Chapter 7
Performance of Distributed Energy Resources in Three Low-Energy Dwellings During the UK Lockdown Period

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7.1 Introduction

In 2019 the UK parliament passed legislation requiring the government to achieve net zero greenhouse gas emissions status by 2050; previously the target was 80% of 1990 levels by 2050 (UK Government, 2019). Unfortunately, there have been road-blocks along the way, namely, the significant, almost five-year void in guidance left after Zero-Carbon Homes and Code for Sustainable Homes (CSH) were withdrawn. As a result, many new homes have been built to only minimum standards (CCC, 2019). Ideally, the way forward involves a change to those minimum standards. This Future Homes Standard set for 2025 is expected to create an average home that would produce 75–80% less CO_2 emissions than one built to the 2013 UK Building Regulations (Ministry of Housing Communities and Local Government, 2019). In order to meet this target, the Committee on Climate Change (CCC) (2019) recommends that from 2025 no new homes should be connected to the gas grid. Instead these homes should use low-carbon systems like heat pumps or be connected to community heat networks.

At the same time the domestic sector is behind the other sectors on reducing emissions (BEIS, 2018), there has been an increase in the number of people working from home. The number of people working from home has nearly quadrupled in the last 20 years (CCC, 2019). This statistic, of course, does not take into consideration the Covid-19 lockdown and cultural shift which may occur as a result of employees and employers becoming accustomed to staff working from home (Kelly, 2020). Except for the self-employed, this means that more energy is being used

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C. Gorse et al. (eds.), *Climate Emergency – Managing, Building, and Delivering the Sustainable Development Goals*, https://doi.org/10.1007/978-3-030-79450-7_7

during the day at home instead of in the office. One positive outcome from this would be a higher rate of self-consumption (SC) in renewable energy, namely, photovoltaics, especially if coupled with a heat pump.

As the recommendations for meeting the low-carbon targets include a significant shift from gas to electrification of heat and transport, several future scenarios forecast an increase in peak demand. To help offset this demand, there will need to be a large increase in low-carbon generation which tends to be variable and intermittent. Balancing the system, especially in the summer, will also be a challenge, wherein a projected 30 GW of solar connected to the distribution network would mean the difference of almost 20 GW transmission demand depending on whether it is a cloudy or sunny day. Solutions to these problems include energy storage, demand side response (DSR), smart networks and increased interconnection (DECC, 2015). Batteries that charge when there is surplus PV generation and discharge during a dwelling's peak demand, or charge based on time-of-use (TOU) settings to coincide with TOU tariffs, are considered smart technologies in this paper.

In response to these current challenges, this paper empirically examines the effectiveness of distributed energy resources (DERs) comprising smart home batteries coupled with rooftop solar PV on actual energy use and peak demand in three dwellings designed to high thermal standards. The paper also explores the change in daily energy use and performance of DERs during the Covid-19 lockdown period (23 March to 31 May 2020). All three dwellings are located in an eco-development in York (UK), occupied continuously by families, and have identical heating systems (district heating), rooftop solar PV systems (4 kWp) and home batteries (14 kWh). The dwellings were constructed as part of a 5-year (2015–2020) research project called Zero Plus, funded by the European Union's Horizon 2020 Research and Innovation programme. The overall aim of the project was to reduce net regulated energy consumption of the dwellings to 20 kWh/m^2/year and achieve renewable energy generation of 50 kWh/m^2/year by deploying advanced energy technologies.

7.2 Literature Review on Solar PVs and Batteries

There are several ways to benefit from photovoltaic (PV) generation and storage in dwellings depending on country or local policy; these include PV with no self-consumption (direct feed-in to the grid), PV self-consumption, PV self-consumption with active load management (i.e. DSR) and PV self-consumption with battery storage (Johann & Madlener, 2014). The right approach depends on the policy and incentives in an area. As an example, as there is currently no feed-in tariff (FiT) in the UK, the first option would not be viable. Grid-export rates through FiTs have been diminishing in several other regions like they have in the UK. Therefore, maximising self-consumption (SC) from electricity production is becoming an increasingly important consideration for standalone electricity generating systems and also those with connected batteries (O'Shaughnessy et al., 2018). For an average UK household with electricity demand of 4000 kWh/year and 2.9 kWp PV system, the SC has been estimated to be about 35–38% (McKenna et al., 2018). One UK study of PV and battery system combinations showed that over the summer months, a sample of 44 dwellings in Oxford had SC ratios which ranged widely from 19% to 70% (average of 43%) (Gupta et al., 2019). For an average household in Germany, SC of electricity using a PV and battery combination was found to be rarely higher than 50% (Johann & Madlener, 2014).

Self-consumption can be a helpful factor in judging the efficient use of a PV system, but one misleading factor in SC can be the influence of an oversized PV system on the ratio. Even with large batteries, an oversized PV system can be more disadvantageous in jurisdictions where no FiT is paid. Self-sufficiency (SS) ratios can be more telling about the ability of the equipment and timing of use to meet household demand. However, the mismatch between heating load and the solar production profile limits the SS ratio. This is true even when coupled with batteries; to increase SS ratio on annual scale would require seasonal storage (Zhang et al., 2016). One study evaluating the return on investment between lead acid, NaNiCl (sodium-nickel-chloride) and lithium ion (Li-ion), in combination with the PV system, found that the Li-ion battery system is superior in achieving a higher SS ratio with the same life cycle cost (Zhang et al., 2016). As batteries help to increase SS, they have the potential to work against FiTs as an economic driver for electricity generating systems (Truong et al., 2016). Currently, in the case of the UK, however, this is helpful as the FiT is no longer available for new electricity generating installations (Jones et al., 2017).

As is shown, batteries help with respect to SC and SS. In the same way, batteries are also beneficial in shifting or alleviating peak grid consumption. As the grid pressure increases, the UK are trying to relieve this pressure focussing on efforts to reduce the peak demand. In the UK study cited above, aggregating solar generation and storage at a community level showed that peak grid electricity demand between 17:00 and 19:00 was reduced by 8% through the use of smart batteries across 74 dwellings (Gupta et al., 2019). Shifting PV production is helpful in achieving this, but also setting up batteries to take advantage of TOU tariffs is also modelled to be beneficial. One study calculated that with 2 kWh of battery storage per household, the peak demand at low voltage substations could be halved. With homes heated with heat pumps, 3 kWh battery storage per household would avoid increasing the peak demand (Pimm et al., 2018).

As it is important that energy-related claims of smart home technologies are scrutinised (Hargreaves et al., 2018), it is also important to understand the capability of batteries in improving self-consumption and self-sufficiency. There is relatively less empirical research on the actual performance of distributed energy resources in homes especially solar PV coupled with home batteries that can meet the daily energy needs of dwelling. This is what this study investigates.

7.3 The Zero Plus Project Case Study Dwellings

There are three Zero Plus (ZP) dwellings (ZP1, ZP2 and ZP3) in a development located in York, England. Figure 7.1 shows the dwellings and the PV panels located on the southwest – south-facing roofs. On the left are ZP1 and ZP2, both two-bed semi-detached dwellings, and on the right is ZP3, a three-bed detached dwelling. Table 7.1 lists various household characteristics for the three dwellings including PV and battery specifications.

7.4 Methodology

The major focus of this paper is on the statistical analysis of the electricity balance in the dwellings, i.e. consumption, generation and storage. Also included is a brief overview of space heating and domestic hot water (DHW) (disaggregated from total hot water supply) to provide a complete view of total energy consumption in the dwellings. A significant limitation of the dataset is that the space heating data logger in ZP1 logged no data for the entire heating season. So that as much data are aligned as possible, the analysis covers the period from 1 February 2020 to 31 May 2020. Also, with respect to electricity consumption in the dwellings, peak grid demand times are taken as 16:00–20:00 (DECC, 2015).

The analysis approach first reports on the overall view of energy consumption, followed by electricity consumed and generated in the homes with a focus on self-consumption (SC) and self-sufficiency (SS) and times when the batteries charge and discharge. The impact of Covid-19 lockdown on energy use in the dwellings is also explored, using ‘pre-lockdown’ dates 1 February 2020–22 March 2020 and ‘during lockdown’ dates 23 March 2020–31 May 2020. Table 7.2 shows the data sources and data gathered in the study and at what frequency these data were gathered. The monitoring was remote; data gathered were transmitted through the wireless network to an online repository.

Fig. 7.1 Zero Plus dwellings: from left to right, ZP1, ZP2 and ZP3

Table 7.1 Household characteristics

	ZP1	ZP2	ZP3
Form	2-storey right-side semi-detached	2-storey left-side semi-detached	2-storey detached with adjacent attached garage
Total floor area (m^2)	84.4	84.4	129.6
Measured air permeability (design 4.0 $m^3\ h^{-1}\ m^{-2}$@50pa)	5.39 $m^3\ h^{-1}\ m^{-2}$	5.44 $m^3\ h^{-1}\ m^{-2}$	7.53 $m^3\ h^{-1}\ m^{-2}$
No. of bedrooms	2	2	3
First full month in dwelling	August 2019	February 2019	September 2019
Period heated	Mid September to mid May	Start February to early April	Mid September to early April
Number of occupants	3	3	4
Household	1 adult/2 children	2 adults/1 child	2 adults/2 children
Occupancy	Always at home	Always at home; 1 adult works away from home	Always at home
Occupancy pattern as viewed through energy consumption	Most active morning hours: 6–8 am Most active evening hours 6–10 pm Most energy consumed in evening	Most active morning hours: 6–8 am Most active evening hours 7–11 pm Most energy consumed in evening	Most active morning hours: 5–9 am Most active evening hours 6–10 pm Most energy consumed in evening
Building fabric specification	*U*-values ($W/m^2.K$): Exterior wall 0.17, party wall 0.23, roof 0.16, floor 0.14, windows 1.33, air permeability 4.0 $m^3/(h.m^2)$@50pa		
Heating	District heating (gas)		
Renewables	Total 4.34 kWp per dwelling: 14×–310 Wp PV panels 50% tilt, 236 SW-W azimuth		
Battery	14 kWh (total), 5 kW continuous power, Li-ion, fully integrated inverter		

Table 7.2 Data sources and details

Variable	Resolution/details	Source
Indoor temperature	Temp.: 0.1 °C at 30 min interval	Orsis data loggers installed in dwellings
Heat energy monitoring, DHW energy monitoring	1 Wh at 30 min interval	Orsis data loggers installed in dwellings
Fans and lighting electricity consumption	1 Wh at 30 min interval	Orsis data loggers installed in dwellings
Total electricity, battery and PV monitoring	0.1 kW at 5 min interval	Battery inverter
Heating degree days (HDD)	0.1 degree day, 15.5 °C base temperature, daily basis	www.degreedays.net

7.5 Results

7.5.1 Total Energy Consumption of the Dwellings

For the period reported, ZP3, the largest in both size and number of occupants, is consuming the most energy overall. Though ZP3 does have more occupants and is a larger dwelling, per area, it is still consuming more heating (gas) and electricity. Space heating is three times of what is used in ZP2 after being normalised by area. With respect to electricity, however, ZP3 has a wheelchair lift installed as one of the occupants uses a wheelchair; they also have a fish tank. For this reason, electricity consumption is expected to be much higher. Table 7.3 lists the overall consumption values in the dwellings.

7.5.2 Electricity Balance in the Dwellings

As ZP3 uses more electricity than the other dwellings, it not only has the highest instantaneous SC of PV electricity, it also consumes more electricity directly from the grid and the battery to offset higher daily power demands. Table 7.4 shows the proportioned breakdown of in- and out-going electricity in the dwellings. The PV and battery combination contributed to a SS range of 76–95%. This, based on a simple annual projection and an electricity rate of 15 p/kWh, could result in annual savings of between £260 and £438.

All dwellings have peak electricity consumption between 16:00 and 18:00. This falls within the typical UK peak grid demand times of 16:00–20:00. Figures 7.2, 7.3, and 7.4 show the average hourly PV generation and source of electricity to meet total HEC. As can be seen in the graphs, both instant consumption of PV generation

Table 7.3 Energy data from 1 February 2020 to 31 May 2020

	ZP1	ZP2	ZP3
Total energy consumption (kWh)	1535[a]	1838	2938
Total heating energy consumption (kWh)	206[a]	243	1144
Total domestic hot water (kWh)	674	863	504
Total household electricity consumption (HEC) (kWh)	655	732	1290
Total PV generation (kWh)	1682	1683	1699
Net electricity consumption	−1027	−951	−409
Net total consumption (kWh)	−147[a]	155	1239
Net total consumption (kWh/m^2)	−1.7[a]	1.8	9.6

[a]ZP1 total heating energy consumption was not monitored due to a faulty data logger. The total heating energy consumption value is roughly estimated normalising ZP2's hourly space heating consumption with hourly living room temperature data and applying this to ZP1's hourly living room temperature data. This is done because ZP1 and ZP2 are identical in form, though slightly different in occupancy. As a result, all values that include space heating energy consumption for ZP1 are estimated

Table 7.4 Energy data from 1 February 2020 to 31 May 2020

	ZP1	ZP2	ZP3
Total household electricity consumption (kWh)	*655*	*732*	*1290*
% of HEC from PV (instantaneous SS)	49%	51%	42%
% of HEC from battery (PV and grid mix)	49%	42%	50%
% of HEC from grid (direct consumption)	2%	7%	8%
Total PV generation (kWh)	*1682*	*1683*	*1699*
% of PV exported to grid	53%	57%	32%
% of PV self-consumed (instant and battery)	47%	43%	68%
% of PV SC (instantaneous only)	20%	22%	34%
Total grid consumption (kWh)	*30*	*153*	*316*
% direct from grid	27%	35%	30%
% grid consumption delayed through battery	73%	65%	70%

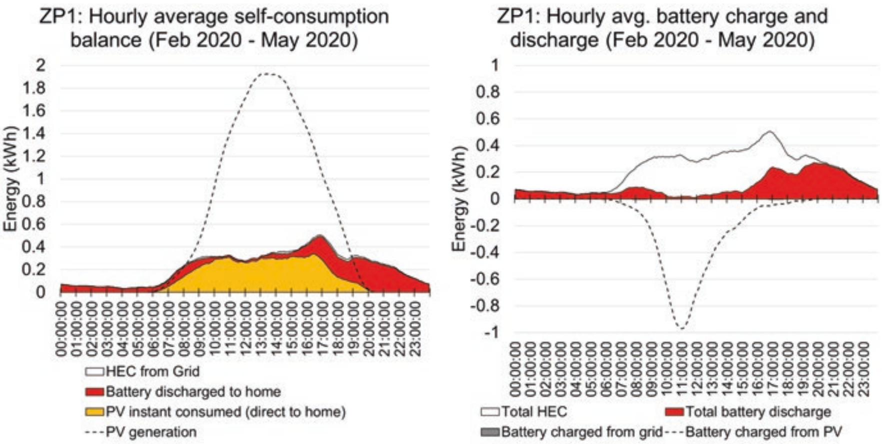

Fig. 7.2 ZP1: Average hourly HEC breakdown (left) and battery balance (right)

and battery discharge are greatly offsetting this peak demand. Between 16:00 and 20:00:

ZP1 average total of 0.8 kWh of direct grid consumption (PV and battery making up 17.8 kWh)—reducing this home grid pressure during peak by 96% on average.

ZP2 average total of 0.4 kWh of direct grid consumption (PV and battery making up 24.2 kWh)—reducing this home grid pressure during peak by 98% on average.

ZP3 average total of 1.7 kWh of direct grid consumption (PV and battery making up 31.6 kWh)—reducing this home grid pressure during peak by 95% on average.

Figures 7.2, 7.3, and 7.4 show the battery charging and discharging times throughout a day over the period. Notably ZP3 performs a significant amount of off-peak charging from the grid overnight; 70% of their total grid consumption is shifted through the battery. ZP1 does not regularly charge the battery from the grid overnight. As can be seen, ZP3 has larger baseline energy consumption than the

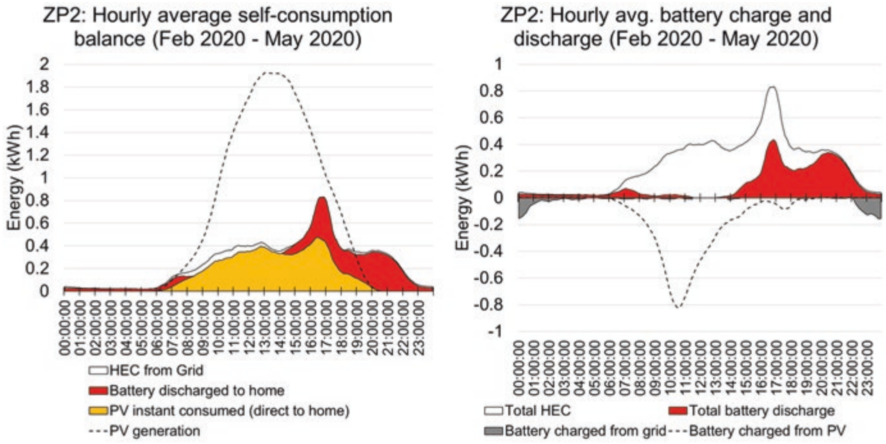

Fig. 7.3 ZP2: Average hourly HEC breakdown (left) and battery balance (right)

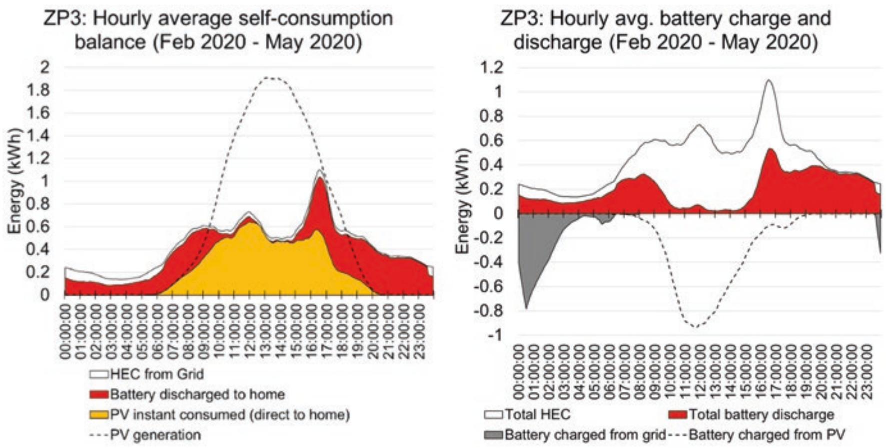

Fig. 7.4 ZP3: Average hourly HEC breakdown (left) and battery balance (right)

other dwellings. Contributors to this are likely their higher use of fans and lights and possibly their fish tank.

7.5.3 Impact of Covid-19 Lockdown on Energy Use in the Dwellings

Overall, in looking at total dwelling electricity consumption, there is an increase in electricity consumption across all dwellings from before Covid-19 lockdown (1 Feb–22 Mar 2020) to during lockdown (23 Mar–31 May 2020). The following presents the investigation of overall daily electricity use, changes to peak demand,

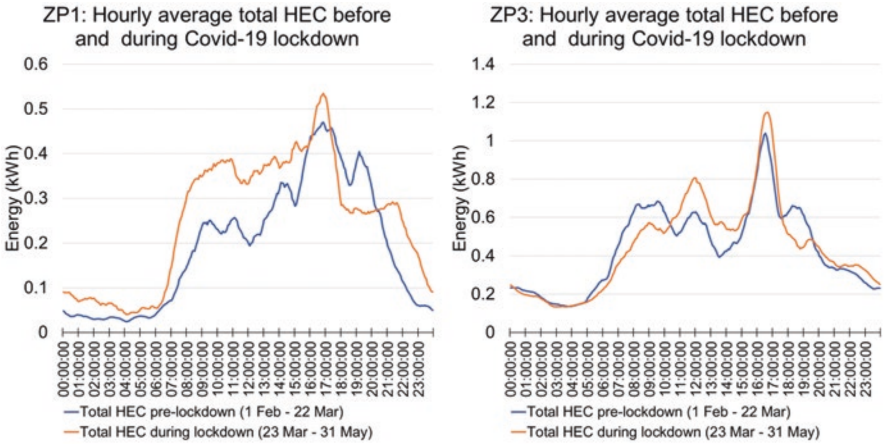

Fig. 7.5 Hourly electricity consumption contrast before and during Covid-19 lockdown (ZP1 left, ZP3 right)

detailing of end uses to investigate the above changes further and finally space heating.

ZP1 increased total daily HEC by 30%, ZP2 increased by 9% and ZP3 increased by only 2%. Figure 7.5 contrasts the shift in average hourly total HEC for each period in ZP1 and ZP3. In ZP1 the increase is notable, where there is more energy consumption in the morning to afternoon and a sharper peak at peak demand times. ZP3 has had a sharper peak during peak demand but no other significant change overall. ZP2, not shown, also had higher noon to peak consumption and a higher peak demand very similar to ZP3. Though during the initial questionnaire assessment both ZP1 and ZP3 stated that they are 'home all the time', it is expected that the occupants in ZP1, in reality, before the lockdown left the house more often to visit friends or relatives albeit possibly not on a regular schedule.

In looking deeper at electricity use in the dwellings, electricity consumption for fans and lighting (sub-metered) was removed from the total electricity use to isolate all remaining uses, called 'appliances' here. The hypothesis is that this 'appliance' consumption should increase as occupants are stuck at home in lockdown; however, this increase is not expected to be overly large, but noticeable. This is because most of the extra use is expected to be in low-power devices like televisions and computers. It is recognised that not being able to isolate cooking energy is a limitation since a shift to cooking at home could be a significant indicator of the occupancy shift. Though lighting consumption could also increase, it is best removed as the lockdown period progressed through days which are increasing in daylight hours. Figure 7.6 shows the fan, lighting and appliance consumption pre-lockdown and during lockdown for ZP1. The only dwelling showing a notable impact of lockdown in appliance use is ZP1, where a slight downward trend before lockdown becomes a significant upward trend. ZP2 and ZP3 (not shown) demonstrated downward trends in consumption during lockdown; however, in ZP2 this is barely noticeable

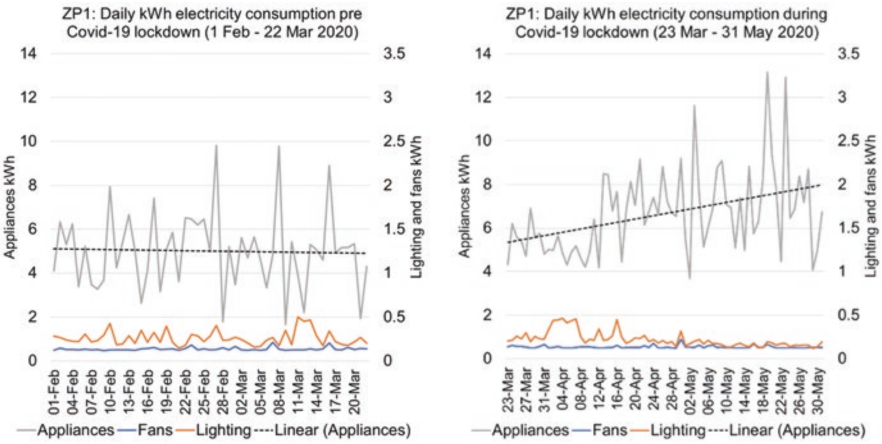

Fig. 7.6 ZP1: Sub-metered electricity use (pre-lockdown left, during lockdown right)

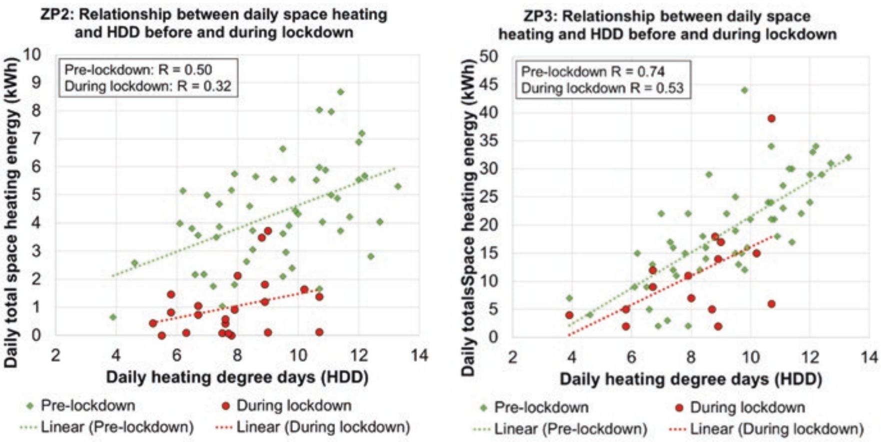

Fig. 7.7 ZP2 (left) and ZP3 (right) correlation between space heating and HDD pre- and during Covid-19 lockdown

and is a little higher than pre-lockdown, and in ZP3 the downward trend also appeared to be slowing during lockdown.

Space heating is another way to observe the impact of lockdown on energy consumption; however, a limitation of this method is that lockdown has occurred as the heating season is ending. For this reason, correlation with heating degree days (HDD) is used to assess impact. Figure 7.7 shows ZP2 and ZP3 daily total space heating as it correlates to the daily HDD for the same period. One aspect to note immediately is that the correlation between space heating and HDD is much weaker during lockdown as opposed to before. This, however, could just be an aspect of the end of the heating season and not necessarily an increase of user heating.

In theory, if there is more use of heating as a result of being at home more, the proportion of total heating consumption above the best fit line will be higher during lockdown. Both dwellings are showing a small increase in proportion of total heating above the best fit line during lockdown (from 63% to 65% in ZP2 and from 61% to 62% in ZP3). This slight increase is, however, not considered high enough to suggest that there is a significant increase in heating in these dwellings as a result of lockdown. As it is the end of the heating season, the number of instances assessed was limited. It is also possible that the warmer than average temperatures had an impact on space heating results (daily measured average 2.3 °C above CIBSE test reference year data for LEEDS—closest location).

7.6 Discussion

The analysis of the Zero Plus dwellings has shown that batteries are 'smart' devices that are helpful in shifting the renewable energy or overnight (off-peak) grid charging to peak demand times in dwellings. As the batteries were able to double the SC of the PV systems and the combined PV and battery combinations were able to reduce average peak load by at least 95%, this technology will undoubtedly help the UK government meet its goals to develop a *smart energy system* and reduce peak electricity demand pressure on the electricity grid. Under several different scenarios, adding storage to the energy system in combination with decarbonisation efforts is considered to increase overall efficiency and resilience in the system (DECC, 2015).

As was demonstrated, based on demand, ZP3 may benefit from an Economy 7 tariff or a dynamic pricing tariff as about 17% of their total HEC was through overnight battery charging. If these homes did not have PV but did have the large batteries, TOU tariffs would be an effective money-saving and peak load shifting option. DSR via appliance timing is perhaps more needed in homes without such large batteries. Future research to explore potential improvement of the dwellings' use of PV and battery storage would include demand side response (DSR) experimentation and evaluation. This is shifting the times when electricity is consumed to take further peak demand pressure off the grid. This can be done in response to a signal (DECC, 2015), perhaps through in-home energy monitoring devices or, as the technology has progressed, through smart phone application linked to smart metering. Obvious examples include timing laundry or dishwasher activation during peak PV generation times or overnight by setting timers on the appliances. If DSR through shifting energy consumption to overnight is recommended, Economy 7 tariff – referring to 7 h overnight where electricity is offered at a cheaper rate—is a potential incentive.

With the Covid-19 lockdown and its potential impact on a larger shift to working from home, generation and storage arrangements such as those exhibited through the case studies would be greatly beneficial. This is particularly true of PV, as there would be more energy consumption throughout the middle of the day particularly in the winter. Furthermore, as there is a recommendation to shift to electrified heating, PV and batteries would be even more relevant. Working from home contributing to greater instantaneous SC of PV generation would provide a greater return on investment. This is important now more than ever as there is no longer FiT for new PV installations. However, incentives are an effective policy tool. Storage will benefit the overall system and, therefore, should be rewarded for its impact (HM Government and Ofgem, 2017). Like the previous FiT for solar renewable technology, there should be a *peak demand shift tariff* that would incentivise PV (again), batteries or even well-managed DSR. This would pay householders a tiered tariff rate based on the proportion of electricity reduced during peak demand hours. The progress could be judged based on a baseline year for the household and paid on a monthly basis. This example, however, would only work for retrofits. For newly built dwellings, the baseline would likely need to be a local-, perhaps, postcode-level average from which to base improved performance.

7.7 Conclusion

To meet the UK's net zero greenhouse gas emissions target and reduce peak demand pressure from the electricity grid as electrification of heating becomes a more prominent solution to reduced emissions, the combination of electricity generation and storage is shown to be smart and resilient solutions. Though the case study dwellings appear to be typical in their peak-time consumption, the PV and battery combination has been shown to reduce their average direct grid consumption during peak hours by over 95%. Because the PV system on each dwelling is large, instantaneous SC was low, between 20% and 30%, but the batteries helped to increase SC up to around 50%. The estimated cost benefit of this ranged from annual savings of between £260 and £438. Overall, with respect to the distributed energy resources installed, the dwellings resulted in 80% reduction in net total energy consumption during 4 months of the year. The demonstrated systems show benefits for householders through a net reduction of total energy consumption and benefits for the overall energy system through a reduction in peak energy demand.

Another aspect of the study briefly looked at the impact of the Covid-19 lockdown on energy consumption in the dwellings. Though the occupants in two of the dwellings claimed to 'always be at home', there was a slight increase in electricity consumption for the two of them and a notable increase in the other. Space heating consumption did not reflect the same impact; however, it did show poor seasonal responsiveness at times. Such empirical studies are vital for providing the learning that is necessary for future scalability and replicability of distributed energy resources to move towards a smart and flexible energy system in the UK. Future research could explore the extent and magnitude of demand side response (DSR) that could be offered by PV systems and smart batteries, with and without time-of-use tariffs.

Acknowledgement The research study is part of the Zero Plus research project, which has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No. 678407.

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