PSB scenarios see cost reductions. In all scenarios before and after the change, the PSB scenario (original) has the highest CO_2 saving while the PB scenario (charged by PV energy) has the lowest financial cost. The total contribution of PV generation on total demand would increase by 4% after the change in PSB scenario, which leads to the slight decrease in financial cost. However, after the change, there would be no energy charged from the grid in low MEF(t) period and export in the high MEF(t) period, which would limit the function of smart battery charging and decrease the CO_2 saving in the PSB scenario.

When the battery is discharged in a load-following mode, costs in the PB and PSB scenarios would be reduced by 31% and 6% respectively. The PSB scenario (original) has the highest CO_2 saving while the PB scenario (discharged on demand) has the lowest financial cost. The proportion of electricity consumed from the grid of the PB and PSB scenarios is declined when the battery is discharged on demand. The export amount of the system in these scenarios is also decreased. The decrease in cost could be explained by the reduction in the grid electricity consumption and export amount in the three scenarios. However, export from the battery is not observed in the high MEF(t) period when the battery is discharged on demand, and 0.4% decrease CO_2 saving is found in the PSB scenario with the unchanged charge amount from the PV panel.

It is observed that the PSB scenario (original) always has the highest CO_2 saving, which could be an effective scenario to reduce carbon emissions in the usage phase. Meanwhile, the battery operation mode has a great impact on the electricity bill. More effective use of PV generation can reduce electricity bills during the use phase and increase consumer acceptance of facilities implementation.

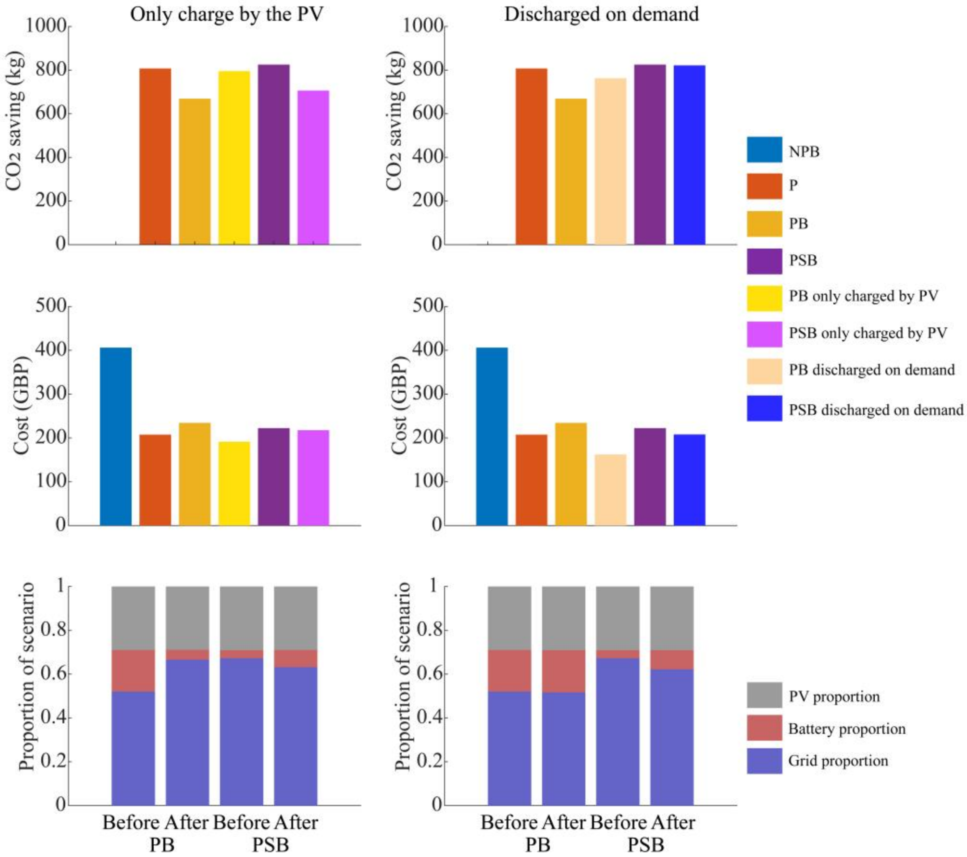

Fig. 8. Results for the change of battery operation mode in 2018. a–c. The CO_2 saving (**a**) and cost (**b**) of the household electricity consumption for four scenarios and the situations when the battery of the PB and PSB scenarios is only charged by PV energy in 2018. The proportion of the grid, battery and PV panel of the household demand before and after the change in the PB and PSB scenarios (**c**). **d–f.** The CO_2 saving (**d**) and cost (**e**) of the household electricity consumption for four scenarios and the situations when the battery of the PB and PSB scenarios is discharged on demand in 2018. The proportion of the grid, battery and PV panel of the household demand before and after the change in the B, PB and PSB scenarios (**f**).

5.3 Life cycle impact assessment

The LCIA and LCC results of each scenario are shown in Table 7 and Table 8 for the three different battery technologies. 2018 is assumed as the first year of 25yr PV system installation, which is the first year of the system's lifecycle to calculate cumulative emissions. The life cycle carbon emission of the original scenario (NPB) is 3.05×10^4 kgCO_2. The negative CO_2 saving results of the PV and battery represent the carbon emissions of manufacturing and disposal.

Table 7: Life cycle CO_2 saving results of each scenario

	Embedded emissions (kg)				CO_2 saving from electricity consumption (kg)	Life cycle CO_2 saving (kg)
	PV	LAB	LNB	LIB		
NPB						*
P	-4.04E+03				1.56E+04	1.16E+04
PB+LAB	-4.04E+03	-8.98E+02			1.41E+04	1.01E+04
PB+LNB	-4.04E+03		-4.05E+02		1.41E+04	1.01E+04
PB+LIB	-4.04E+03			-3.81E+02	1.41E+04	1.01E+04
PSB+LAB	-4.04E+03	-8.98E+02			1.78E+04	1.38E+04
PSB+LNB	-4.04E+03		-4.05E+02		1.78E+04	1.38E+04
PSB+LIB	-4.04E+03			-3.81E+02	1.78E+04	1.38E+04

Table 8: LCC results of each scenario

	Cost of manufacturing and disposal (£)				Cost of electricity consumption (£)	LCC (£)
	PV	LAB	LNB	LIB		
NPB					5.50E+03	5.50E+03
P	4.86E+03				2.81E+03	7.67E+03
PB+LAB	4.86E+03	3.63E+03			3.18E+03	1.17E+04
PB+LNB	4.86E+03		4.40E+03		3.18E+03	1.24E+04
PB+LIB	4.86E+03			8.32E+03	3.18E+03	1.64E+04
PSB+LAB	4.86E+03	3.63E+03			3.14E+03	1.16E+04
PSB+LNB	4.86E+03		4.40E+03		3.14E+03	1.24E+04
PSB+LIB	4.86E+03			8.32E+03	3.14E+03	1.63E+04

The key elements of each scenario from environmental and economic aspects are identified to improve the system. The results are shown in Fig.9.

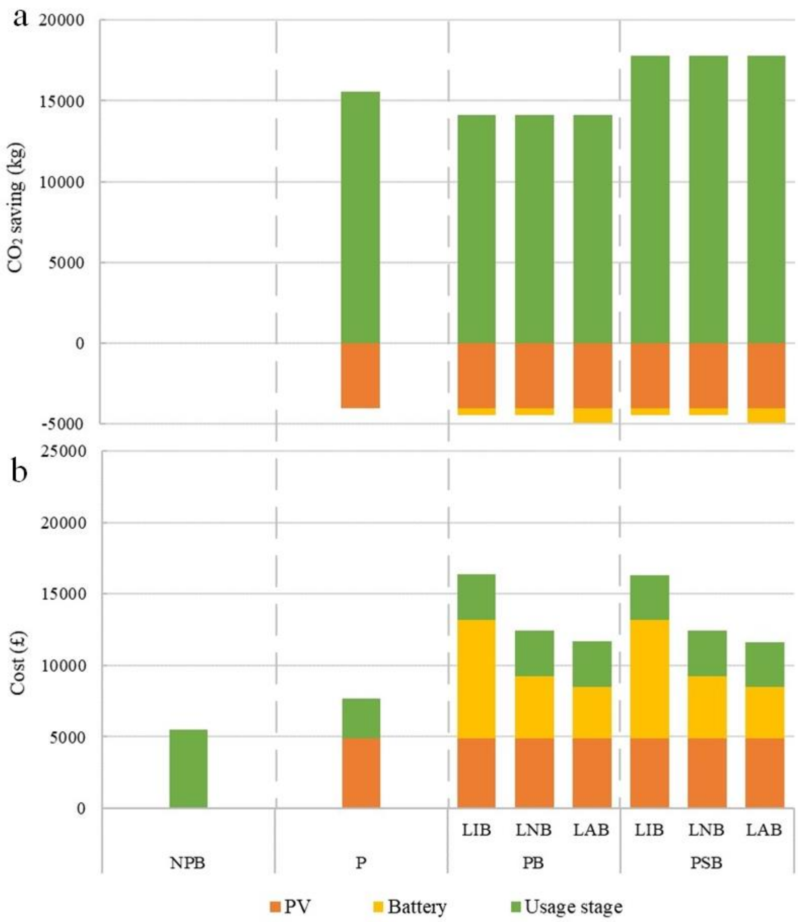

Fig. 9. LCIA and LCC results of each scenario. The CO_2 saving (**a**) and cost (**b**) of the household electricity consumption for four scenarios for the life cycle. The negative CO_2 saving results of the PV and battery represent the carbon emissions of manufacturing and disposal.

Through 25 years life span of the household system, around 11 tons of CO_2 savings could be achieved in the scenarios with the PV system (P, PB and PSB) while the scenario with battery only will bring an additional 2 tons of carbon emissions. The electricity consumption during the usage stage is the key factor influencing carbon emissions of the system life cycle. The cost of battery system and PV system is relatively high, accounting for more than 25% of the total life cycle cost of the scenarios with these systems. Our analysis illustrates that the deployment of rooftop solar PV leads to significant benefits in terms of CO_2 savings, and that adding battery storage provides little or no further benefit, regardless of which battery technology is used. Notably, realising further environmental and cost improvements by changing the battery operating mode and system size should be considered.

5.4 Life cycle interpretation

The analysis of CO_2 saving and cost reveals the contributions of each life stage. The maximum value of CO_2 saving in the usage stage is found in the scenario with smart battery charging system, at 17.8 tons. This scenario still has the best carbon reduction after taking into account the embedded carbon emissions of the PV and battery systems. The different types of battery have different environmental and economic performance. The LIB has the lowest life cycle carbon emission among the three types of battery but has the highest life cycle cost, at £8,320. The LNB has 25 kg higher carbon emissions (a very small fraction of total life cycle emissions) but costs £3,930 less than the LIB. Focusing on carbon emissions reduction, followed by cost, the scenario with smart LNB battery charging system is the suggested scenario. This scenario provides a 13.8 tons CO_2 saving compared with the original scenario, but increases total cost by £6,900. This equates to a marginal abatement cost (MAC) of £500/tCO_2.

The scenario with just a PV system is the recommended choice considering cost priority. This scenario increases total electricity costs by £2,170 and achieves 11.6 tons of CO_2 savings compared with the original scenario. This equates to a negative MAC of £187/tCO_2. If battery storage is deployed alongside rooftop solar PV, implementing smart battery charging could achieve significant carbon reductions. However, the cost of battery systems is considerable. This finding may reduce the public's motivation to adopt battery storage [23,24]. The costs of batteries are expected to reduce due to the surge in demand for batteries in electric vehicles and households [39]. Furthermore, the improvement of battery lifespan could be an effective method to reduce the life cycle costs of batteries. It has been shown in previous research that battery operation mode could extend lifespan [75]. The electricity price will presumably be more expensive because of the changes in the power generation structure and carbon costs in the electricity market [76], which means that more economic benefits could be obtained from PV generation.

Our dispatch model is mainly based on the trend as for 2018 GB data and may perform poorly on the simulation results in 2030 and 2050, which could be the case that the storage schedule rapidly changes the output of other generation types. Furthermore, the assumption of future grid structure may not necessarily hold true. This could be the case that the installed generation capacity of renewable generation types may fail to meet the Paris Agreement target [77]. However, we believe this simplified model could be a useful means of predicting future carbon emissions from grid electricity. The simulation results demonstrate that the MEFs of the grid gradually reduce over time and general results will be true for GB. Future work will continue to improve the performance of the dispatch model and deal with forecast uncertainty.

5.5 Sensitivity analysis

Finally, the effect of smart charging condition, C-rate, the battery system size and PV system size is analysed, as shown in Fig.10.

In terms of the sensitivity effect of the delta, the life cycle CO_2 saving is highest when the delta is around 20 gCO_2/kWh. At higher deltas, the additional CO_2 savings are offset by the reduction in charging/discharging activity. Therefore, 20 gCO_2/kWh should be the best value for the delta in terms of the UK grid structure. As for the effect of C-rate, the CO_2 saving increases with C-rate up to a maximum CO_2 saving of 13.4 tons at 0.4 C, and then reduces at higher C-rates. This finding is similar to that of Sun [13].

There is a positive linear relationship between CO_2 savings and both PV size and battery size. The benefits from increased PV system size are more significant than those of increased battery system size. This result shows that PV capacity has clear environmental benefits compared with the grid mix at present. However, the PV capacity in households is limited by roof area and is affected by atmospheric conditions. In addition, the smart charging system could achieve carbon reductions from the grid mix by shifting load, and the preferential policy could improve the implementation of smart battery system.

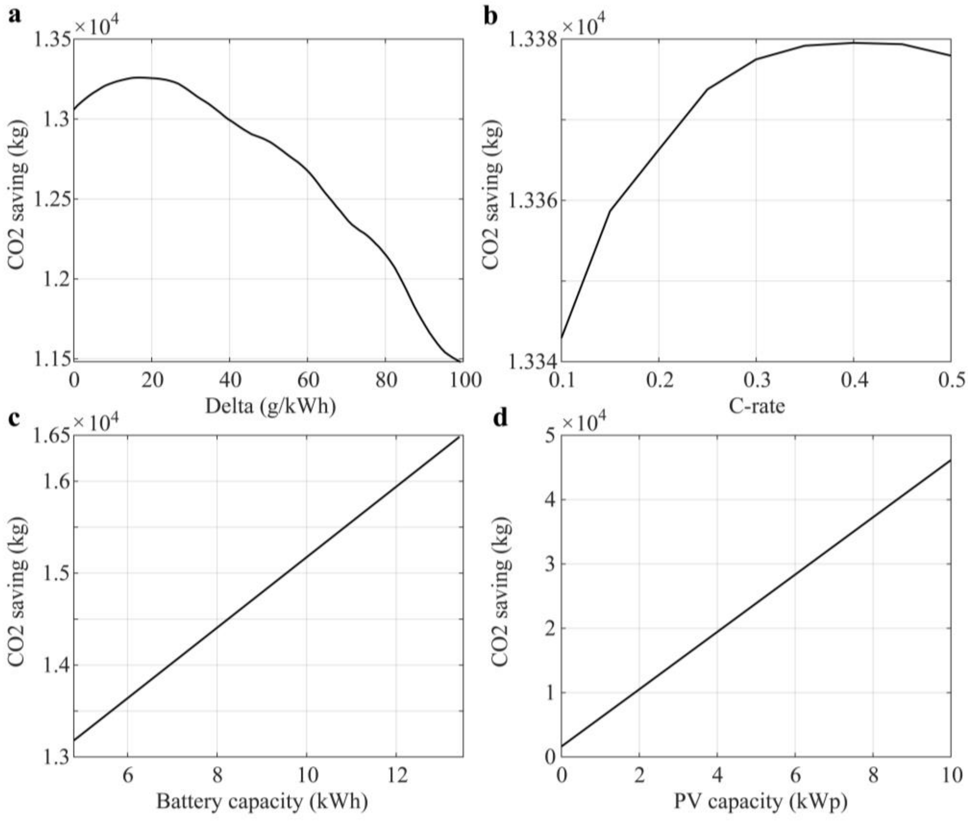

Fig. 10. Sensitivity analysis results.

6. Conclusion

The battery system, PV-battery system, and smart charging system are implemented in the UK household to meet the net-zero CO_2 emission target with the consideration of marginal emissions factors for electricity. Life cycle assessment and life cycle cost methods have been used to compare the carbon emissions and economic cost of household electricity consumption for these scenarios.

The application of the PV system could have achieved about 650kg annual CO_2 savings and £200 cost reduction in the usage stage in 2018, which will encourage the public to accept the proposed strategies. The PV system with smart charging battery system would have achieved the highest annual CO_2 saving (825 kg) in 2018. The benefits of the scenarios featuring a PV system are significant in summer months. By changing the battery operation mode, more of the PV generation and the energy discharged from the storage system could be used to meet the household demand, thereby reducing electricity bills but having little impact on CO_2 savings.

The life cycle assessment results show that the electricity consumption of the usage stage is a key driver of the carbon emissions in each scenario. The implementation of the PV system could bring nearly 11 tons of CO_2 savings over its life span. The life cycle cost analysis reveals that the application of battery and PV systems could reduce electricity bills in the usage stage though the cost of battery and PV systems is relatively high. The scenario with lithium nickel-manganese-cobalt battery and smart battery charging system and PV system is the scenario with highest CO_2 savings, and could achieve around 14 tons of CO_2 savings compared with the original scenario, but increasing electricity costs by £6,900 over the 25-year system life. This equates to a marginal abatement cost of around £500/tCO_2. The scenario with PV system only is the recommended choice if cost is prioritised, rising total electricity costs by £2,170 and CO_2 emissions by 12 tons compared with the original scenario. This equates to a marginal abatement cost of around £187/tCO_2. The electricity tariff used in the paper is stable and the electricity tariff changing in the future could reflect the variation of renewable generation is disregarded.

The delta of smart charging was found to have a crucial impact on smart charging performance, and 20 gCO_2/kWh provides the best value in terms of the current UK grid structure. The sensitivity analysis reveals that the system could achieve the best CO_2 saving when the charging rate is around 0.4 C (1.92 kW for a 4.8 kWh battery). There is a positive linear relationship between CO_2 savings and both PV size and battery size. The benefits from increased PV system size are more significant than those of increased battery system size.

Battery storage systems are expensive, limiting their widescale deployment, however improvements in battery production that increase life span could potentially serve to reduce life cycle cost. If battery storage is already deployed, the marginal abatement cost of reducing CO_2 emissions by implementing smart charging according to marginal emissions factors is effectively zero. However, this could reduce the scope for provision of grid services such as frequency response, and there are presently no financial incentives for households to adopt battery control systems that reduce emissions by responding to grid marginal emissions factors.

We expect that the findings of this study will provide a reference for the strategic implementation of energy storage, PV systems and smart battery charging systems in UK households, although the methods employed are applicable to any country.

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Declaration of competing interest

There are no conflicts to declare for this manuscript.

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