Using smart energy storage to increase self-consumption of solar-generated electricity and reduce peak grid load at household and community level

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Keywords

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Abstract

This paper evaluates how distributed smart storage can bring energy flexibility in a community by reducing average peak load and increasing self-consumption of local solar photovoltaic (PV) electricity at an individual household and aggregated community level, as part of a new community energy research project in a socially-deprived community in south-east England. The research study brings together solar PV power and (behind the meter) smart energy storage across a cluster of 82 households and community centre to create a virtual localised energy grid within the existing infrastructure. The batteries are linked to solar PV in each house, and also have internet connections allowing them to be virtually coupled, so as to ensure that the maximum amount of solar generated electricity is used within the community. The methodological approach of the evaluation comprises dwelling surveys, energy audits, householder interviews, monitoring and evaluation of high frequency household electricity consumption, PV generation, battery charge and discharge data. Householder feedback shows that even in a socially disadvantaged community, as well as being anxious over rising energy bills, householders are still concerned about climate change and the future of energy supplies. In the monitored households, average daily electricity consumption ranges from 2.9 kWh to 21.7 kWh, and is found to be positively related with dwelling size, number of occupants and number of appliances used. Although 155 MWh of solar PV electricity has been generated within a year across 47 households, electricity consumption and generation profiles show that in most households, generation exceeds consumption, but peak generation does not match peak consumption. Analysis of the contribution of smart battery show that self-consumption of PV electricity has increased by 6 % and 12 % in the summer and winter periods respectively. The study seeks to demonstrate the case for a cluster of buildings comprising decentralised renewable generation and smart storage that empower communities to achieve energy flexibility.

Introduction

In the UK, the Feed in tariffs (FITs) scheme was introduced by the government to encourage the uptake of a range of small scale renewable and low carbon electricity generation technologies. FITs are payments made to households and businesses that generate their own electricity through methods that do not contribute to the depletion of natural resources, proportion to the amount of power generated (Ofgem, 2017). The scheme came into effect in 2010 and at the start of the fifth year (2015) after the scheme was introduced, uptake of small scale renewable and low carbon electricity generation technologies was approximately 1,800 installations per week and by the end of that year, 2.2 % of all UK homes were generating electricity onsite due to the scheme (Ofgem, 2015a). In 2015 alone, a total of 592,065 installations were registered under the scheme with solar PV making up 99 % of all installations. However by March 2019, FIT rates will reduce by approximately 18 % compared to June 2016 rates (Ofgem, 2017). This reduction in the additional benefits of installing renewable energy (RE) systems will have an impact on the uptake of RE systems, particularly on the domestic level. At the grid level, the penetration of renewable energy into the grid is limited by the capacity of the electricity grid infrastructure which was designed and built for relatively stable and predictable energy generation. Hence, not all excess renewable energy may be exported to the grid, which results in wastage of valuable renewable energy. Renewable energy exported to the grid is sold back to consumers at the unit price of conventional energy, which means that the householders lose out on the financial benefits of distributed generation. In socially-disadvantaged communities, it is not surprising that householders are concerned about rising energy prices (Department of Energy & Climate Change, 2013) which they do not have much control over. The price of energy comprises of the wholesale cost, the cost of distribution and transmission, value added tax (VAT), environmental costs, meter provision and the energy company's supply costs and profits (Ofgem, 2017). The wholesale price which is the largest part of the bill is reliant on the availability of energy, so when availability is low and demand is high, prices rise and vice versa. It can fluctuate widely as it is also related on global prices. Network costs, covering distribution and transmission, are charged for maintaining the networks and these costs are passed on from the supplier to the customers through household energy bills. There are costs incurred for balancing supply and demand of energy and for electricity this is done on a second-by second basis. Some costs are also related to government programmes to save energy and reduce emission, government tax and market participation. Energy suppliers are for-profit companies and hence they have to cover their cost of supplying energy as well as make a profit. In the UK, the government regulatory body for energy promote competition in the market however they do not control the energy prices. Customers also do not have control over energy prices. Comparing with other European countries, the UK ranks above average on electricity prices (Ofgem, 2017) and there has been an increase in annual domestic electricity bills from 2008 to 2016 (Department of Business, Energy & Industrial Strategy (BEIS), 2016). Energy prices may decrease with more renewable energy in the generation mix (as part of new energy policies), however, costs such as network costs have been estimated to increase as approximately £30 billion will be needed to improve systems such as replacing aging infrastructure (Ofgem, 2011) wholesale costs may also increase resulting in higher household energy bills. With consumers facing a possible increase energy bills that they do not have much control over, this can result in a greater proportion of consumers being at risk of energy poverty with consequent effects for the wider society. As well as their concern for rising energy bills, it has been found that residents in socially-disadvantaged are concerned about climate change and the future security of energy supplies (Gupta et al., 2015).

To achieve a shift towards a low carbon economy, an energy system consisting of a significant proportion of decentralised renewable energy sources and a decarbonised power system in local communities will play an important role in how electricity is generated and consumed. In this instance, it makes sense to match household power consumption with power generation in order increase self-consumption of locally generated power and maximise the benefits of using locally generated renewable energy both for the householders, the power providers and for the environment. At a household level and community level where renewable energy systems are installed, increasing self-consumption of the RE energy will ensure that householders are maximising their use of the energy they are generating and as a result reducing their electricity bills (i.e. reducing grid electricity consumption) and reducing their carbon emissions. This also allows them to have more control over their energy consumption.

Energy storage is a form of energy flexibility which also aims to manage the supply and demand of energy, making sure that the energy generated and supplied matches the amount of energy used, maximise the use of low carbon/renewable generation and optimise energy infrastructure investment. Storage systems such as batteries enables cheaper energy (i.e. in cases where there are changes in energy prices throughout the day) or free energy (i.e. in cases where locally generated renewable energy is greater than the instantaneous demand) to be stored and used at a later time. The time shift in energy use has the benefit of reducing peak demand from the grid and where locally generated energy is stored for later use, the amount of exported energy to the grid is reduced. It also helps households to reduce their household bills, particularly where 'free' energy from their installed renewable energy systems is stored.

The uptake of energy storage systems is increasing in several countries. In 2016, Australia announced the introduction of a support package to encourage the uptake of solar storage in both domestic and commercial sectors as part of plans to shift the country to 90 % renewables by 2030 (Hutchens, 2016). In the UK, storage and flexibility has been identified as one of the better and smarter ways to power the nation with substantial cost savings (Anderson, 2014; Lever et al., 2016). In a response to the closure of existing power stations and the resulting challenges, the chair of The National Infrastructure Commission said that the UK has the opportunity to benefit from the innovations including storage and demand flexibility (Press Association, 2015). Policy Exchange, a leading think tank in the UK are also advocating for lower carbon taxes in battery, where surplus electricity generated is saved and released at a later time (Howard & Bengherbi, 2016).

There has been some research on the use of batteries on a domestic level. Examples are Hoppman et al (2014), Widen and Munkhammer (2013), Luthander et al (2015) and Divya and Østergaard (2009). These studies have shown the positive impact of energy storage in increasing self-consumption of renewable power generation or cheaper supplied electricity. Luthander et al went further to illustrate, using a model, that increase in self-consumption of PV generated electricity through storage was higher in a shared network (i.e. aggregated on a community level) compared to individual household level. This is because the random peaks in consumption even out when aggregated and excess PV electricity (after in situ instantaneous consumption and storage) from one household can be consumed by the neighbour. Bruch and Müller (2014) demonstrated the economic benefit in terms of increasing savings to the householder and concluded that the combination of solar PV systems with batteries can be profitable.

Statistics on household energy consumption in England show that approximately 18 % of households are on a time of use electricity tariff (which offers cheaper electricity during off-peak demand periods such as night time) (Office for National Statistics, 2011). This low proportion makes a case for the need to couple energy storage systems with a form of renewable energy system. As the demonstration of the use and benefits of batteries on domestic level is currently in the pilot stages, rigorous evidence from real life studies is required to progress in the investigation and understanding of the contribution of storage in increasing self-consumption of locally generated renewable energy.

Against this context, the aim of this study is to demonstrate how distributed storage can bring energy flexibility in individual households and a community by increasing self-consumption of on-site PV electricity generation and reducing average peak grid load. The research project has brought together solar PV power and behind the meter smart energy batteries to households in a community. This study has been undertaken as part of a new community research project called ERIC, a two-year research project which started in March 2016. The batteries are linked to solar PV in each house and also have internet connections allowing them to be virtually coupled, so as to ensure that the maximum amount of solar generated electricity is used within the community.

Methodology

Table 1 presents the mixed method approach used for the monitoring and evaluation of the smart storage and the time line the activities were carried out. A detailed methodology for the data processing was developed in order to evaluate the objectives of the project and the proposed savings from the installed solar PV and battery systems.

Figure 1 is a graphical representation of a typical household's electricity consumption and generation and the operation of the battery. It shows the daily profiles of electricity consumption, PV electricity generation, the battery state of charge over time and the discharge of electricity from the battery. The state of charge increases (when there is excess PV generation) until it reaches the maximum of 2 kWh. The useable capacity (i.e. the depth of discharge) is approximately 60 % of the maximum. This graph shows electricity consumption and generation in the household in June 2016 in one household. In this month, the daily average consumption was 8.7 kWh and generation was 5.7 kWh (from a 2.0 kWp system). For consumption, on average 3.3 kWh was from the PV) and 1.2 kWh was discharged from the battery, hence, 4.2 kWh was supplied from the grid.

Figure 2 shows the methodology for assessing self-consumption of the generated solar PV electricity. The smart batteries are programmed to charge only when PV electricity generation exceeds household consumption and to discharge when consumption exceeds generation. The shaded areas under the graph represent the amount of PV generated electricity consumed by the household.

Table 1. Monitoring and evaluation methods.

#	Monitoring method	Purpose	Time line
1	Dwelling survey	Assess the physical conditions of the dwellings	Mar -15
2	Household survey and energy audit	Assess the household characteristics and evaluate household electricity use behaviours	Mar -15–Jun -15
3	Monitoring of household electricity consumption	Assess patterns and profiles in household electricity use	Mar -15–Apr -17
4	Monitoring of solar PV electricity generation	Assess the PV electricity generation and ascertain the savings from using PV electricity and the potential for increase in self-consumption	Mar -15–Apr -17
5	Monitoring of battery power charge and discharge	Assess the contribution in smart storage in increasing self-consumption of PV electricity and reducing peak grid power demand	Mar -16–Apr -17

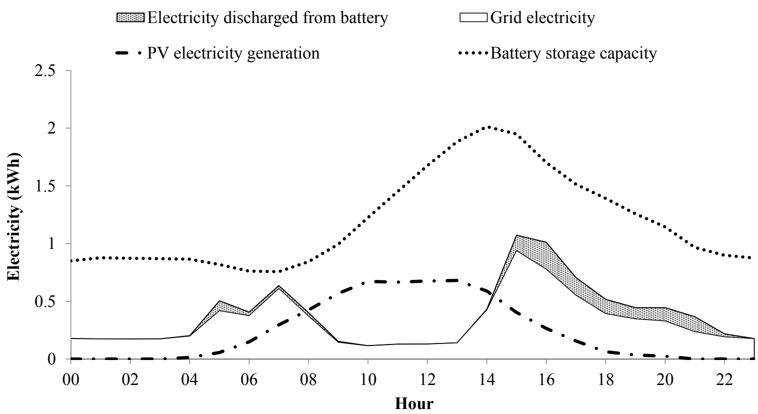


Figure 1. Daily household electricity consumption, PV generation, and discharge profiles, together with the battery's state-of-charge. Average monthly values for June in 2015.

CASE STUDY COMMUNITY, DWELLING AND HOUSEHOLDS

The case study community is located in the south-east region in England. It is a socially-deprived community with predominantly local council and housing association rented households. In the community, 82 households (occupying 82 dwellings) were recruited to participate in the project which required installation of solar systems in majority of the households (the remainder of the households already had solar systems) and smart storage in all the households. The PV systems in the case study households range from 1.5 kWp to 4 kWp and the batteries are 2 kWh in capacity. All 82 households were included in the dwelling survey and 60 households were included in the household survey (with 54 out of the 60 having reliable baseline electricity consumption data). Table 2 presents the characteristics of the 82 households and the 54 households. The dwelling and household characteristics were recorded in order to assess their impact on household electricity consumption.

Results

HOUSEHOLD ELECTRICITY CONSUMPTION

Daily average baseline consumption data from 54 households were assessed from electric meter readings taken in 2015 and 2016. Grid consumption ranged from 2.9 kWh/day to 21.7 kWh/day. The average consumption was 7.3 kWh/day which is below the national average of 11 kWh/day but is expected as consumption in social rented households tends to be lower than average (DECC, 2015). Dwelling and household

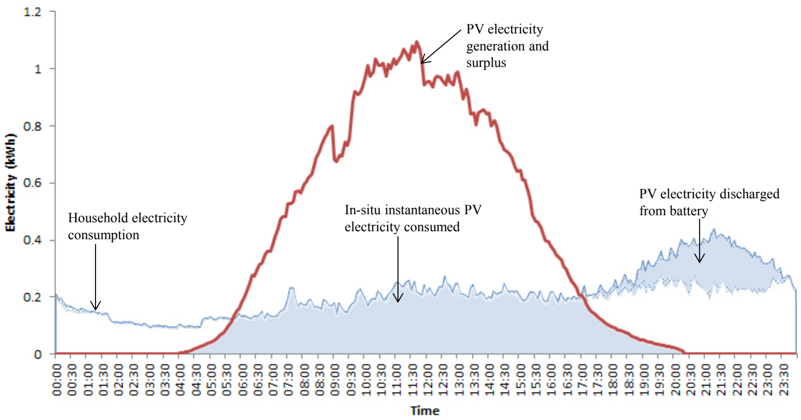


Figure 2. Methodology for assessing self-consumption of generated PV electricity (profile taken from a household using consumption and generation data from March 2016).

Table 2. Dwelling and household characteristics.

Dwelling and household characteristics		All households (n=8)	Households surveyed and with baseline consumption (n=54)
Dwelling type	Terraced house	58	38
	Semi-detached house	10	9
	Detached house	2	2
	Bungalow	4	0
	Flat	8	5
Dwelling age	Pre 1944	10	6
	1945 – 1989	46	32
	Post 1990	26	16
Household type	Family (dependent children)		18
	Family (no dependent children)		5
	Family (no children)		9
	Single person (over 65)		15
	Single person (under 65)		4
	Two or more unrelated adults		3
Household size	One or two		33
	3 or more		21
Occupancy pattern	Always occupied		37
	Evenings and weekends		11
	Other (variable due to shift work)		6

Table 3. Difference in daily electricity consumption due to dwelling and household characteristics.

Dwelling and household characteristics		Average daily electricity consumption (kWh)
Dwelling type	Detached house	10.9
	Semi-detached house	8.9
	Terraced house	7.3
	Flats	4.8
Household size	One or two	6.2
	3 or more	9.5
Occupancy pattern	Always occupied	7.9
	Evenings and weekends and variable due to shift work	6.3

Low consumption household
Number of occupants: 2
Daily average consumption: 4.3 kWh
Occupancy pattern: always occupied
PV system size: 2.5 kWp

High consumption household
Number of occupants: 4
Daily average consumption: 21.7 kWh
Occupancy pattern: always occupied
PV system size: 2.75 kWp

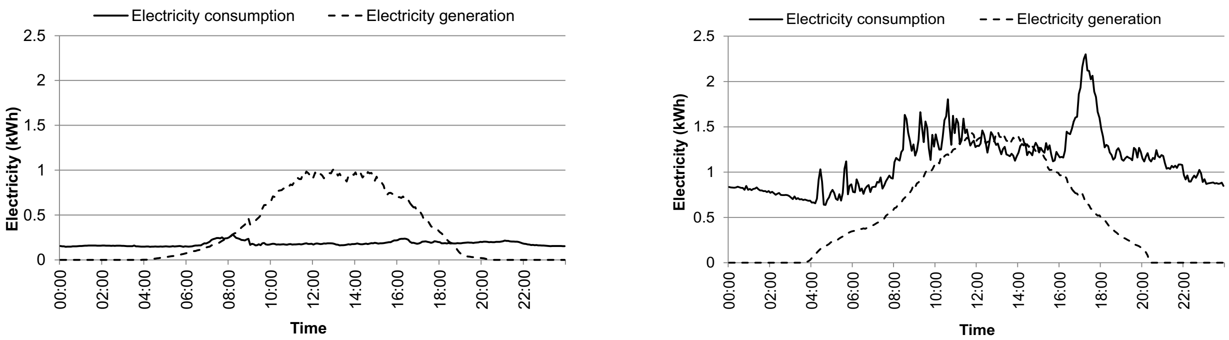


Figure 3. Profiles of electricity consumption and generation in a typical low and high consumer household in the Summer (Jun -15–Sep -15).

characteristics had some noticeable impacts on consumption as there were differences in the daily average consumption in the categories of characteristics (Table). The difference in consumption in dwelling type relates to dwelling size as the detached houses are the largest and the flats are the smallest. This result was also reported in the study conducted by Yohanis *et al* (2008). There was also a different in consumption due to household size: as expected larger households consume more electricity compared to smaller households and occupancy patterns also affect electricity demand: households that are always occupied consumer more than those that are not. This could be because lifestyle factors in the households that are always occupied (e.g. having the TV for longer hours, using the kettle to make cups of tea, etc.).

PV ELECTRICITY GENERATION

Approximately 155,702 kWh of PV electricity has been generated from 47 households since installation (April 2015 to December 2016) of the PV systems (not all the PV generated electricity is included due to a lack of incomplete, including data from the 1.5 kWp systems). As expected PV electricity generation was highest in the summer with a daily average of 4.8 kWh from the 2.5 kWp systems, 5.2 kWh from the 2.75 kWp system and 5.4 kWh and 6.6 kWh from the 3.25 kWp and 3.5 kWp systems respectively. The daily average PV generation on an annual level from the aggregated system is close to the daily average electricity consumption of the community. Where export meters are not fitted (which is the case for these households), FIT payments are based on an assumption that 50 % of electricity generated is consumed on site and the remainder is exported to the grid (Department of Energy & Climate Change, 2012). On this assumption, 77,851 kWh of grid electricity can be offset within this subset of householders alone in the period of the generation, providing a significant saving of £11,678 (using £0.15/kWh) as the unit price for electricity[1]). However, the profiles plotted from the high frequency data on consumption and generation for the summer period (Jun -15–Sep -15) confirms the mismatch between consumption and generation peaks and in the lower consumption households, amount of generated electricity exported to the grid is greater than the assumed 50 %. Figure 3 presents average daily profiles for a typical low consumer and a typical high consumer household in the summer period (Jun-15 – Sep-15). The typical low and high consumers are based on Ofgem's typical domestic consumption values (Ofgem, 2015b). Instantaneous self-consumption of PV generated electricity increases as household electricity consumption increases.

1. Current standard value for electricity from htpps://www.britishgas.co.uk/products-and-services/gas-and-electricity/our-energy-tariffs/tariff-information.html.

CONTRIBUTION OF SMART BATTERIES

The batteries are linked to the solar PV as they are only charged on PV electricity and never from the grid. The model for charging and discharging in each household is such that they charge when there is excess PV electricity generation and discharged when the household consumption exceeds generation. A minimum power rate is set for the battery to allow for better battery cycling. The contributions of solar PV and batteries were assessed for the summer and the winter period in 2016 across 34 households. A full dataset was available for these households in both monitoring periods. The winter period follows directly on from the summer period with the summer period taken from 1 June to 18 September (110 days) and the winter period taken from 19 September to 11 December (84 days). The 34 households are a mix of dwelling and households types. The consumption, generation and discharge data is presented as daily averages (kWh/day). Figure 4 shows the average daily household consumption and PV electricity generation in the summer (above) and winter (below). As expected, PV electricity generation is greater in the summer compared to the winter, and generation exceeds consumption in more households in the summer than in the winter. Daily average summer generation exceeded daily average winter generation by 3.9 kWh and daily average winter consumption exceeded daily average summer consumption by 1.2 kWh. The proportion of PV electricity consumed instantaneously on a household level ranged from 19 % to 70 % in the summer and 17 % to 87 % in the winter (of the total generated).

Figure 5 shows the total household demand split into the contributions from the grid, the solar PV and the battery for the summer (above) and winter (below). In the summer, the proportion of PV generated electricity in the household's total demand ranged from 24 % to 53 % and discharge from the battery made up 0 % to 13 %. In the winter, the proportions of PV electricity ranged from 7 % to 38 % and discharge was 0.4 % to 25 %.

Table 4 presents the make-up of total electricity demand for a low, average and high consumer household in the summer and winter. These are three individual households which are typical of the case study households. In the summer in the low electricity consuming households, although only a small proportion of the generated electricity was consumed, it was able to

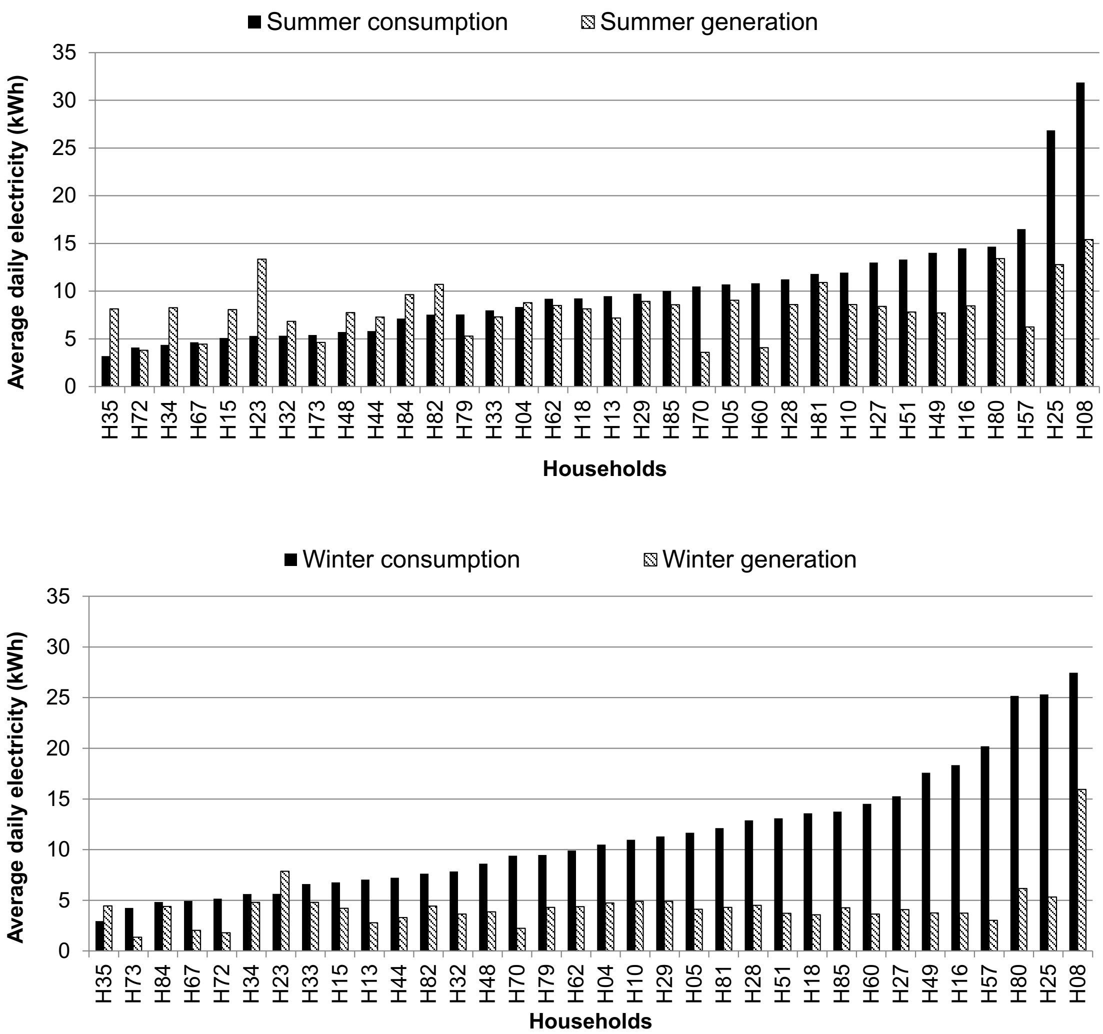


Figure 4. Daily average electricity consumption and generation in the summer (above) and winter (below) in 34 households.

meet a significant amount of the household demand. This could have been due to the householder's electricity use behaviour that carries out activities that require electricity during the day when PV electricity is being generated, and also having a low consumption baseline (the discharge model of the battery is set that the batteries have a fixed power output and will discharge into a household which is at this output level). In the high electricity consuming household, the maximum amount of PV electricity was consumed during generation and hence only a small amount was stored. But due to the high total demand, a significant proportion of electricity was still supplied from the grid. As PV generation has a peak in the middle of the day, the main reason for the differences in use of battery between the low/high and average consumer is the occupancy pattern. As the low and high consumers were always occupied, they were at home when the PV generated the electricity, hence, there was less PV electricity available to be stored in the battery and thereby less to be discharged in the evening. Whereas the average consumer household was only occupied in the evenings and weekends, hence more excess PV electricity was stored for later use.

In the monitored winter period, with the exception of the high consumer household, average daily consumption was higher in this season compared to the summer season. The reduction in the high consumer household may be due to a number of factors: changes in household energy use behaviour, a change in occupancy pattern or household size. On the contribution of the smart batteries, the summer performance showed that the project aim was not achieved (increase self-consumed by 50 %). In order to improve the performance, the model for charging and discharging was fine-tuned to optimise the charge and discharge cycle. The performance of the batteries in the summer presented several learnings for the suppliers which were applied in the winter to fine-tune the batteries. Since household demand was higher in the winter, the baseload level was also higher and so the batteries were able to discharge more efficiently into most of the households. Although PV generation was lower and consumption was higher in the winter compared to the summer, overall the contribution of the battery was greater in the monitored winter period. However, some of the changes in the proportions of electricity from the three sources can also to put down

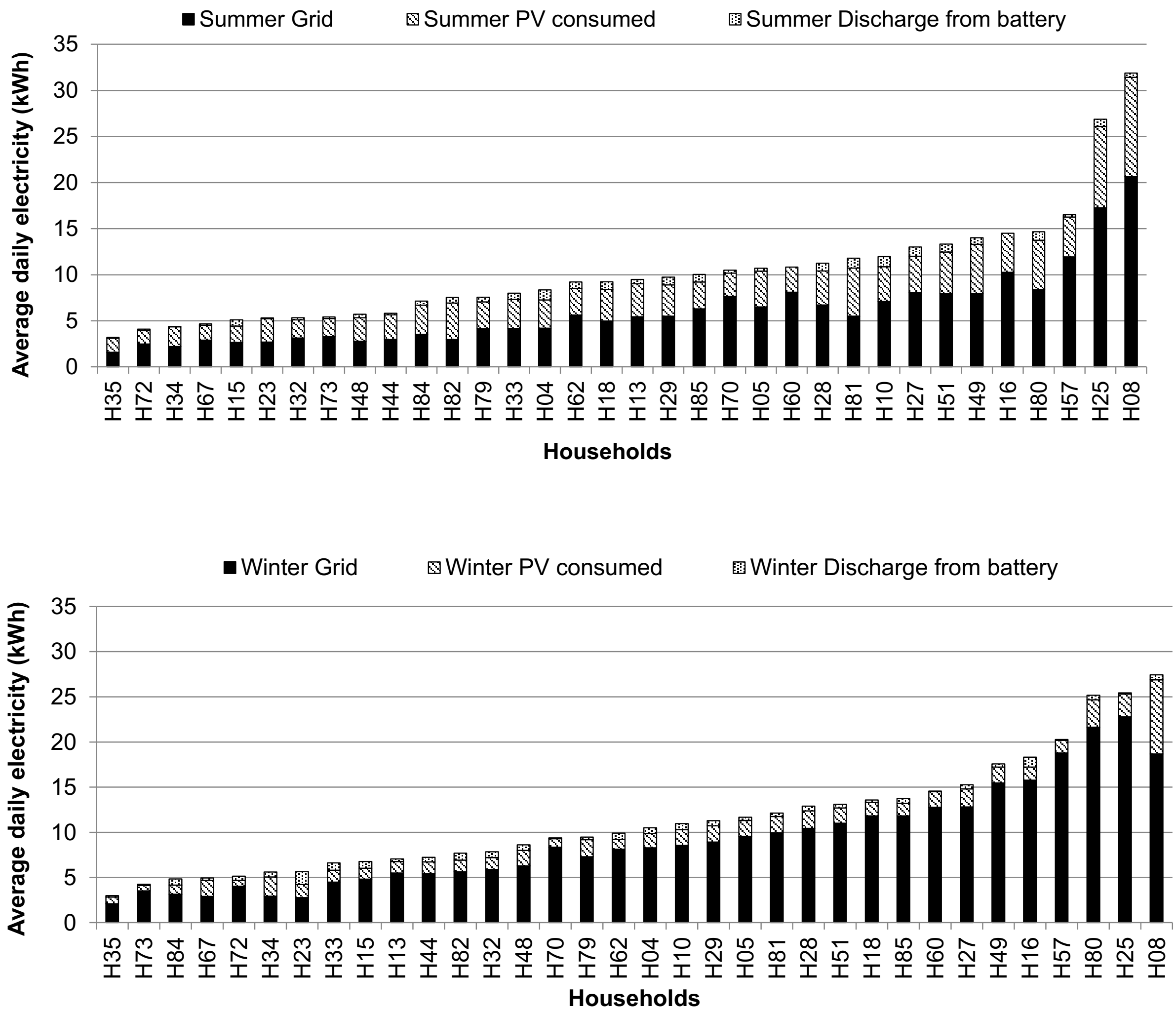
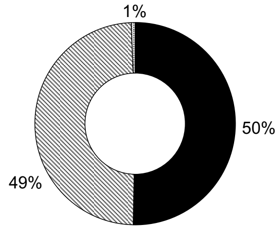
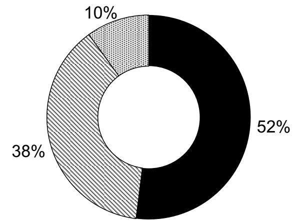
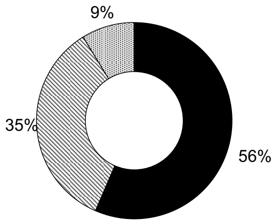
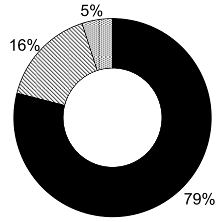
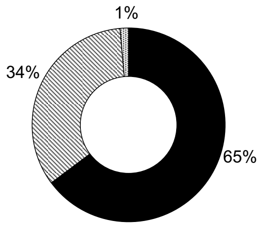
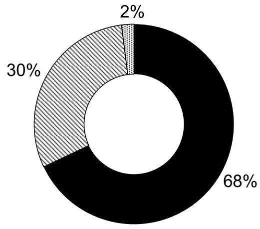


Figure 5. Daily average electricity demand split into grid, solar PV and battery contributions for the summer (above) and winter (below) in 34 households.

Table 4. Grid, solar PV and battery electricity contributions in three specific households in the summer and winter monitoring periods: low, average and high consumer households.

	Summer ■ Grid electricity ▨ PV electricity ▩ Battery electricity	**Winter** ■ Grid electricity ▨ PV electricity ▩ Battery electricity
Low consumer household • Dwelling type: Terraced house • Household size: 2 • Occupancy pattern: Always occupied • PV system size: 2.5kWp	 Total average daily consumption: 4.4 kWh % of PV consumed (before storage): 26 % % increase in self-consumption: 0.3 %	 Total average daily consumption: 5.6 kWh % of PV consumed (before storage): 45 % % increase in self-consumption: 12 %
Average consumer household • Dwelling type: Terraced house • Household size: 2 • Occupancy pattern: Evenings and weekend • PV system size: 2.5 kWp	 Total average daily consumption: 9.7 kWh % of PV consumed (before storage): 38 % % increase in self-consumption: 10 %	 Total average daily consumption: 11.3 kWh % of PV consumed (before storage): 37 % % increase in self-consumption: 12 %
High consumer household • Dwelling type: Terraced house • Household size: 4 • Occupancy pattern: Always occupied • PV system size: 2.75 kWp	 Total average daily consumption: 31.9 kWh % of PV consumed (before storage): 70 % % increase in self-consumption: 3 %	 Total average daily consumption: 27.5 kWh % of PV consumed (before storage): 52 % % increase in self-consumption: 3 %

changes in household characteristics, hence these will require further investigation.

On a community level, on a theoretical aggregation of consumption and generation of the cluster of households monitored is presented to demonstrate the increase in self-consumption and the reduction in peak demand. Reduction in peak demand is estimated by calculating the difference in maximum peak consumption between electricity supplied by the grid and the additional electricity discharged from the battery. Table 5 presents the aggregated electricity consumption and generation in the monitored seasons for the whole community, and Figure 6 presents the aggregated average daily profiles in the seasons. In the winter graph, when aggregated, self-consumption of PV electricity is close to 100 %. This is a good representation of the positive effect of a community network where connected households can store and share locally generated electricity. On just the household level, the percentage of self-consumption was lower (winter graph in Figure 5).

In the summer, storage of PV generated electricity increased self-consumption by an average of 6.3 % so that total PV electricity consumed before export was 50 % of generated electricity. PV electricity made up 40 % of total demand (instantaneous consumption was 35 % and battery discharge was 5 %) and the remainder 60 % was supplied by the grid. Hence in this period the cost saving was approximately £2,301 and carbon reduction was approximately 6,284 kg CO_2 (using a carbon conversion factor of 0.40957 kg CO_2 for electricity[2]). In the monitored winter period, although a smaller amount of PV electricity was generated, the amount consumed instantaneously was comparable to that in the summer. This could be because aggregating across the cluster smoothens out the peaks from the individual households (the peaks will also be related to the household characteristics such as the occupancy pattern which has an in-

2. https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2016.

fluence on electricity use patterns). In the monitored winter period PV self-consumption was increased by 9.4 %, so 49.1 % of the PV generated electricity was consumed before export. However, PV electricity only made up 19 % of the cluster's total demand (15 % from instantaneous PV consumption and 4 % of battery discharge). This resulted in a cost saving of £922 and a reduction of 2,518 kg CO_2 in carbon emissions.

Discussion

The holistic approach adopted for the evaluation of this project allowed detailed information to be collected on dwelling and household characteristics in order to conduct a rigorous assessment of the contribution of the smart storage. Initial findings from the assessment of the baseline electricity consumption showed that household electricity consumption varies widely from household to household and different elements in the dwelling and household characteristics have varying impacts on consumption. In general, the average electricity consumption of the case study households was lower than the UK average household consumption. This finding could be because of the social status of the community and hence the households.

The PV systems installed in the households have generated a significant amount of electricity, offering significant savings to the households. It is however important to consider the capital cost of installing the PV system which will affect its payback period, although in this case the cost to social housing dwellings was taken up by the local authority. Nonetheless, there are also significant environmental benefits from distributed generation. As the daily electricity consumption and generation profiles showed, there is a mismatch between peak demand and peak consumption. The average daily PV electricity generated in the summer season is close to average household daily consumption in the community. This finding from the data analysis shows the potential of meeting a substantial proportion of household electricity demand through a combination of instant consumption of PV electricity and indirect consumption through storage.

On self-consumption of PV generated electricity, most of the households have excess PV electricity with lower consumers having the highest proportions of excess. The amount of excess PV is also dependent on the PV system but in the case study households, most of the installed PV systems are between 2.25 and 2.75kWp and there are low and high consumers with same system sizes. The other explanation for the low consumers having higher proportions of excess PV could be due to the dwelling and household characteristics: they tend to have smaller dwelling sizes and smaller household sizes as opposed to the higher consumers who tend to have bigger dwellings and more occupants. From the analysis, consumption of PV electricity during generation was lowest in the low consumer household albeit the PV meeting most of household's demand during this

Table 5. Aggregated electricity consumption and generation in the monitored summer and winter seasons.

	Summer (110 days)	Winter (84 days)
Total consumption (kWh)	38,174	32,558
Total generation (kWh)	30,834	12,526
Total PV consumed (kWh)	13,393	4,967
Total discharged (kWh)	1,949	1,181
% of PV electricity consumed instantaneously	43.4 %	39.7 %
% Increase in self-consumption	6.3 %	9.4 %
Reduction in peak demand (%)	6 %	3 %

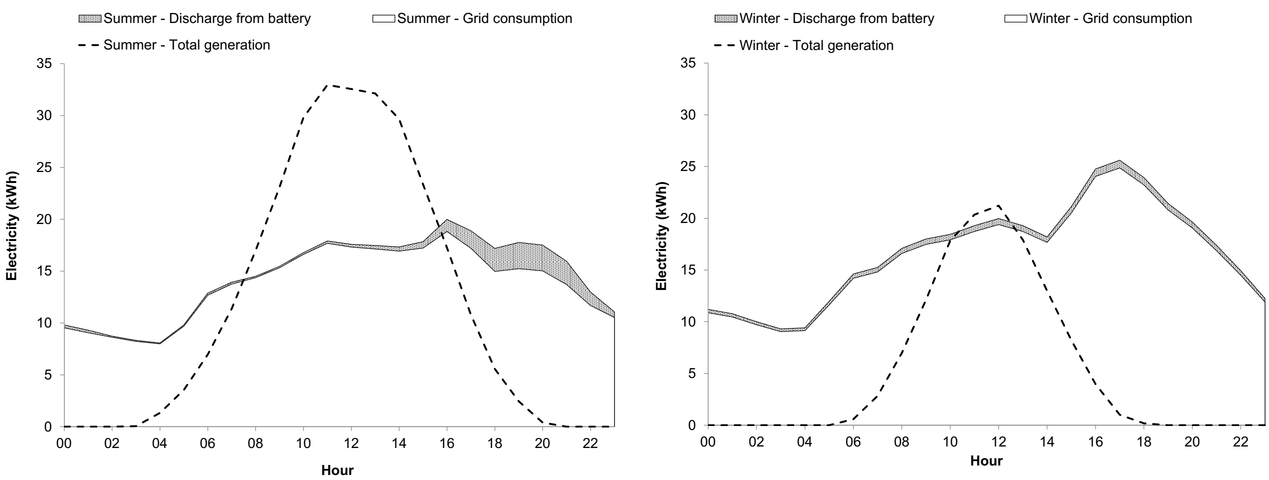


Figure 6 Average daily profiles of electricity consumption, generation and contribution of the batteries in the community in the summer (left) and winter (right) seasons.

time. The higher consumer households were also households that were occupied most of the time, hence most of PV electricity was consumed during generation. As they were high consumers, a significant proportion of their demand was still supplied from the grid and discharge from the battery made only a small contribution to their total demand. The low contribution of the battery could also be due to the small capacity of the installed battery. A large battery size will be able to store a greater amount of excess PV which will make a bigger contribution when discharged. The analysis showed that in the summer, average consumer household made the best use of the battery. This is most likely due to their occupancy pattern as the households are only occupied in the evenings and weekend, and hence a significant amount of excess PV electricity was stored and discharged at the later time. In the summer, the discharge model was set that electricity was pushed from battery at a fixed output. This output was however higher than the baseload in some of the households (on average the case study households are low electricity consumers compared to the average) hence discharge from the batteries was low. The learning in the project from the summer period was applied in the following winter monitoring period and the discharge model was assessed and revised in order to optimise the performance of the batteries. In addition to this, the baseload in the winter is higher than in the summer and so more electricity can be discharged into most of the households during this period. This was evident in the winter monitoring period in the case study households.

The results of the summer and winter analysis showed an increase in self-consumption of PV electricity when adding a battery, although marginal. In the summer a higher amount of PV electricity is generated and consumed instantly, hence a reduced amount is available for storage compared to the winter. In the winter although a smaller amount of electricity is generated, a similar amount as in the summer is consumed. However, household characteristics such as occupancy patterns may also have an influence on self-consumption of locally generated electricity. For the community, the study demonstrated the need for a sharing scheme in a cluster of households. From the household level analysis, it was showed that consumption during generation of PV electricity is lowest in the low consumer householders. As the case study households are generally lower consumers (compared to the national average), an aggregation across the community will have a significant impact as it will ensure that a higher amount of the locally generated electricity is consumed within the community. In the winter a similar amount of PV is consumed during generation as in the summer and as a lower amount of electricity is generated, the battery offers the potential to ensure that a maximum amount of the generated electricity is consumed in order to offer significant reduced bills to the households and also reduced carbon emissions in the community.

One potential possibility for increasing self-consumption is in the sharing scheme where PV electricity from one household can be stored in a battery in another household. This is the aim of the creation of the virtual localised grid. Through the smart batteries, charging can be optimised for each household and through the virtual grid, even more excess PV electricity (for instance from the low consumer households) can be used to charge batteries in households where there is not enough excess. In this case, maximum excess PV electricity is stored and discharged for consumption within the community or within the cluster of households in the grid. The amount of excess PV electricity stored will also increase if batteries have larger capacity, however, cost of the battery may be a limiting factor. A future development for the PV-battery concept should therefore include the idea of a community sharing scheme where not all households will have PV systems but rather have storage facilities connected to their neighbours PV systems. Currently, the savings achieved from the use solar PV systems far outweighs that achieved from the use of the battery, or savings from the batteries is significantly improved by the use of solar PV systems.

Conclusion

The study presented in this paper is part of a wider research study which has a two year monitoring period comprising of a baseline period and a period after the intervention, i.e. installation and use of the battery storage technology. In the assessment of the baseline electricity consumption, differences were found between average daily electricity consumption and dwelling type, household size and occupancy pattern. The solar PV systems installed in the households as part of the project are efficient and effective in generating a significant amount of electricity and in sunnier seasons, daily average PV electricity generated was close to household's daily average electricity demand. However, due to the mismatch between peak demand and peak generation, across the cluster of households monitored, PV electricity only offset a low to moderate proportion of household electricity demand especially in households that are only occupied for some of the time compared to those occupied all the time. Storage was shown to increase self-consumption of PV electricity and further offset grid demand through discharge of stored excess PV electricity, although only marginally, again dependent on household type. As self-consumption of PV generated electricity is influenced by factors such as type of consumer and occupancy pattern of the household, a community energy share scheme would contribute significantly in improving the impact of storage through smoothing out consumption patterns. The analysis presented has demonstrated the effect of having a community share scheme. Across the cluster of households, the aggregated PV electricity (instantaneous consumption and discharge) made 40 % of total demand in the monitored summer period and 15 % in the monitored winter period, also resulting some cost and environmental savings for the community. The combination of PV and battery will be important in the drive towards achieving energy resilience and moving closer to a low carbon economy. The analysis has demonstrated the potential benefits of domestic storage coupled with solar PV systems by showing the cost savings that can be achieved which will contribute towards reducing fuel poverty.

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