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Establishing the Value of Community Energy Storage: a comparative analysis of the UK and Germany

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Abstract

Both UK and Germany have committed to mitigating the greenhouse gas emission and tackling the climate change. In the past decade, a surge of residential solar and storage applications has been accelerated by subsidies, cost reduction of the system and increasing energy prices. Many advantages of community energy storage have been identified and its applications have been widely investigated. However, its profitability is still questionable, and more work is needed to improve its accessibility. Here we compare and contrast community energy storage using lithium-ion batteries in the UK and Germany – two countries with different solar profiles and different electricity tariffs. Results indicate that the primary impacting factor on self-sufficiency is the solar generation, meaning that communities in Germany can be up to 30% more self-sufficient than their UK counterparts. Additionally, the profitability of households in Germany is also higher (achieving a simple payback time of less than 10 years) due to the subsidies for storage and on-site generation. The results highlight the importance of using a location-specific approach for system planning. For example, households in Germany should aim to fully exploit on-site generation, whilst UK households should improve generation output, for example by using a hybrid PV plus wind turbine system. In addition, more financial and regulatory support is needed in the UK to improve project feasibility.

Keywords: Agent-based modelling, Community energy storage, 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]. Many efforts have been made by the European and UK governments to pursue low-carbon and sustainable energy alternatives, encouraged by the governmental incentives, environmental benefits and cost reduction of low-carbon technologies [2]. Several countries have focused driving the transition to low carbon energy, but many issues still remain, particularly: affordability, reliability and sustainability [3].

In recent years, the cost reduction of solar photovoltaics (PV) and wind turbines have made them cheaper than fossil-based energy in various parts of the world [4]. Europe has been undergoing a fast energy transition due to the cheap renewables [5], flexible demand and battery storage [6]. This has led to a shift of the European power system away from fossil fuels and nuclear to one built around various renewables and emission-free energy. The UK [7] and Germany [8] have, in particular, put huge efforts to tackle the economic and security threats of the climate change. This rapid change in energy sector will continue over the coming decades in Germany, which plans to phase out coal and nuclear and increase significant amount of renewables to 96% for generation by 2050 [9]. While in the UK, the transition in energy system is also happening. The Department of Business Energy and Industry Strategy (BEIS) is determined to achieve the growth in a clean and sustainable manner [10]. The carbon price to be introduced will further drive the transition from coal to gas and eventually phases out the coal plants from the energy mix [10]. There is a fast growth in renewable as well, but the uptake of solar is still less than wind, as the onshore wind projects provide the cheapest source of power generation. In 2019, the UK recorded 83 days of generation without fossil fuels [11]. It is expected that there will be around 183GW of wind and solar by 2050 along with 13 GW battery storage, which will contribute to approximately 87% of total generation in the UK [9].

The greater penetration of renewables makes it vital for the power system to increase flexibility so that a stable, reliable and resilient electricity supply can be delivered [12]. It is widely recognised that batteries are an essential complement for renewable energy generation and can balance an energy system dominated by variable renewables. In recent years, reduced government support [13,14], costs of battery system [15], and expensive energy prices, have contributed to an increasing number of end users adopting decentralised generation (DG), such as PV coupled with battery storage. Bloomberg New Energy Finance (BNEF) stated that 35 GW behind-the-meter (BTM) storage capacity will be installed by 2030 in the world [9]. Some believe that decentralised household energy storage (HES) is a desired technology to solve the grid stability challenges due to increasing penetration of PV generation at local level [16]. However, the main application of BTM storage is to enhance PV self-consumption, which helps energy consumers lower the reliance upon the external power grid and hence reduce their energy costs. A study in Germany [17] suggested that the economic feasibility of PV plus HES was already profitable, but the assumed cost of HES at €171 kWh^{-1} was unrealistically low. Truong et al. [18] assessed a particular HES model in the Germany context and concluded that the profitability of the system requires substantial subsidies and increasing electricity tariffs. Uddin et al. [19] even argued that the addition of HES could not provide any economic benefits, and loss could be higher when degradation effects were included. Some studies [20] focused on improving the feasibility by optimising the system's design, but uptake was still found to be too expensive and further cost reduction was required. Although the cost of battery storage has fallen considerably since 2010 from £1000 kWh^{-1} to £140 kWh^{-1} today, the price of battery storage units still remains very high [15]. Many options were proposed to improve the feasibility by combining multiple applications with PV self-consumption, such as peak shaving, avoiding PV curtailment and load-shifting [21]. Some also argued that scaling up of storage capacity to community energy storage (CES) could be helpful to increase the accessibility of battery storage to users [22].

CES has been widely studied recently as an alternative to grid-scale and single-household scale storage solution. A typical CES is shared between community members and located in a spatial proximity [23], which enables the community and inherent members to have greater control in managing DG collectively at a local level. CESs can be connected to either low or medium voltage level, which can potentially provide both BTM and front-the-meter services [24], including end-user orientated applications, such as enhancing self-consumption, and operator applications, such as frequency regulation. Several advantages of CES were identified by Parra et al. [25], including better battery system performance due to the aggregation effects, and lower energy and power ratings of CES compared to household energy storage. Scheller et al. [26] suggested that CES can reduce relative storage capacity per household by 9%, which could be reduced by up to 23% if the operation integrated with demand-side flexibility options. Schram et al. [27] investigated the trade-offs of different operational goals during CES operation, where the CES was found to be able to reduce financial costs and CO_2 emission at the same time. Parra et al. [28] investigated and compared the feasibility of a community with a CES adopting lead-acid and lithium-ion batteries. The Levelised Cost of Storage (LCOS) of lithium-ion batteries can be reduced to £0.3 kWh^{-1} by self-consumption, and can be even lower by combining self-consumption and demand side management (DSM) under time-dependent tariffs [22]. Van der Stelt el at. [29] assess and compare the performance of both HES and CES in the Netherlands. Although HES and CES can produce extra profits by arbitrage, the storage systems are found to be more economically efficient by increasing self-consumption of on-site PV production. The battery price is still the main obstacle for the feasibility. Our previous study has identified the advantages of CES for communities and end-users, and also addressed the significance of realising the value of inter-house energy trading within the CES network [30]. However, key regulatory frameworks and schemes are yet to be in place, which requires clear guidance on the ownership and operation of the CES [23].

These previous studies have shown the value of CES and addressed the significance of financial support and cost reduction of the batteries. Comparison between case studies in different locations will enable the key parameters and trade-offs for feasibility to be assessed and prioritised. Comparing CES in the UK with a country that has well-established solar and energy storage development, such as Germany, is one such important comparison. This paper aims to compare and analyse the performances of HES and CES using lithium-ion phosphate cells in the UK and Germany so that key factors can be identified and hence improve future applications. The paper is arranged as follows: the methodology adopted in this study is described in Section 2; Section 3 presents three different evaluation criteria used for technical, economic and environmental analysis respectively; Section 4 presents the simulation results, including self-consumption rate (SCR), self-sufficiency rate (SSR), carbon avoidance, etc.; Section 5 discuss the results and identifies potential improvements; and the conclusions of this study are presented in Section 6.

2. System Model Design

2.1. Cases Considered in Study

The agent-based model developed in our previous study [30] is adopted here to simulate the interaction between households and the power grid. Three 10-household communities are considered, including a community with PV-Only, a community with HES and a community with CES. In the model, household agents can reflect the realistic balance between the demand and generation. All households are assumed to install a rooftop solar panel with the same configurations coupled with corresponding energy storage technologies. The HES and CES can operate in multiple power dispatching strategies to either maximise the cost savings or the self-consumption of PV generation. More details of the system set-ups are described in the following sub-sections.

2.2. PV and Storage Set-up

A typical household in the UK installs a PV system with a capacity at 3 kWp [31]. For households in Germany (DE), the PV size of most installations ranges from 3 to 5 kWp, as the majority of private households do not have enough roof area to fit more solar panels [32]. In our case study, households in Germany and the UK are assumed to install the same PV size at 3kWp in order to investigate the difference in PV production and the utilisation of electricity. The HES capacity ranges from 2 kWh to 4.5 kWh and correspondingly the CES capacity is between 20 kWh and 45 kWh in order to ensure the same total storage capability of the community. Both HES and CES are assumed to use the same Li-ion battery technology. The battery storage model developed in our previous work [30] is employed here, assuming 80% depth of discharge with a minimum state of charge of 20%. The battery is set to have a maximum 1C charge/discharge rate. The batteries are managed by a control management unit built in either HES or CES, which enables HES/CES to work in different modes, including Self-Consumption Mode under flat (HES/CES-Flat) and TOU tariff (HES/CES-SC), and Grid-Charging Mode (HES/CES-GC) under TOU tariff. Details of the management strategies are fully described in [33].

2.3. Demand Profile

To understand the effect of introducing PV plus storage within households, it is important to acquire data on the electricity demand profiles of domestic households. Due to the lack of real measurement of demand, synthetic load profiles are generated and adopted in our research. The CREST demand model is used to generate demand profiles to represent the energy demand in UK households [34]. The model is based on the UK Time Use Survey to stochastically produce synthetic and realistic load profiles for a household according to several parameters, including number of residents, time of year, etc. Five different households are chosen in our model and their consumption profile data are in 1-minute intervals of 34 typical household appliances. Their demands range from Electricity Profile Class 1 Low to High band according to Ofgem [35]. The characteristics of each household type vary from each other, in terms of relation between peak and base load and load fluctuations.

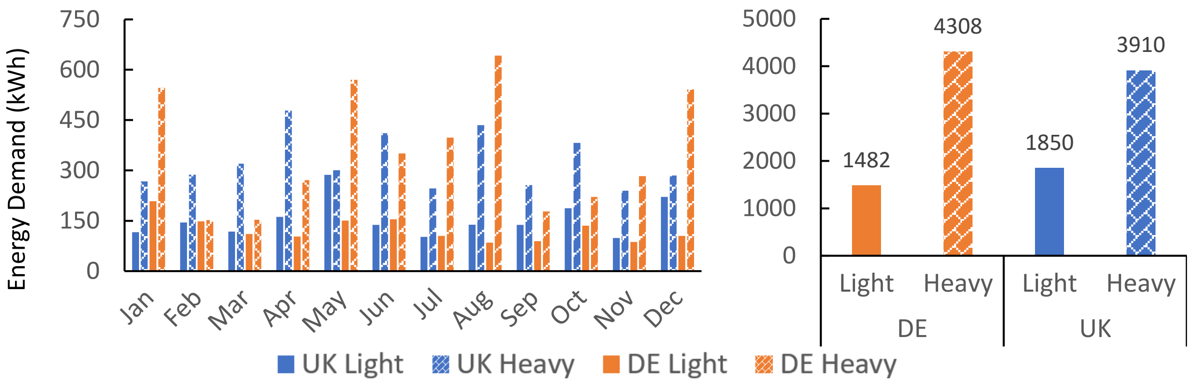


Figure 1 Monthly and Annual Demand of Light and Heavy Users in the UK and Germany

The load profiles of Germany are obtained using a similar method. The profile generator developed by Technical University Chemnitz [36] can simulate the behaviour of the residents and includes typical operation patterns for domestic appliances. The load profile is calculated by adding the energy use of each device of a chosen predefined household. Five different types of household in Germany are chosen to represent the household diversity. The household types and corresponding annual energy consumption are shown in Table 1. For the analysis, two households are chosen to represent light and heavy energy users for each country. CHR19 and HH2 are chosen to represent the intensive consumers, while CHR29 and HH0 are selected as light energy users. The monthly and annual energy demand are shown in Figure 1.

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

UK [34]			**DE** [36]		
Household Type	**Description**	**Demand (kWh)**	**Household Type**	**Description**	**Demand (kWh)**
HH0	Adult-Single	1850	**CHR19**	Couple, 30-64, both at work, with home help	4308
HH1	Adult-Couple	2562	**CHR02**	Couple, 30 - 64 age, with work	1857
HH2	Adult-Couple with a Child	3910	**CHR29**	Single man under 30 years with work	1482
HH3	Adult Couple and two Children	3507	**CHR45**	Family with 1 child, 1 at work, 1 at home	3563
HH4	Retired Couple	4752	**CHR54**	Retired Couple, no work	2736

2.4. Solar Radiance Data

German PV data is based on a measured time series in Southern Germany in 15 min time slots for the year 2013 [37]. UK Solar radiance data is obtained from the Microgen Database developed by Sheffield Solar [38]. As mentioned previously, all the households are assumed to install a 3 kWp solar panel on their rooftops and hence the difference in PV production can only be attributed to geographical reasons. Figure 2 illustrates the monthly PV production in the UK and Germany.

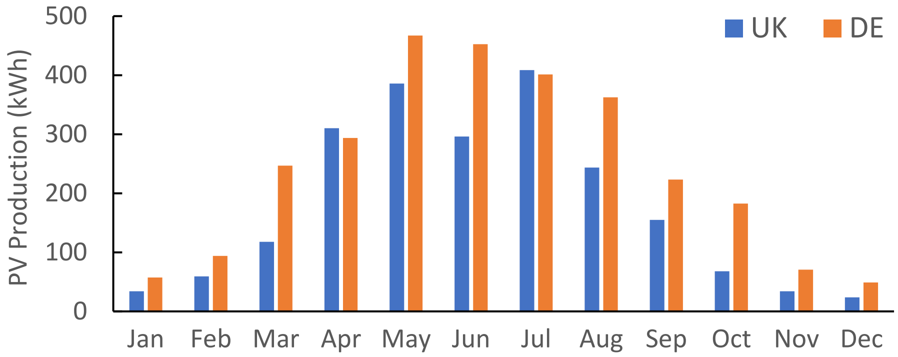


Figure 2 Monthly Production from a 3kWp PV in the UK and Germany

2.5. Feed-In Tariffs (FIT)

Feed-in tariffs have been widely introduced around the world. In the UK, the BEIS introduced a FIT scheme to promote the uptake of renewable and low-carbon electricity generation technologies in 2010. Participating licensed energy suppliers are required to make payments on both generation and export from the eligible installations. The FIT scheme includes most domestic renewable and low-carbon electricity-generating technologies with a total installed capacity up to 5 MW [39]. There are two main components: i) a generation tariff, which is a payment for every unit of electricity generated regardless of whether it is exported or consumed on-site and ii) an export tariff, which is a payment for each kWh exported to the grid.

A FIT was first introduced in 2004 in Germany [40], ensuring priority access of renewable energy to the power grid. The FIT rates vary with the type and capacity of technologies, and also are high enough to recover the capital investment. The FIT in Germany has been set at a high rate since it started compared to the UK. With the growing penetration of renewable sources in the energy mix, FIT rates are much reduced. Table 2 shows the monthly FIT rates for both UK and Germany in £ (€1 = £0.85, price taken on 20th February 2019).

Table 2 FIT Rates for the UK [39] and DE [13]

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

2.6. Retail Electricity Tariff

Global electricity prices have increased in the past decade. In Germany, the retail electricity prices are amongst the highest in the Europe [41], resulting from the increasing costs of RES technologies and the continuous support for a national energy transition [40]. In recent years, wholesale electricity prices on average have declined, but bills have increased due to other charges, such as surcharges, taxes and network costs. The electricity tariff in Germany is around £0.255 kWh^{-1}. The electricity tariffs in the UK are relatively high compared to the rest of Europe at £0.186 kWh^{-1}. The UK has a low absolute contribution from taxes and levies of around 20%, while the energy and supply component accounts for a greater proportion in the total UK electricity price[42]. In the UK, electricity production still relies heavily on the traditional fossil fuel sourced generation, and hence the UK's electricity price is in line with global coal and gas price changes. The addition of a carbon price on the top of the EU Emission Trading System price further increases the generation costs of energy suppliers [43]. The wholesale price therefore increases further, making it the largest share of the UK domestic electricity price.

In the past few years, with public endorsement of smart homes and the regulator's desire to mandate more accurate settlement for electricity users, the Time-of-Use (TOU) tariff is becoming increasingly popular. In the UK, GreenEnergy was the first energy supplier offering a three-tier TOU tariff, as shown in Table 3 [44], offering a three-tier tariff during weekdays and two-tier tariff during weekends. In Germany, a variable tariff was introduced to the market by aWATTar [45]. The electricity tariff rate varies with the wholesale energy price [46] on an hourly/half-hourly basis so that it enables consumers to shift their consumption more freely to reduce their energy bill. More details regarding the tariff are shown in Table 4.

Table 3 TIDE Tariff in the UK

Tariff Name	**Day**	**Time**	**Electricity Price (£.kWh^{-1})**	**Standing Charge (£.day^{-1})**
TIDE Tariff [44]	Weekdays	00:00 – 06:59	0.09	0.32
		07:00 – 15:59	0.16	
		16:00 – 19:59	0.32	
		20:00 – 23:59	0.16	
	Weekends	00:00 – 06:59	0.09	
		07:00 - 23:59	0.16	

Table 4 aWATTar Tariff Information [45]

Parameter	**Price**	**Unit**
Basic Price	EPEX Spot DE + 0.21	£.kWh^{-1}
Maximum Basic Price	0.17	£.kWh^{-1}
Minimum Basic Price	-0.17	£.kWh^{-1}
Network Usage	0.05	£.kWh^{-1}
Levies, Duties, Taxes	0.11	£.kWh^{-1}
Measuring Point Operation	0	£.kWh^{-1}
Monthly Connection Charge	10.80	£

3. Evaluation Criteria

In order to comprehend the system performance and the energy consumption behaviour, this study uses several key performance indicators (KPIs) proposed previously [30] to assess the system in both UK and Germany national contexts. The assessments are carried out at both household and community levels so that the best system configuration and operation strategy can be identified.

3.1. Technical Analysis

The technical assessment of the households and communities were demonstrated by the use of SCR and SSR. The SCR aims to represent the utilisation of PV-sourced power while SSR represents the proportion of self-supplied power within the community. The definition of SCR is self-consumed PV electricity excluding exported electricity (E_{exp}) over the total amount of PV generated electricity (E_{PV}):

$$SCR = (E_{PV} - E_{exp})/E_{PV} \tag{1}$$

The SSR is defined as the level of the energy supplied not from the external grid (E_{imp}), accounting for the total demand (E_{dmd}):

$$SSR = (E_{dmd} - E_{imp})/E_{dmd} \tag{2}$$

3.2. Economic Analysis

Several KPIs are used to assess the economic performances of the system, including simple payback time ($SPBT_{sysytem}$), levelised cost of energy (LCOE) and levelised cost of storage (LCOS). In our study, $SPBT_{system}$ is used to indicate economic feasibility [47]. The system can only be paid off within its lifespan so that the system is considered economically feasible. The $SPBT_{system}$ is defined as the net cost divided by the yearly energy cost savings [38]:

$$SPBT_{system} = Total\ Net\ Cost/Annual\ Savings \tag{3}$$

The total net costs of the system include the PV, battery costs with or without subsidies for the purchase and a distribution network modification charge [48]. The CES is assumed to be collectively purchased and owned by households within the same CES network. The energy cost can be obtained by:

$$Energy\ Cost = E_{imp}p_{grid} + dp_0 - E_{PV}p_{gen} - E_{exp}p_{exp} + \left(E_{toCES} - E_{fromCES}\right)p_{CES} \tag{4}$$

where p_{grid} is the energy tariffs, d is the service time, p_0 is the standing charge, p_{gen} and p_{exp} are the FIT generation and export rates respectively, E_{toCES} and $E_{fromCES}$ are the energy injected to and received from the CES network, and p_{CES} is the tariff applied in the CES network. The tariffs described in Section 2.6 are used to minimise the result of Equation (4). This function is specifically proposed as the predominant interest for domestic consumers to install batteries is to reduce energy costs [49]; similarly, it is also the primary reason for the adoption of renewable energy communities [50]. The value of electricity traded between neighbours and a sensitivity analysis on $SPBT_{system}$ are investigated respectively in Section 4.2.

The LCOE is a common parameter to indicate the economic value of assets, which includes all the expenditures occurring during the asset's lifespan and energy production. It is defined as the net present value of every unit of electrical energy in kWh over the lifetime. In this study, the LCOE of PV is calculated as:

$$LCOE = \sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t} \bigg/ \sum_{t=1}^{n} \frac{E_t}{(1+r)^t} \tag{5}$$

Where I_t represents investment in year t; M_t represents the costs on operation and maintenance in year t; E_t represents PV electricity production in year t; r represents the discount rate and n is default PV lifespan. The LCOS can be obtained via formulated in Eq (6). It is based on the definition of LCOE, using the total amount of energy discharged from storage and also with the addition of charging cost.

$$LCOS = \sum_{t=1}^{n} \frac{I_t + M_t + C_t}{(1+r)^t} \bigg/ \sum_{t=1}^{n} \frac{E_{discharge}}{(1+r)^t} \tag{6}$$

Where C_t represents the energy cost for the amount of electricity charged in the battery in year t and $E_{discharge}$ represents the amount of electricity discharged by the battery in year t. All the parameters used in this study are shown in Table 5.

Table 5 Economic Values Adopted in This Study

Parameter	**Value**	**Unit**
Li-ion Battery [51]	*570*	£.kWh^{-1}
Battery Inverter [52]	*500*	£.kW^{-1}
Battery Casing [51]	*293*	£
PV inverter [53]	*500*	£.kW^{-1}
Solar Panel [54]	*0.4*	£.Wp^{-1}
Solar Optimiser [54]	*0.25*	£.Wp^{-1}
PV mounter [54]	*328*	£
Accessories [54]	*150*	£
O&M Cost [54]	*50*	£.year^{-1}
Discount Rate [55]	*5*	%.year^{-1}

3.3. Environmental Analysis

The renewable system can substantially reduce carbon emission from the electricity generation process, which encourages to replace the conventional carbon-intensive technologies. However, the manufacture of these renewable technologies comes along with significant carbon emission. In this research, environmental impacts of the system are quantified by two KPIs, carbon emission savings and payback time of carbon emissions from manufacturing. The total CO_2 emission (Q_{total}) only includes CO_2 emitted from manufacturing PV and battery storage. The Q_{total} can be obtained by:

$$Q_{total} = Q_{PV} + Q_{battery} + E_{import}q_{grid} \tag{7}$$

Where the Q_{PV} and $Q_{battery}$ represent the total amount of CO_2 emission from manufacturing PV and battery respectively, and the grid CO_2 intensity in the UK is q_{grid}. Table 6 lists the cradle-to-use values of environmental factors for the calculation [56–58]. The on-site PV generation and reduced grid import are the main methods to avoid carbon emissions (Q_{avoid}), which can be calculated by:

$$Q_{avoid} = \left(\left(E_{demand} - E_{import}\right) + E_{PV}\right)q_{grid} \tag{8}$$

The amount of surplus PV exported to the grid are unlikely to substantially lower the grid carbon intensity. The calculation therefore only considers the carbon savings by the households and the community. The Payback Time of the system's CO_2 (PBT_{CO2}) is defined as:

$$PBT_{CO2} = Q_{total}/Q_{avoid} \tag{9}$$

Table 6 Carbon Emission Parameters

Parameter	Value	Unit
Grid Carbon Intensity of the UK [59]	*0.26*	$kg.kWh^{-1}$
Grid Carbon Intensity of the Germany [60]	*0.49*	$kg.kWh^{-1}$
Grid Carbon Intensity of the China [61]	*0.84*	$kg.kWh^{-1}$
CO_2 Emission During Inverter Manufacture [57]	*12.03*	$kg.kWh^{-1}$
CO_2 Emission During PV Manufacture [58]	*865.44*	$kg.kWp^{-1}$
CO_2 Emission During Battery Manufacture [57]	*175*	$kg.kWh^{-1}$

4. Results

4.1. Technical Assessment

4.1.1. Technical Performance Assessment at Community Level

Figure 3 compares the technical performances of communities with different operating modes. It is obvious that the energy savings are directly linked to the PV production, where more energy import can be avoided by on-site generated PV electricity in Germany than the UK, especially with a storage system. In contrast, for communities without a storage system, the UK can save more energy than Germany, which means that the majority of energy saving is from direct self-consumption. This may be because the energy of UK communities is consumed during the time of PV production, effectively lowering the export of surplus electricity, while the majority of the energy in Germany may be consumed after production. This is also supported by the growth in energy savings with increasing storage capacity. For the German community, an extra 2 kWh per household can contribute to nearly

5800 kWh energy savings and almost 30% higher SCR and SSR respectively, compared to approximately 2600 kWh extra saved energy in the UK. The battery storage system is therefore more useful for German users compared to households in the UK. In addition, the CES in both countries tends to have higher SCR and SSR, especially when CES operates under the Flat tariff. The higher average SCR in the UK suggests that the community can make slightly more efficient use of PV-sourced electricity, while higher average SSR of a German community indicates that more demand can be met by the local generation. Considering the difference in the annual community demands in two countries, the addition of storage system to the existing PV is certainly more beneficial for the German community, especially with CES.

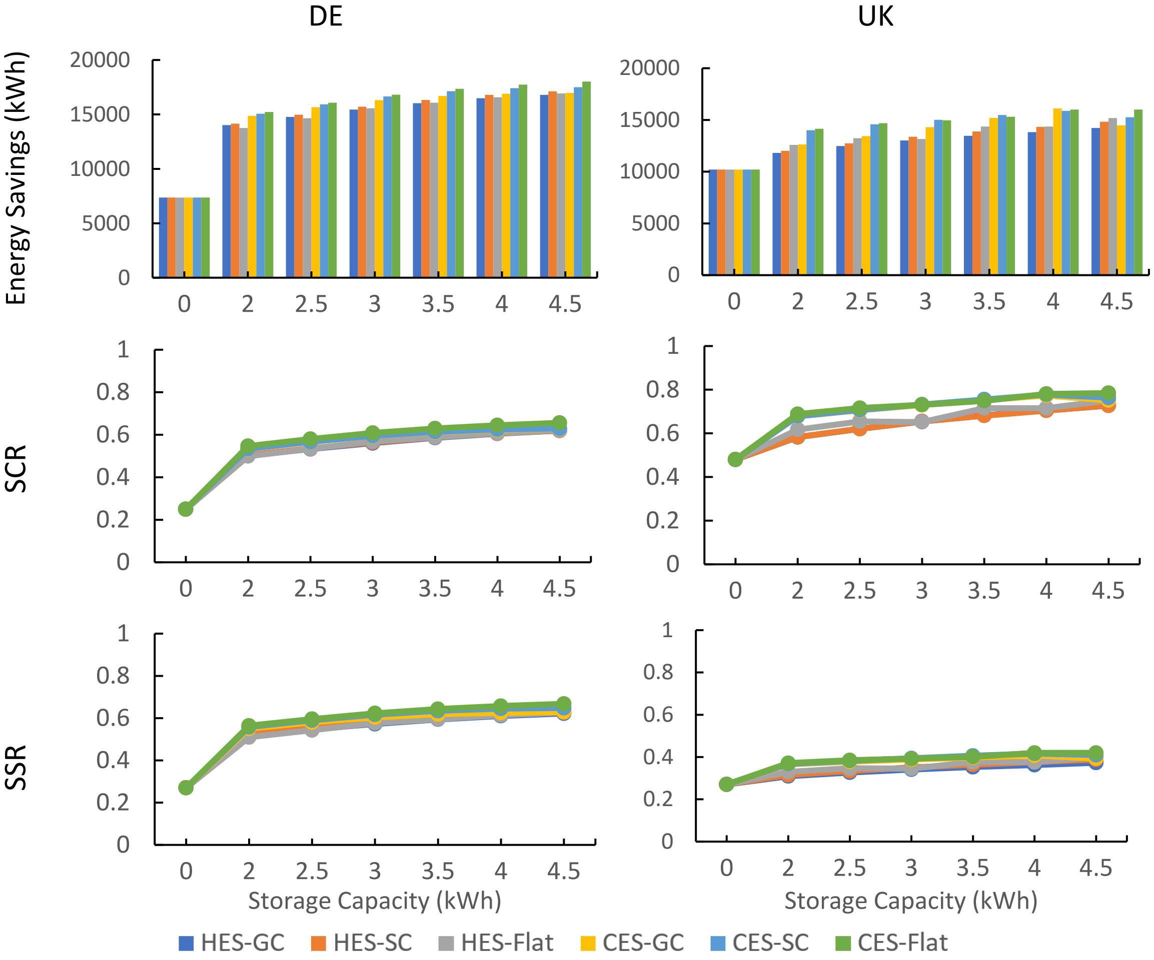


Figure 3 Comparison of Communities’ Annual Performances of DE and UK

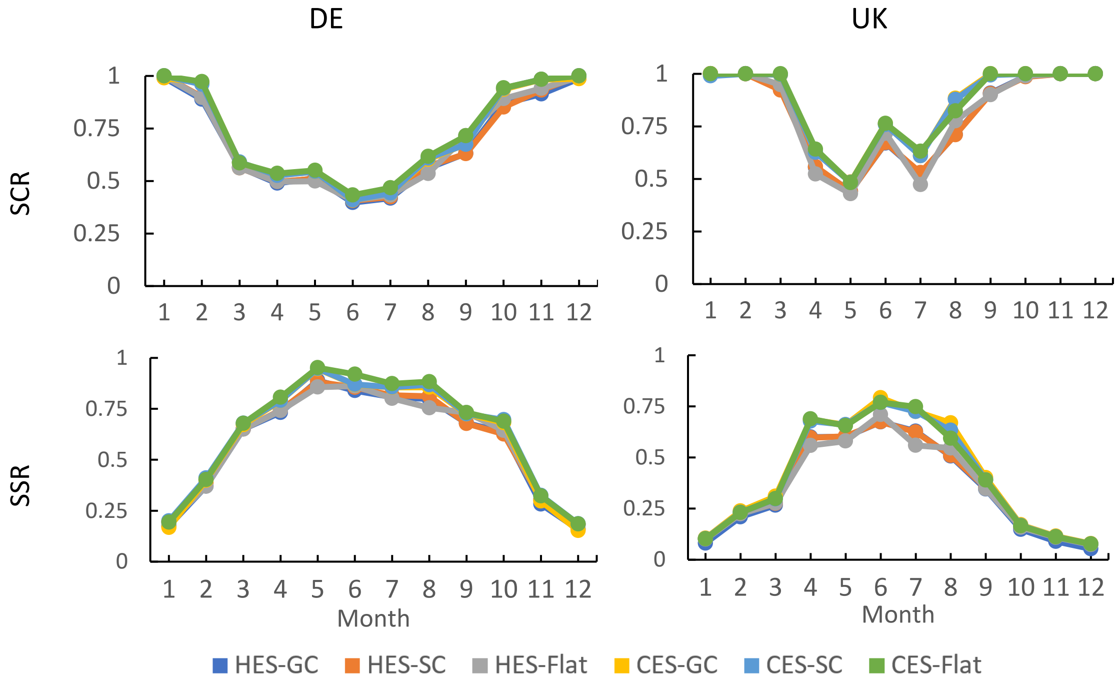


Figure 4 Monthly SCR and SSR of a Community with 30kWp PV and 30 kWh Storage

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

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

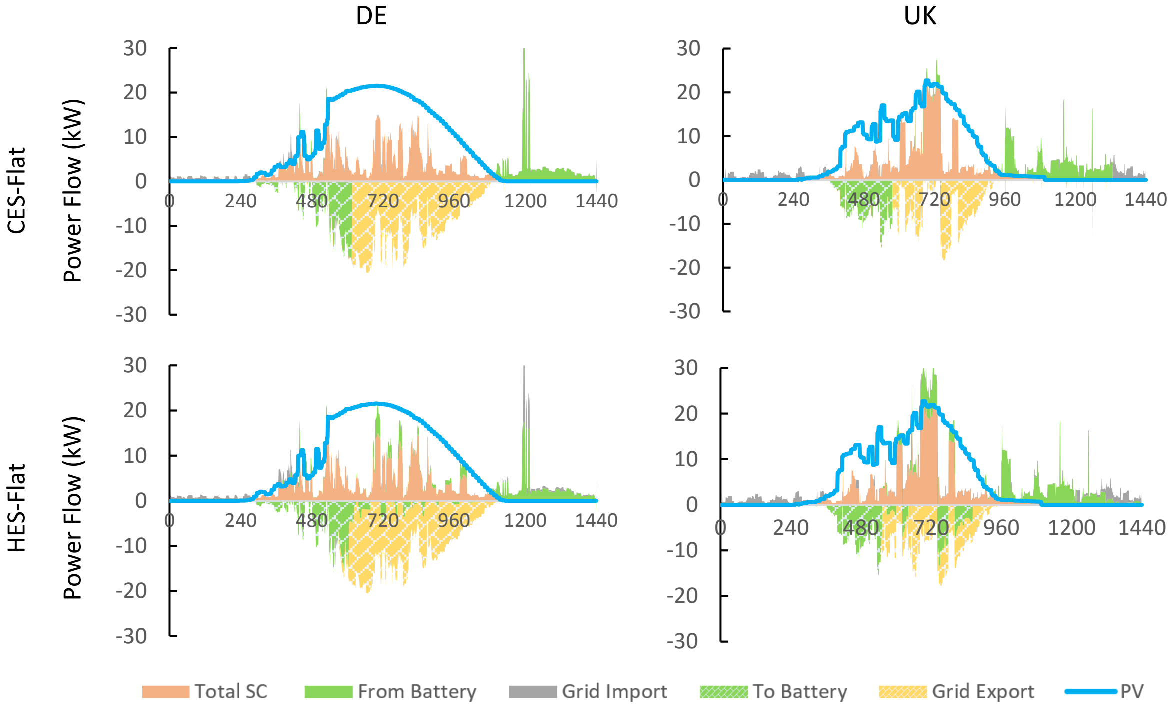
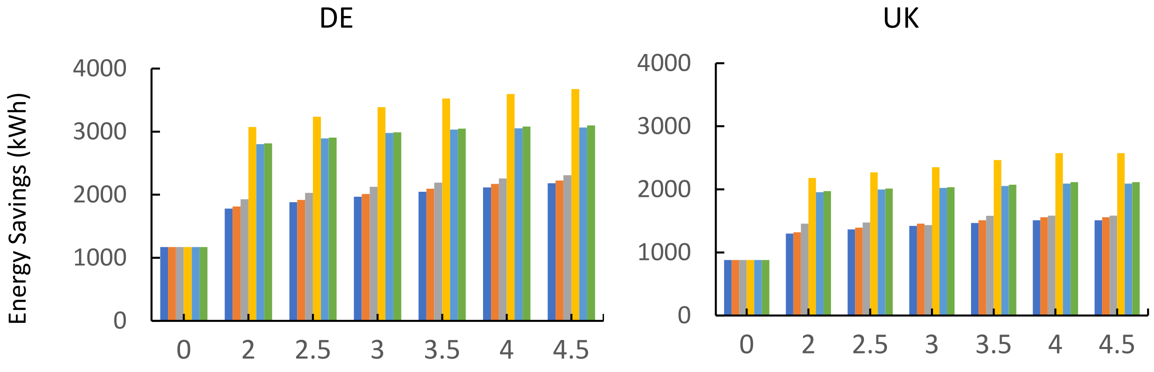


Figure 5 Power Flow Profiles of UK and DE Communities in June

4.1.2. Technical Performance Assessment at Household Level

Figure 6 shows a comparison of heavy users in DE and UK and the addition of storage system contributes to significant energy savings compared to those without storage. The minimum annual energy savings of a heavy consumer in Germany 1780 kWh, equal to the maximum energy savings of a UK heavy household. For heavy users, it is obvious that CES provides a more effective utilisation of PV electricity than HES, while in the UK it shows the opposite trend. However, the differences in the SCR for both countries are marginal. Regarding the SSR, though the heavy users in both DE and UK benefit more from the CES, the DE households can supply more demand locally compared to the UK, and the highest SSR can achieve 0.85 when connecting to a 45 kWh CES working under CES-GC mode. However, it is important to note that part of the energy saving from CES-GC mode is by using cheap grid-imported electricity stored in the CES. In this way, the CES-GC does not necessarily reduce the total grid import, but the benefits can be harvested economically that will be presented in Section 4.2.



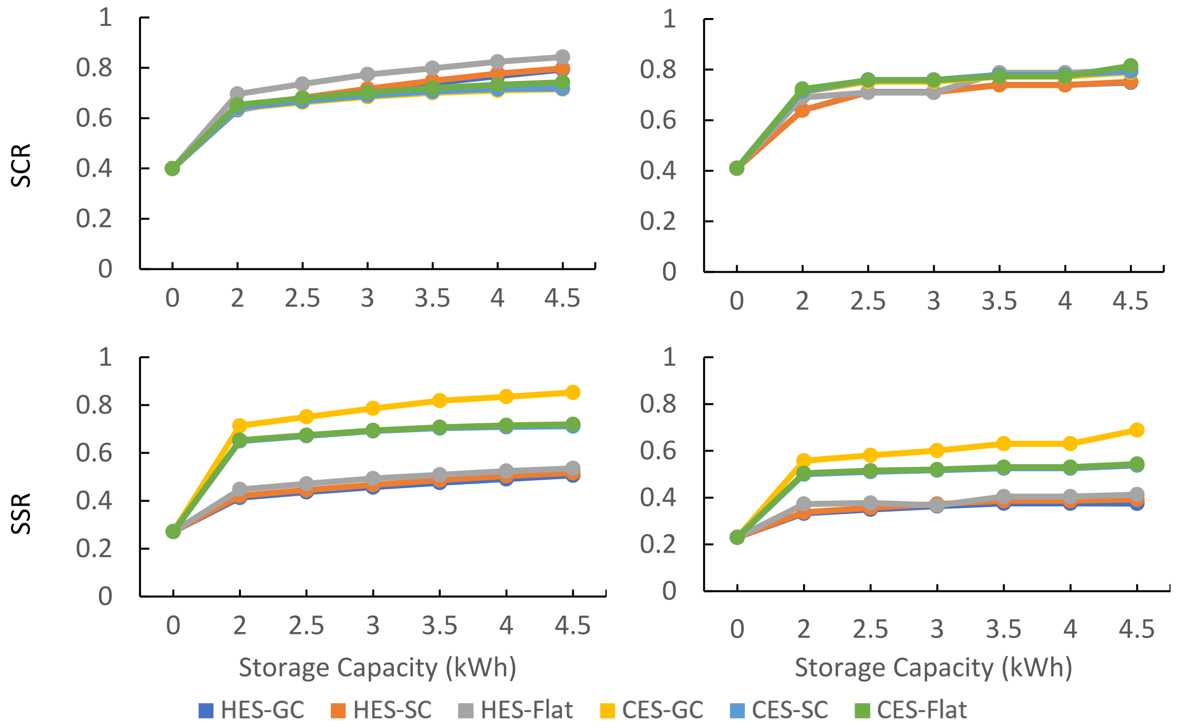


Figure 6 Comparison of Heavy Users' Annual Performances of DE and UK

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

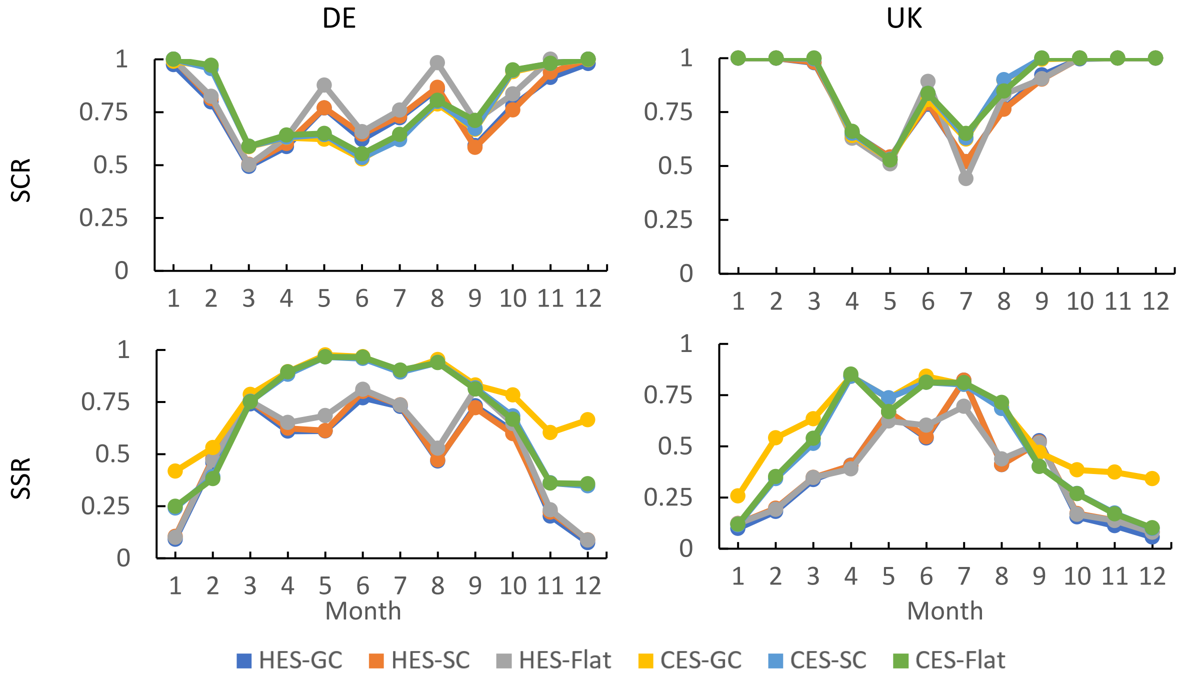


Figure 7 Monthly SCR and SSR of Heavy Users with 3kWp PV and 3kWh Storage

Figure 8 energy savings of light consumers, around 1000 kWh, are significantly less even after the installation of a storage system compared to heavy consumers. The users in UK have an obvious divergence that CES is approximately 20% higher than HES regardless of the operation mode. For the DE light user, CES-Flat achieves the highest SCR because the majority of the PV production is exported to supply the neighbours that also connect to the CES, and the difference in SCRs of each operation modes are very noticeable. This is due to the amount of curtailed energy by DE light users is much greater than that of UK users. More PV production and lower demand therefore collectively contribute to higher SSR of the DE light users. Figure 9 shows the monthly SCR and SSR of light users with 3kWp PV coupled with 3 kWh storage. The SCRs and SSRs mirror the findings in Figure 8.

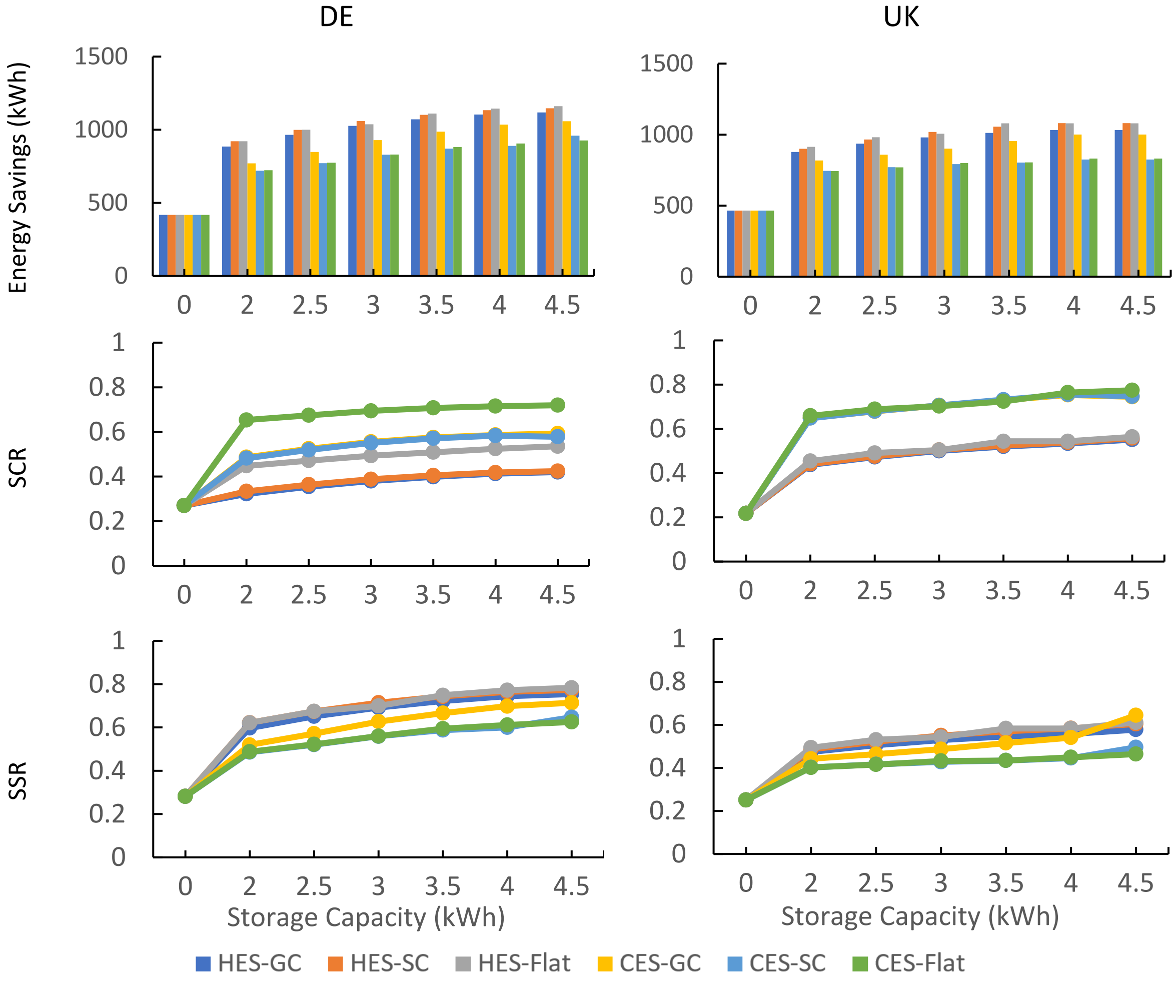
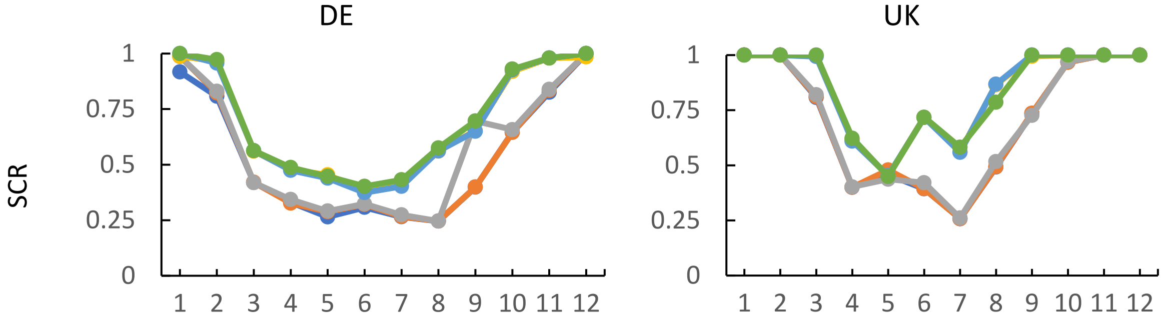


Figure 8 Comparison of Light Users' Annual Performances of DE and UK



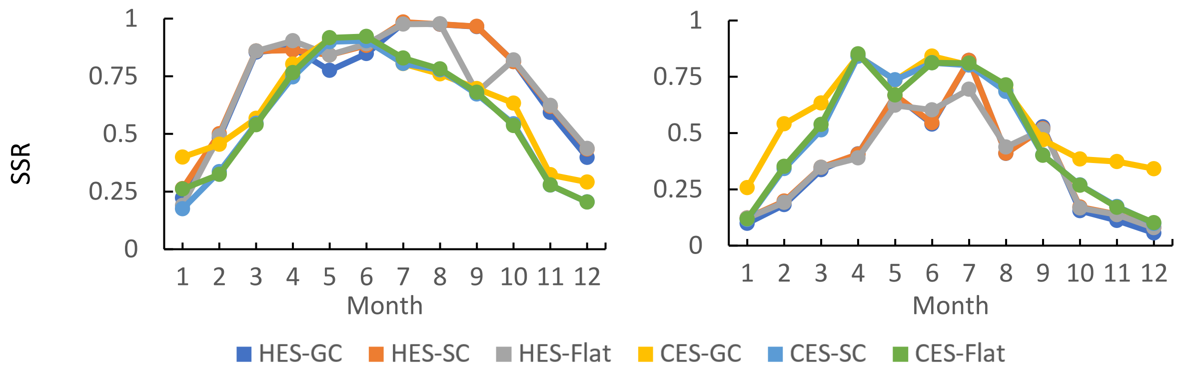
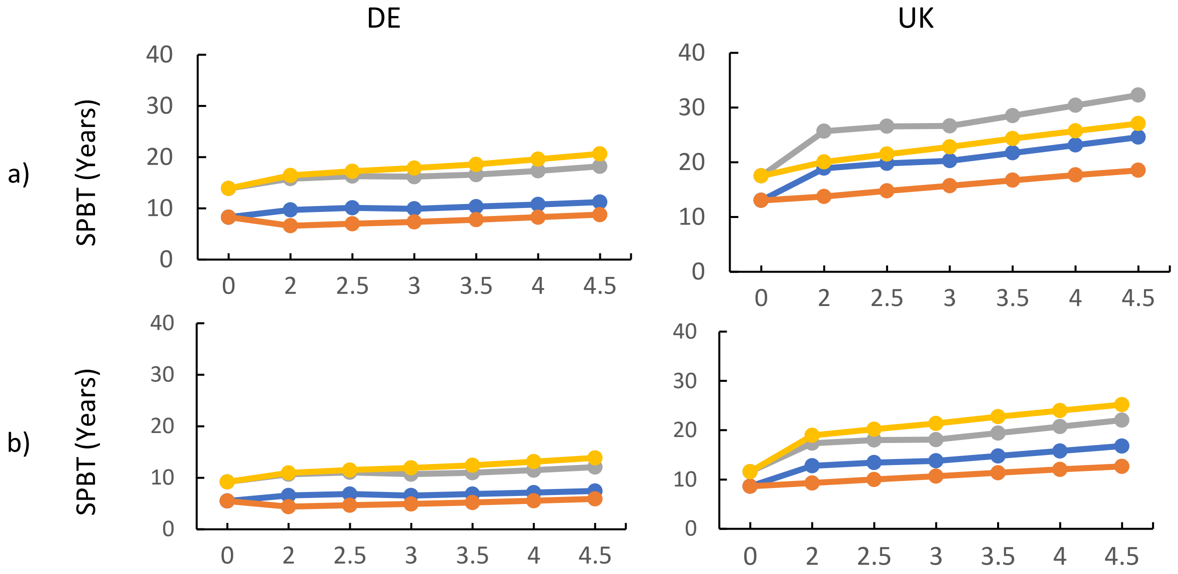


Figure 9 Monthly SCR and SSR of Light Users with 3kWp PV and 3kWh Storage

4.2. Economic Assessment

Figure 10 shows the simple payback time (SPBT) of the systems for both heavy and light users in Germany and the UK when they adopt flat tariffs. It is obvious that the SPBTs of DE users are much shorter. In Year 2020, the SPBTs of heavy users in DE can payback the initial capital investment within 10 years, while light users can only pay back upfront costs between 13 and 20 years. In contrast, the SPBTs of users in the UK are much longer, up to 32 years. According to Schmidt et al. [62], the costs of residential energy storage technologies will reduce by 35% and 50% compared to the current price. In this way, the estimated SPBTs of households installing the systems with the same specifications in Year 2030 and 2040 are also included. As shown in Figure 10, the cost reduction can effectively shorten the SPBT. Both light and heavy users in Germany can payback system within 10 years, and the heavy users can even payback a HES/CES at 4.5 kWh within 5 years. Compared to the users in the UK, the SPBTs are reduced to below 20 years while the heavy users connecting to the CES can even recover the initial investment within 10 years.



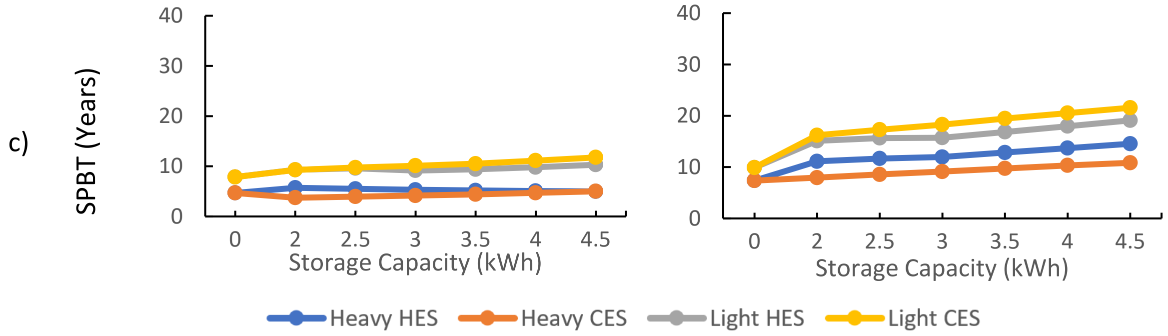


Figure 10 SPBTs for Heavy and Light Users in Year a) 2020, b) 2030 and c) 2040

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

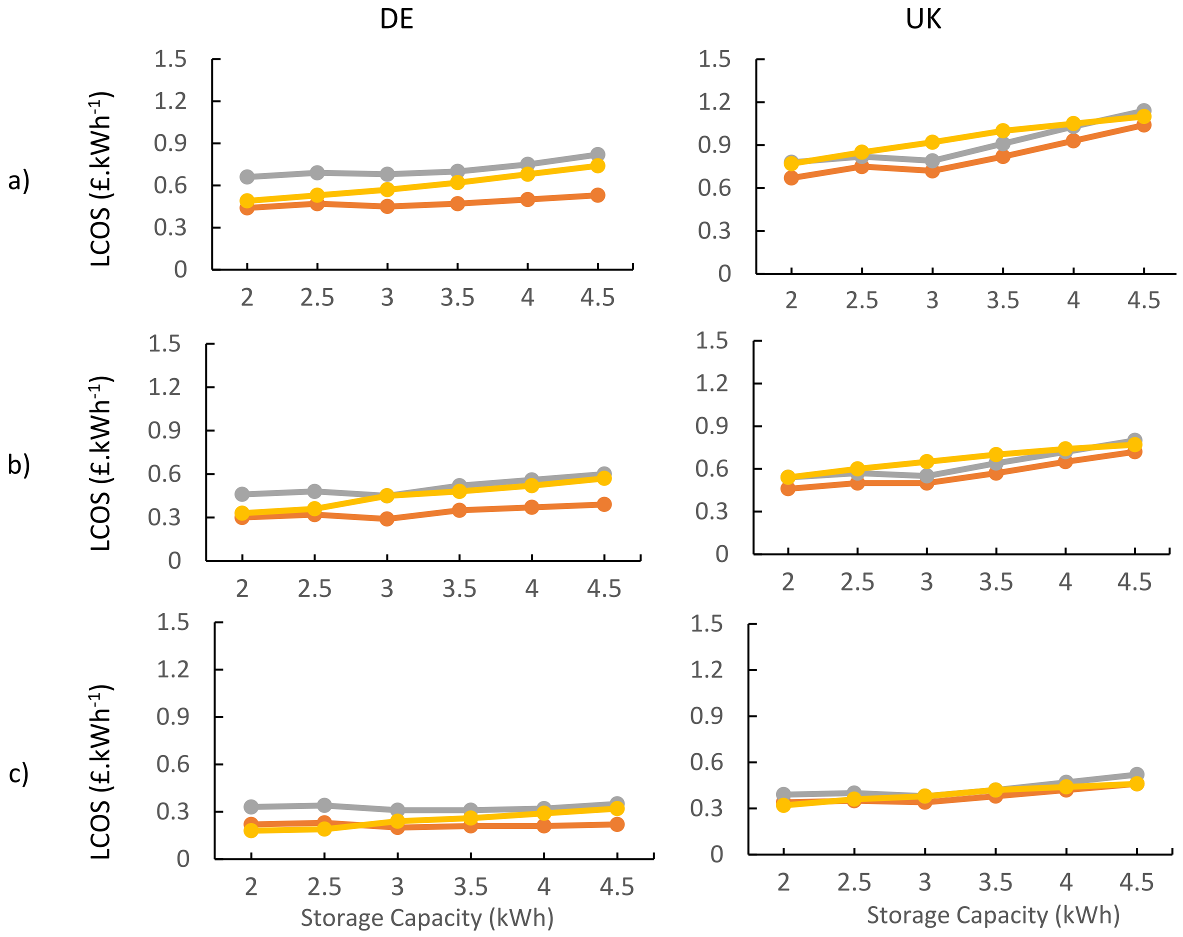


Figure 11 LCOS for Heavy and Light Users in DE and UK Year a) 2020, b) 2030 and c) 2040

Table 7 compares the LCOSs of heavy energy users with 3kWh storage system under various operation strategies. The LCOSs of DE users range from £0.38 kWh^{-1} to £0.58 kWh^{-1} much lower than those of UK users. When the HES operate under HES-SC mode, the design of this strategy is to reduce the energy bills at the cost of more PV curtailment and less battery operation. The HES-GC mode enables UK heavy users to charge electricity from the grid when there is not enough PV production, which increase the use of battery and hence lowers the LCOS to around £0.51 kWh^{-1}. In contrast, the DE households have lower LCOSs compared to UK users, but they are still beyond £0.38 kWh^{-1}. Additionally, in order to incentivise the installation of storage, many financial supports for storage are provided. The Bavarian state government provide €500 for a storage system at least 3kWh and further €100 for each additional 1kWh storage capacity to a maximum of €3200 [63]. The impact of the subsidy for storage is apparent and the LCOSs of a 3.5 kWh HES are around even cheaper than a 2.5 kWh, which are almost around half of the LCOSs of UK users' HES.

Table 7 LCOSs of Heavy User with 3kWh Storage in DE and UK

Capacity (kWh)	DE (£.kWh^{-1})			UK (£.kWh^{-1})		
	HES-GC	HES-SC	HES-Flat	HES-GC	HES-SC	HES-Flat
2	0.45	0.52	0.44	0.52	0.76	0.65
2.5	0.46	0.54	0.47	0.52	0.79	0.68
3	0.41	0.50	0.45	0.51	0.82	0.86
3.5	0.38	0.47	0.47	0.51	0.86	0.78
4	0.43	0.54	0.50	0.51	0.91	0.85
4.5	0.45	0.58	0.53	0.51	0.94	0.91

Table 8 shows the LCOSs of CES with different capacities under various operation strategies. The increasing capacity contributes to higher LCOSs, but the CES-SC and CES-Flat have significantly higher LCOSs than other cases. For the CES in Germany, the sufficient PV production can ensure an effective operation of the CES, even if the charging/discharging process of the CES is triggered after the instantaneous inter-house surplus energy trading. In comparison, the LCOSs in the UK are much higher, unless the storage system can charge from the grid; but it does not necessarily reduce the energy bills for the users. Therefore, more alternatives are needed to further reduce the LCOSs.

Table 8 LCOS of 30kWh CES Operating in Different Modes in DE and UK

Capacity (kWh)	DE			UK		
	CES-GC	CES-SC	CES-Flat	CES-GC	CES-SC	CES-Flat
20	0.42	0.52	0.49	0.46	0.75	0.77
25	0.43	0.56	0.53	0.48	0.82	0.85
30	0.44	0.60	0.57	0.48	0.89	0.92

35	0.47	0.65	0.62	0.49	0.95	1.00
40	0.50	0.72	0.68	0.50	1.00	1.05
45	0.54	0.78	0.74	0.52	1.01	1.10

4.3. Environmental Assessment

Figure 12 shows the annual carbon avoidance by the two communities. The carbon avoidances in Germany ranges from 1433 kg - 2591 kg over a year, compared to that of a UK household around 820kg CO_2, due to the more solar generation and higher grid carbon intensity in German. It is also obvious that heavy energy users connecting to the CES are able to save the most annual CO_2 emission, which grows with the increasing storage capacity. In contrast, the light users can only save slightly more CO_2 compared to the PV-only case (1433kg per year).

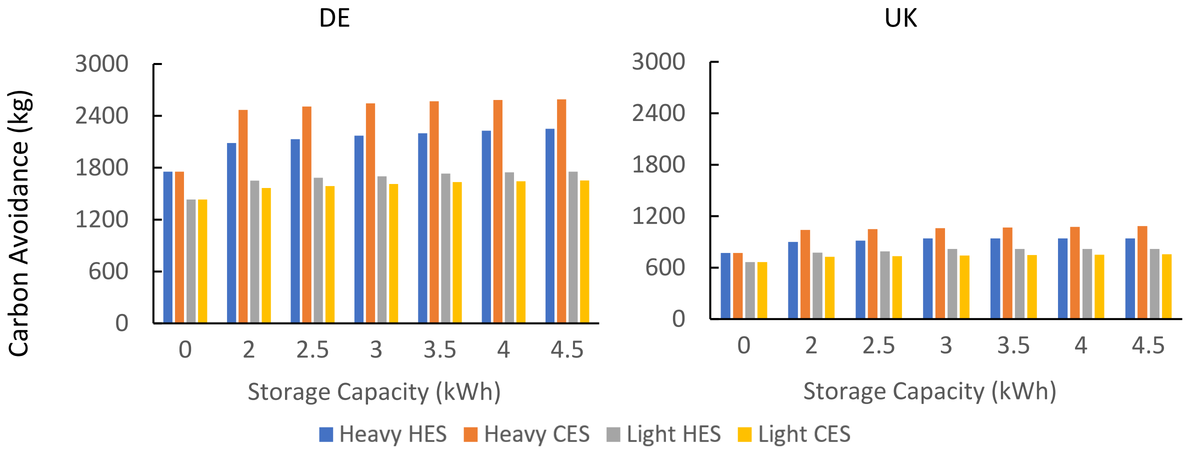


Figure 12 Annual Carbon Avoidance (kg)

Table 9 Impacts of Different Manufacture Locations on PBT_{co2} of Household

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

Table 9 shows the PBT_{co2} of households with 3kWp PV plus 3kWh storage from different manufacture locations. The UK households have more than 2 times longer payback time than the DE users due to less annual carbon avoidance presented in Figure 12. The manufacture locations also play an important role in the PBT_{co2}, because of the carbon intensity. In China, the electricity is still mainly produced by coal-power plants and hence the carbon intensity of China is much higher compared to the UK and DE, which contributes to the longest $PBTs_{co2}$. In contrast, the increasing penetration of low-carbon energy production in the UK significantly lowers the carbon intensity, which can make the households pay back the carbon emission from manufacture much sooner, less than 3 years. Overall, it is certain that the addition of PV plus storage system can effectively reduce the carbon emission. Although the total carbon emission during manufacture may vary with the locations, the systems are found environmentally beneficial overall.

5. Discussion

The solar resource in Germany is much more abundant than in the UK; a DE household (2900 kWh) can produce markedly more electricity than a UK household (2136 kWh) with the same rooftop PV configuration. This enables DE users to generate more energy savings when coupling with storage systems compared to UK households. Improving energy efficiency and reducing energy demand are certainly helpful to enhance the self-sufficiency. The main question for Germany is how to capture and maximise the value of the existing solar resource and therefore the addition of larger storage system would be beneficial. In contrast, the question for the UK is how to diversify and enhance generation because of the limited solar resources. An effective solution is to adopt a hybrid generation system in a UK community, for example PV plus wind turbine system to increase generation. The complementarity between wind and solar can potentially enhance the generation output and total energy export [64], and also can reduce total system costs and required storage capacity [65]. However, this is not enough to solve the problem for good. Different approaches are therefore required for renewable system planning, such as considering the renewable energy resource distribution [64] and energy demand density [66].

Urbanisation has imposed a challenge to the energy system [67], and energy demand is determined by the location, land use, shape and the inherent demand type. The distribution of renewable energy resources in an area can be significantly lower than that of demand, which further limits renewable production. The mismatch between renewable energy resources and demand will become more challenging with the increasing size and number of cities and will also put the security of electricity supply and the durability of the existing utility infrastructures at risk in the future. Therefore, tailored planning may need to combine multiple solutions, including combine heat and power [68], district energy, and PV or wind power generation [69], as well as other flexibility options, such as energy efficiency [70] and demand response [71]. In this study the performances of a small 10-hosehold community varies significantly in Germany and UK, and it is expected that a community with the same size may behave differently in other countries. To determine the optimal system setup, a more comprehensive planning method is required, including analysis of demand heterogeneity, renewable energy resource distribution, etc. However, the greatest challenge remains the economic feasibility. Although there are several solutions, they can be generalised into two main categories [72], increasing financial returns and lowering the investment risk.

The financial returns of a project are mainly from the revenues and savings the project generates, and the FIT payment is one of the most important revenues. Recently, the FIT for domestic solar in the UK has decreased significantly, particularly compared to the markedly higher FIT rates in Germany. The Smart Export Guarantee [73] has removed the deemed export that used to consider 50% the on-site generated electricity as the export. It further reduces profits obtained from domestic solar applications. In addition, the profit margin is also subject to the retail electricity tariffs, because the increasing electricity price is one of the reasons for the growing shift towards self-consumption [74].

In Germany, the expensive electricity tariff rates provide households stronger incentives to reduce grid electricity import by introducing a domestic PV plus storage system. The consumption of every kWh of PV-sourced electricity can contribute to 25.5 pence saving and 9 pence profit via the FIT scheme, which is much higher than the UK. It is therefore necessary to seek other alternative to enhance the financial returns in the UK.

The growing popularity of Li-ion batteries is mainly attributed to their high power, energy density and capability of rapid charge/discharge process [75]. The battery power dispatching needs to match the power and energy profiles of different applications, but most of the applications do not require the battery's capacity the entire time. As a result, idle capacity can be used in additional applications and provide multiple services, including end-user self-consumption and arbitrage, and balancing services through aggregators. Researchers from Switzerland [72] and the UK [76] have found that revenue stacking can effectively improve the battery profitability, but the market is yet to be exploited. More measures and supports are also needed to lower the investment risks. The solar plus storage systems are more accessible to households in Germany with the extensive supports from the government and industry, such as subsidies [63] and loans [77] for storage systems. However, there is much work to be done in the UK. Gardiner et al. [76] suggest that several policy options should be considered, including 1) improving availability of TOU tariffs; 2) adjusting the VAT rate for retrofit installations; 3) direct subsidy; 4) reforming deemed PV export payment; 5) establishing a market for network savings. Cost reduction must be achieved so that the storage will eventually become accessible without subsidies, and Pena-Bello et al. [21] argue that further up to 55% cost reduction in Li-ion batteries is required. Mass production will effectively decrease the production costs and improve the technology to give longer lifespan, which should lower the LCOS. The other alternative is to vertically integrate the industry that provides components of solar plus storage systems. Currently, most solution providers need to procure components from various vendors, leading to higher system costs and difficulties in dealing with warranty and liability issues. For example, most battery storage systems need to be coupled with inverters that usually are provided by different brands. There is actually no clear line of warranty responsibility in the event of inverter or battery failure. Therefore, the vertical integration can enhance the product quality control and provide customers a better warranty, and may as well lower system costs and increase the market share and competitiveness.

6. Conclusion

In this paper, a techno-enviro-economic assessment is undertaken to study PV plus HES/CES system in Germany and the UK. The magnitude of the solar resource is a critical factor in the effectiveness of the system. The SSRs (at least 0.5) and annual energy savings (at least 14100 kWh) of DE communities and users are much higher compared to those in the UK. CES is found to be the better than HES for communities and heavy users in both UK and Germany, whilst light users are better with HES. A whole community analysis is needed to decide the best system approach. A comprehensive and location-specific approach is required for the planning of renewable energy systems, due to differences in renewable resource distribution and energy demand density.

Households in Germany can payback their system between 8 and 20 years compared to the UK households 13 - 32 years. The SPBT of light users in both countries are the longest. The current PV plus storage system price is still too high, but the system is expected to recover the upfront investment within 10 years if the costs of PV and storage can reduce another 30%. The LCOE in Germany ranges from £0.5 - £0.8 kWh^{-1} while that of the UK is between £0.65 - £1.1 kWh^{-1}. Additionally, the study found the government subsidy and price arbitrage can effectively reduce the LCOEs, but all the cases investigated in our research are still not profitable. To make the storage system feasible, battery owners will require government financial support and diversify revenues streams by combining multiple applications with other pricing schemes, such as electricity arbitrage, demand shaving under capacity tariff, inter-house trading, etc.

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

CRediT authorship contribution statement

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

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