Use of Storage and Renewable Electricity Generation to Reduce Domestic and Transport Carbon Emissions—Whole Life Energy, Carbon and Cost Analysis of Single Dwelling Case Study (UK)

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1. Introduction

The IPCC investigated the relationship between likely atmospheric CO_2 by the year 2100 and the resulting climate change. The report found that the likelihood of staying below a 1.5 °C temperature increase in the 21st century (relative to 1850–1900) was more unlikely than likely even if atmospheric CO_2 did not exceed 450 ppm CO_2 by 2100 (Intergovernmental Panel on Climate Change 2014). The case for reducing our atmospheric carbon emissions is clear.

Globally, transport and building energy use are both major causes of CO_2 emissions. Focusing on the UK, direct carbon emissions from homes were 64 MT CO_2 in 2017 (Climate Change Committee 2019a), while UK road transport emissions were 118 MT CO_2, representing a 6% increase since 1990 (Office for National Statistics 2019).

Net-zero energy buildings have been established as an aim globally, at the European level and in the UK (World Green Building Council n.d.; European Parliament 2010; Government Property Agency 2020). In the UK, battery storage (including electric vehicle charging) has potential to reduce the need to upgrade local electricity grids and enable greater deployment of renewable electricity generation.

2. Literature Review

The UK (Climate Change Committee 2019b) has acknowledged that large-scale onshore wind, offshore wind and solar PV are now the cheapest forms of electricity generation in the UK and expects their contribution to UK electricity to rise to 50–65% by 2030 and potentially even higher afterwards. This will be needed to reduce the UK grid electricity carbon intensity to 100 g CO_2/kWh by 2030, then even further to 10 g CO_2/kWh by 2050. However, this level of penetration requires additional energy storage infrastructure to (1) make best use of renewable generation, (2) ensure that peak demand continues to be met and (3) bring electricity system costs down. Currently, the UK has the equivalent of 3 GW of pumped hydro storage, but only 0.4 GW of battery devices.

In the UK, the important role of storage is presented in the recent Heat and Buildings Strategy (HM Government 2021). Previously, it was not specifically considered, but there have been references to "enabling smart homes" and commitments to introducing time of use tariffs and creating an opportunity for domestic demand load shifting (HM Government 2017) which support the implementation of domestic storage. Although battery storage is eligible for an interest-free loan in Scotland (Home and Energy Scotland n.d.), there are currently no nationwide domestic energy storage incentives (Zakeri et al. 2021).

2.1. Benefits and Financial Viability of Domestic Energy Storage

Recent academic analysis of domestic energy storage has focused on its benefits to the electricity grid and its financial viability. The benefits of domestic energy storage paired with on-site renewable energy generation include the following:

- Enables load management/load shifting (Sheha and Powell 2018);
- Peak load management (Jankowiak et al. 2020; Koskela et al. 2019; Gardiner et al. 2020);
- Balancing grid frequency (Gardiner et al. 2020);
- Reduced grid import/export (Zakeri et al. 2021; Jankowiak et al. 2020; Dong et al. 2020);
- Reduced consumption from the electricity grid (Jankowiak et al. 2020);
- Improves electricity self-consumption and self-sufficiency (Jankowiak et al. 2020; Koskela et al. 2019; Gardiner et al. 2020; Dong et al. 2020).

On a community scale, storage can improve the voltage quality of the local distribution grid and is a cheaper alternative to distribution and transmission network expansion (Dong et al. 2020). However, domestic battery storage is commercially unviable—this has been tested across a wide range of markets (Zakeri et al. 2021; Sheha and Powell 2018; Gardiner et al. 2020; Dong et al. 2020). This explains why the rate of storage with PV is still very low (Zakeri et al. 2021). Although there are many benefits to increased domestic energy storage (Zakeri et al. 2021; Jankowiak et al. 2020; Koskela et al. 2019; Gardiner et al. 2020; Dong et al. 2020), there is a gap in the linkages and markets which would enable the prosumer to gain financially from providing these benefits (Gardiner et al. 2020).

Fewer studies are available on the environmental impact of energy storage systems. (Üçtuğ and Azapagic 2018) analysed a system in Turkey and found that it generates 4.7–8 times more energy than it consumes while having a 1.6–82.6-fold lower impact than grid electricity. It has been found that community installations require less battery capacity than individual installations (Dong et al. 2020; Mair et al. 2021); this shows that embodied carbon of battery storage could be reduced significantly if implemented on a larger scale than single dwellings.

2.2. Policy

California and Germany are making headway in encouraging domestic energy storage. California offers a USD 400/kWh subsidy and a 30% tax credit—despite this, adoption has been low until recently (Gardiner et al. 2020). Germany's success is attributed to subsidies and low-cost loans (Gardiner et al. 2020; Uddin et al. 2017). Australia has little policy support, but increasing electricity prices are driving a surge in domestic battery storage (Gardiner et al. 2020).

A range of policy options have been analysed for the UK (Zakeri et al. 2021; Jankowiak et al. 2020; Gardiner et al. 2020). These include the following:

- Arbitrage (import electricity at a low price and export at a higher price)—This relies on dynamic purchase and export tariffs. Although time of use tariffs exist for purchase, domestic export tariffs are fixed. Even though this improves the financial case for storage, it does not make it profitable unless a policy is implemented to widen the price gap of off-peak and peak hours (Zakeri et al. 2021). Although storage capacity needs to be retained for PV-generated electricity (reducing arbitrage availability), this does not have an operational cost and thus is only a disadvantage if it displaces grid electricity at a negative purchase price.
- Peak shaving tariff—Remuneration of GBP 0.24/kWh of peak shaved would improve profitability of battery storage and incentivise prosumers to purchase a larger battery and operate it in a way that benefits the electricity grid (Jankowiak et al. 2020). Enabling monetisation of a peak shaving service is also supported by (Gardiner et al. 2020).
- Capital subsidy—A 30% capital subsidy would make storage break even assuming a time of use tariff is used; otherwise, a 50–60% subsidy would be required (Zakeri et al. 2021). Another analysis of subsidy found that GBP 2660 was required to support the purchase of a 4 kWh battery along with a 4 kW PV system—this is significantly more than most international programmes (Gardiner et al. 2020).

- Storage tariff—This could be used to reward owners for electricity discharged at peak times. The current electric vehicle subsidy could be repositioned to only support vehicles with vehicle-to-grid capability (Zakeri et al. 2021).
- VAT reduction to 5% for retrofit installation only has a modest impact on the investment case (Gardiner et al. 2020).

There is a consensus that policies which monetise multiple services outperform subsidies, and that battery owners need to be rewarded for the benefits they provide to the electricity grid (Gardiner et al. 2020).

2.3. Research Gap

There is a lack of information and supporting data which can be used to inform prosumers on the energy and carbon payback of their potential investment in PV renewable energy generation and energy storage. This study addresses this by analysing the financial, energy and carbon payback based on a single dwelling case study.

3. Methodology

The key components to the methodology are as follows:

- Description of the case study including capital cost (Section 3.1);
- Calculation of embodied energy and carbon of the case study (Section 3.2);
- Calculation of expected energy, carbon and financial payback of the case study before installation (Section 3.3);
- Process to analyse embodied energy, embodied carbon and financial payback (Section 3.4).

3.1. Case Study Description

The dwelling is a split-level detached house in South Wales (UK) which was built in 2006. In November 2013, it received an EPC rating of C (78 points), with a recommendation that it could achieve an EPC rating of B (84 points) if 2.5 kWp of PV was installed.

On 30 July 2014, a 3.6 kWp vertical, monocrystalline, 2-string PV array with an SMA 3600 TL single-phase inverter and a Sunny web unit was commissioned. The south gable façade was chosen for PV installation as plans for an attic conversion were being considered. As the PV system was at street level, it incorporated matt glass to reduce potential reflection nuisance to neighbours, and it was shaped to maximise the space in the peak of the gable. These factors resulted in a higher cost

(GBP 10,610 including 5% VAT) than that of a roof-mounted system. The system has a PV orientation within 5° of south, vertical inclination and a shading factor of 95% (due to potential shading from nearby trees in winter) and was based on the MCS irradiance dataset of 668 kWh/kWp.

In 2019, the decision was made to purchase an electric vehicle, and thus increased renewable generation was planned. As the vehicle was likely to be off site during the day, energy storage was also planned.

On 28 April 2020, a Tesla Powerwall 2 AC with Gateway 2 was installed in an attached garage. This provides 13.5 kWh of storage with a 10-year warranty for 80% of the capacity at a cost of GBP 8040.

On 16 May 2020, a 6.12 kWp monocrystalline PV array with a Solar Edge HD 4 kW inverter and optimisers was commissioned. The west-facing roof was chosen for PV installation as the east roof suffered from shading in the morning. Initially, a 6.8 kWp system had been specified; however, Western Power set an export limit of 5.18 kW (including the existing façade PV system) and reduced the roof PV array to 6.12 kWp despite the inclusion of the Powerwall and optimisers which could be used to control the export. The system cost GBP 7803 including 5% VAT and warranty for the inverter. The system has a PV orientation within 5° of west, 35° inclination and a shading factor of 1 and was based on an irradiance dataset of 778 kWh/kWp.

The electric vehicle (EV) arrived on 11 September 2020 having been significantly delayed by restrictions related to the COVID-19 pandemic. The vehicle cost GBP 29,710 including 20% VAT and after deducting the GBP 2500 UK government plug-in grant. In addition, a Zappi charger was purchased to enable home charging and make use of potential excess from the PV electricity generation. The Zappi charger cost GBP 1219 including 20% VAT and after deducting the GBP 350 UK government Electric Vehicle Homecharge Scheme grant. The EV consumption is indicated as 270 Wh/mile (Electric Vehicle Database n.d.) which is equivalent to 167.8 Wh/km, 5.95 km/kWh or 3.7 mile/kWh. Although the UK government considers electric vehicles as having zero CO_2 emissions for vehicle tax purposes, there will be CO_2 emissions from the electricity unless the car is entirely charged from renewable sources. Assuming the 2018 annual average electricity carbon intensity of 260.25 g CO_2/kWh (Electricity Info n.d.), this results in EV emissions of 43.9 g CO_2/km. This is expected to decrease as electricity carbon intensity reduces in line with future targets (Energy UK 2016). The electric vehicle replaced a diesel car with published emissions of 109 g CO_2/km (Vehicle Certification Agency n.d.). However, the diesel car performance over a 10-year period proved to be 125.8 g CO_2/km based on actual fuel efficiency.

3.2. *Embodied Energy and Carbon*

Embodied energy and carbon data were sought for PV and storage and then applied to the case study.

3.2.1. Photovoltaics

There is a range of embodied energy and carbon data available for renewable energy generation and storage technologies (Reddaway 2016; Circular Ecology n.d.; Finnegan et al. 2018; Ito et al. 2011; Kristjansdottir et al. 2016; Feng and van den Bergh 2020; Wong et al. 2016; Kurland 2019; Hausfather 2019), but the data must be treated with care as they often relate to different materials, locations, assumed service life, balance of system, year of analysis, functional units, analysis approach and analysis boundaries.

Over the period 1998–2014, the embodied energy of monocrystalline (m-Si) PV modules was found to range between 2397 and 11,673 MJ/m^2, while polycrystalline (p-Si) PV modules ranged between 2699 and 5150 MJ/m^2 (Ito et al. 2011; Wong et al. 2016). The data are more stable over the period 2009–2014 and averaging these data returns values of 3597 MJ/m^2 for m-Si and 2848 MJ/m^2 for p-Si. More recent data for a fully installed PV system in Australia show values of 4185 kWh/kWp for m-Si and 3708 kWh/kWp for p-Si (Reddaway 2016). Although polycrystalline PV (as a byproduct) has a lower embodied energy than monocrystalline PV, it also has a lower efficiency (13.9% vs. 14.3%) Ito et al. 2011, meaning monocrystalline PV is often chosen for dwellings (as in this case study) because it is more space efficient.

Over the period 2011 to 2016, embodied carbon of monocrystalline (m-Si) PV was found to range between 150 and 300 kg CO_2/m^2 (Finnegan et al. 2018; Ito et al. 2011; Kristjansdottir et al. 2016). Additional 2016 data show values of 2560 kg CO_2/kWp for m-Si (Circular Ecology n.d.). Feng analysed the CO_2 emissions of a range of PV module types manufactured in China, the EU and the USA and found that the carbon intensity of the electricity in the country was the dominating factor, resulting in EU production having the lowest embodied carbon, followed by that of the USA and then China (Feng and van den Bergh 2020).

Analysis of embodied energy of PV systems in Norway (Kristjansdottir et al. 2016) and Australia (Reddaway 2016) indicated that panel manufacturing accounts for over 80% of emissions, with the next highest impact being from the inverter.

3.2.2. Lithium Batteries

In the UK, 2020 saw 108,205 battery electric vehicles sold, representing a 180% rise on the previous year (Attwood 2021). This represents a significant increase in lithium-ion battery production. Already 10% of Tesla's batteries get reused, while 60% get recycled (Forfar 2018), and stationary power storage applications are seen as a valuable use of second-life batteries (Engel et al. 2019). Stationary power storage requires a lower current density than EVs, meaning it can use batteries with 80–85% of their original capacity (Pagliaro and Meneguzzo 2019). Nissan and Renault have partnered with organisations to reuse battery packs (Engel et al. 2019), while Tesla already has a stationary power storage product—the Powerwall.

Kurland's analysis of energy use in lithium-ion battery production indicated significant improvements from 2014 (163 kWh/kWhc) to 2019 (50–65 kWh/kWhc). Key factors include the following:

- Increased scale, although this did not seem to have an impact after increasing the size of the facilities with an annual capacity above 2 GWh;
- All electricity production in comparison to utilising steam from fossil fuels;
- For Tesla and Northvolt Ett, embodied carbon has reduced due to the use of renewable electricity (Kurland 2019).

The importance of the grid carbon intensity was also reflected in Hausfather's analysis of lifecycle carbon emissions of EV batteries, which found that US- or Europe-sourced batteries had approximately 20% lower lifecycle emissions than Asia-sourced batteries. This was attributed to the widespread use of coal for electricity generation in Asia (Hausfather 2019). Lifecycle carbon emissions of batteries analysed between 2017 and 2019 ranged between 61 and 106 kg CO_2/kWh, with an average of 100 kg CO_2/kWh (Hausfather 2019).

3.2.3. Embodied Energy and Carbon Data Applied to Case Study

Due to embodied energy and carbon data from the literature being based on different functional units, these are now considered in relation to the case study elements to allow comparison. Embodied energy data are shown in Table 1, with the calculated results for both PV systems and storage presented in kWh for comparison. Similarly, embodied carbon data are shown in Table 2, with the calculated results presented in kg CO_2 for comparison.

Table 1. Embodied energy data calculated for façade PV system, roof PV system and battery.

Element/Functional Unit		PV System—Austral 2016 4185 kWh/kWp	PV Modules + Inverter—Japan 2011 3986 MJ/m^2	PV Modules Ave 2009–2014 3597 MJ/m^2	Tesla Battery (Large Scale 2019) 57.5 kWh/kWc
Roof PV	6.12 kWp	25,612 kWh [1]	-	-	-
	32.5 m^2	-	36,664 kWh	32,514 kWh	-
Roof inverter	4 kWp	-		-	-
façade PV	3.6 kWp	15,066 kWh [1]	-	-	-
Tesla Powerwall	13.5 kWh	-	-	-	776 kWh

[1] Data used in calculations. Source: Table by author, adapted from Reddaway (2016); Ito et al. (2011); Wong et al. (2016); Kurland (2019).

Table 2. Embodied carbon data calculated for façade PV system, roof PV system and battery.

Element/Functional Unit		UK Panels 2560 kg CO_2/kWp	PV Modules Ave 2011–2016 225 kg CO_2/m^2	Battery—Large Scale 2019 100 kg CO_2/kWh
Roof PV	6.12 kWp	15,667 kg CO_2 [1]	-	-
	32.5 m^2	-	7322 kg CO_2	-
Roof inverter	4 kWp	-	-	-
façade PV	3.6 kWp	9216 kg CO_2 [1]	-	-
Tesla Powerwall	13.5 kWh	-	-	1350 kg CO_2 [1]

[1] Data used in calculations. Source: Table by author, adapted from Circular Ecology (n.d.); Finnegan et al. (2018); Ito et al. (2011); Kristjansdottir et al. (2016); Hausfather (2019).

As an accurate area measurement is not available for the façade PV system, the only embodied energy data which can be used for both case study PV arrays are from the Australian PV system. It is acknowledged that this is possibly an underestimate of the total embodied energy for the PV system.

The embodied carbon data, which are available for both PV arrays, are based on UK panels and are significantly higher than the alternative data. Given the potential assumption differences between embodied energy and carbon data, this variance was accepted as inevitable, and the higher embodied carbon value was used for further calculations in this paper.

The embodied energy and carbon data for the Powerwall were considered to be the most appropriate estimates from the data available and were used for further calculations in this paper.

3.3. *Expected Energy, Carbon and Financial Payback before Installation*

Data provided before installation were used to calculate a simplified energy carbon and financial payback.

3.3.1. Façade PV

Based on the installer information, the system was expected to produce 2295 kWh annually. To pay back the 15,066 kWh embodied energy (Table 1) would take 6.56 years.

The carbon intensity of the UK grid electricity in 2013 (European Environment Agency 2020) was 467 g CO_2e/kWh. To pay back the 9216 kg CO_2 embodied carbon (Table 2) based on the predicted energy generation would take 8.6 years.

The PV system was registered for the UK Government Feed in Tariff (FiT) scheme. This paid 14.9 p/kWh with an assumed 50% export qualifying for an additional 5.5 p/kWh. Based on installer information, the PV system was anticipated to make an annual electricity cost saving of GBP 359.09, with an annual FiT contribution of GBP 627.39 (total GBP 986 per year), leading to a payback of the GBP 10,610 cost over 10.75 years.

3.3.2. Roof PV

The system was expected to produce 4761 kWh annually. To pay back the 25,612kWh embodied energy (Table 1) would take 5.37 years.

The carbon intensity of the UK grid electricity in 2019 (European Environment Agency 2020) was 228 g CO_2e/kWh. To pay back the 15,667 kg CO_2 embodied carbon (Table 2) based on the predicted energy generation would take 14.43 years.

The PV system was assumed to save GBP 675 in electricity costs with an additional GBP 145 in export sales, leading to a financial payback time of 9.5 years. However, it was not cost effective to take an export tariff for the roof PV system instead of the FiT scheme for the façade PV system, meaning the financial payback time increased to 11.56 years.

3.3.3. Tesla Powerwall

It is more complex to calculate the energy, carbon and financial payback for the Tesla Powerwall as more factors are involved.

The first factor in the financial payback for the Tesla Powerwall is the electricity tariff used. The tariffs considered were as follows:

- Bulb standard tariff (from Bulb energy statement of 30 June 2020)—14.35 p/kWh
- Bulb EV tariff (Bulb n.d.):
    - 00:00–07:59 9.03 p/kWh (off peak)
    - 08:00–16:59 and 20:00–23:50 13.53 p/kWh (standard)
    - 17:00–18:59 30.22 p/kWh (peak)
- Octopus Go (from Octopus energy statement of 6 July 2020):
    - 00:30–04:29 5.00 p/kWh (off peak)
    - 04:30–00:29 14.02 p/kWh (standard)
- Octopus Agile (Energy-Stats n.d.):
    - Tracking tariff which varies at half-hourly intervals depending on the predicted combination of supply and demand, published at 17:00 the day before use;
    - Initial analysis of diurnal electricity cost trends (Figure 1) indicated that the period 16:00–18:59 had a significantly higher tariff than the rest of the day, with a slightly cheaper period of 01:00–04:49. Averaging costs for these periods over the year resulted in a mean Agile tariff of:
        - 16:00–18:59 23.00 p/kWh (peak)
        - 19:00–15:59 7.00 p/kWh (standard)

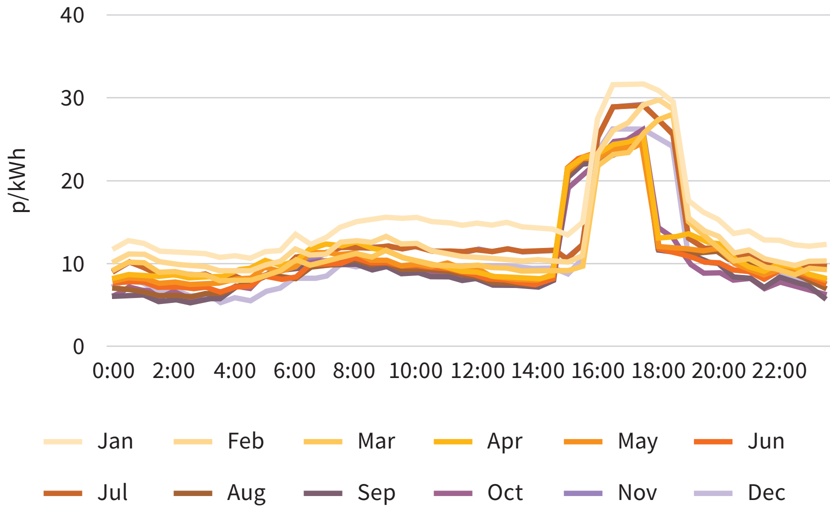

Figure 1. Half-hourly costs for Octopus Agile tariff 2019. Source: Graphic by author.

It was assumed that no grid electricity would be required in the period 16:00–18:59 to avoid the most expensive periods, but that the Powerwall could charge at any other time of day. Electricity consumption was based on actual consumption data from 1 January to 31 December 2019. Energy consumption for the planned EV was assumed to be 42.6 kWh per week for 48 weeks (allowing 4 weeks in the year without significant commuting). It was assumed that the EV would charge during the off-peak period. These assumptions resulted in an assumed consumption for 2019 of:

- Peak electricity 1834.53 kWh
- Standard electricity 10,225.76 kWh
- Off-peak electricity 4708.76 kWh (2044.8 kWh for EV)

Table 3 indicates the 2019 electricity cost for the following:

- Each tariff;
- The potential saving over the Bulb standard tariff;
- The cost saving of using a Powerwall via load shifting from grid (and financial payback in years).

Table 3. Electricity tariff options and financial benefit for load shifting.

Tariff	Octopus Go	Octopus Agile	Bulb EV	Bulb Standard
2019 electricity cost (GBP)	2017.54	1544.01	2437.75	2477.42
Saving vs. Bulb standard (GBP)	459.88	933.42	39.68	-
Powerwall load shifting saving (GBP)	165.47	293.52	388.74	-
Powerwall load shifting payback (y)	48.6	27.4	20.7	-

Source: Table from author, adapted from Bulb energy statement of 30 June 2020; Bulb (n.d.); Octopus energy statement of 6th July 2020; Energy-Stats (n.d.).

On its own, load shifting to avoid peak costs does not justify the financial cost of a Powerwall. However, in 2019, 172.571 kWh of PV energy was exported to the grid from the gable PV system, and with the planned installation of an additional PV system, the likely export of PV (or throttling of generation) could be mitigated by using the Powerwall.

The embodied energy of the Tesla Powerwall is 776 kWh (Table 1), while the embodied carbon is 1350 kg CO_2 (Table 2). Insufficient data were available to enable calculation of energy and carbon payback at this stage.

3.4. Process to Analyse Embodied Energy, Embodied Carbon and Financial Payback of the Case Study

Payback is calculated for each of the elements in relation to energy, carbon and capital cost:

Energy payback (years) = Embodied Energy/Annual Energy Generation[1]

Carbon payback (years) = Embodied Carbon/Annual CO_2 savings

Financial payback (years) = Capital Cost/Annual financial benefit

The embodied energy, embodied carbon and capital cost have already been presented in Sections 3.1 and 3.2.

Annual energy generation was obtained through monitoring (Section 3.4.1) up until December 2020. Beyond this, the performance was based on the period July–December 2020 (justified in Section 4.1.2).

Annual CO_2 savings were derived from monitored energy generation and analysis of existing UK electricity grid carbon intensity data (Section 3.4.2) and predicted grid carbon intensity (Section 4.2.2). This includes the capability of the Powerwall to store off-peak low-carbon electricity to use at higher carbon periods. For the EV, the CO_2 savings are based on the reduction in carbon emissions in comparison to the diesel car it replaced (Section 4.4).

Annual financial benefit was derived from monitored energy generation and electricity tariff, FiT and export payments (Section 4.3.1).

3.4.1. Monitoring

The monitoring options for each element of the renewable generation and storage system are discussed in the following paragraphs, summarised in Table 4 and illustrated in Figure 2.

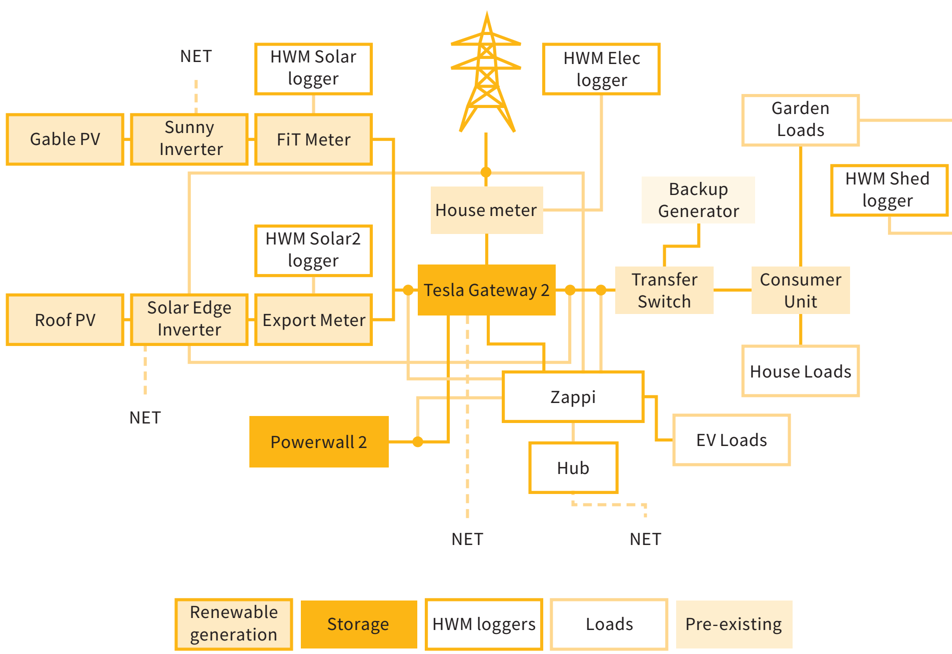

Figure 2. Schematic of equipment for monitoring renewable generation and storage. Source: Graphic by author.

Table 4. Summary of monitoring equipment.

Monitor	Data	Source	Start Date/Time Zone	Interval	Accuracy
Car dashboard	EV efficiency and distance travelled [2]	EV	11 September 2020 n/a	Manual	-
Export meter	Roof PV generation	Wired between inverter and incoming grid	16 May 2020 n/a	Manual	Schedule 7: Electricity Act 1989
FiT meter	Façade PV generation	Wired between inverter and incoming grid	30 July 2014 n/a	Manual	Schedule 7: Electricity Act 1989
HWM Sarn Solar [1]	Façade PV generation	Pulse counter on FiT meter	19 December 2014 BST/GMT	15 min	1 pulse/Wh
HWM Sarn Solar 2 [1]	Roof PV generation	Pulse counter on export meter	17 May 2020 BST/GMT	15 min	1 pulse/Wh
Solaredge.com	Roof PV generation [2] Grid import Grid export	Solar Edge inverter Current clamp below Gateway 2	16 May 2020 BST/GMT	15 min	1% var vs. Utility bill
Sunnyportal.com	Façade PV generation [2]	Sunny inverter	30 July 2014 BST/GMT	60 min	-
Tesla app	Total PV generation Powerwall import [2] Powerwall export [2] Grid import Grid export	Tesla Gateway 2 and current clamp below Gateway 2	29 April 2020 BST/GMT	5 min	1% var vs. Utility bill
Utility billing data	Grid import [2]	House electricity meter	24 May–19 October 2020	30 min	Schedule 7: Electricity Act 1989

[1] Equipment loaned by HWM-Water Ltd., Wales, UK; [2] Data used for monitoring. Source: Table by author.

Façade PV—Energy Generation

The Feed in Tariff export meter meets the requirements of Schedule 7 of the Electricity Act 1989; however, only manual readings can be taken from it. The Sunny web unit transmits data directly from the inverter to Sunnyportal.com, which are recorded at hourly intervals. Unfortunately, a data service change resulted in lost data in 2018. The HWM "Sarn Solar" logger was installed in December 2014 and records data at 15 min intervals. Unfortunately, this suffered some data loss in 2016 and 2017. In years with no apparent data loss, the HWM "Sarn Solar" logged electricity generation figures 95.3–97.7% of those logged by Sunnyportal.com. Sunnyportal.com was used as the primary source of data for the façade PV system. HWM "Sarn Solar" was used for the periods of data loss by Sunnyportal.com.

Roof PV—Energy Generation

The export meter meets the requirements of Schedule 7 of the Electricity Act 1989; however, only manual readings can be taken from it. Data are transmitted directly from the inverter to monitoring.solaredge.com and recorded at 15 min intervals. The HWM Sarn Solar 2 logger is battery operated and suffered from some data loss in September 2020. Prior to this (17 May–31 August 2020), the HWM Sarn Solar 2 and solaredge data were within 1% of each other. As electricity generation reduced in October–December 2020, the discrepancy increased to 2–3%. Solaredge was used as the primary source of data for the roof PV system.

Total PV—Energy Generation

A current clamp on cables between the utility meter and Gateway 2 transmits data to the Tesla app, which are recorded at 5 min intervals.

Electricity Import to Site for Electricity Stored by Powerwall and EV

The utility meter meets the requirements of Schedule 7 of the Electricity Act 1989, with half-hourly data available from 24 May 2020 until 19 October 2020. However, no data after that date have been published.

Data from a current clamp on cables between the utility meter and Gateway 2 are available at 15 min intervals via monitoring.solaredge.com. Over the period 24 May to 19 October, solaredge and the average daily utility data were within 1% of each other.

Data from a separate current clamp on cables between the utility meter and Gateway 2 are available at 5 min intervals via the Tesla app. Over the period 24

May–19 October, the Tesla app and the average daily utility data were within 1% of each other.

Utility billing data were used as the primary source of data for electricity import to the site. When utility billing data were not available, the Tesla data were averaged to half-hourly intervals and used.

To Powerwall/From Powerwall—Electricity Stored by Powerwall

The electricity directed to and from the Powerwall is available at 5 min intervals via the Tesla app.

EV Efficiency and Distance Travelled

Electric vehicle efficiency and distance travelled data were read manually from the car dashboard at monthly intervals.

The monitoring options are summarised in Table 4, and their relationship to the case study is illustrated in Figure 2.

Figure 2 illustrates the relationship of the monitoring equipment to the house, renewable generation and storage infrastructure.

3.4.2. UK Electricity Grid Carbon Intensity Data

The UK electricity grid carbon intensity was required to calculate the carbon payback. High-resolution (half-hourly) data were required for the Powerwall analysis. There are different sources of UK grid carbon intensity data depending on the time period and resolution required. These are explained below and presented in Tables 5 and 6 and Figure 3.

Average annual data for 1990–2019 are available from the (European Environment Agency 2020). Data for 2014–2019 are presented in Table 5. The progress in decarbonising the UK grid electricity is clear from these data.

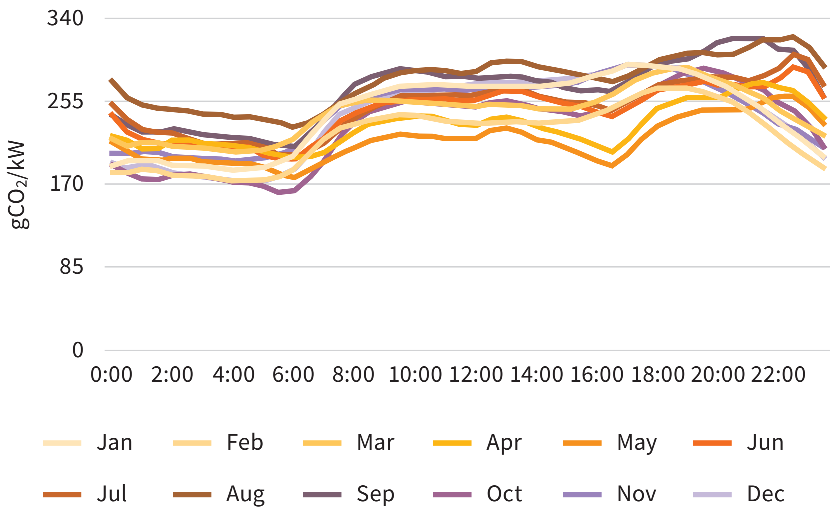

Figure 3. Monthly averaged UK grid electricity carbon intensity 2020 (half-hourly data). Source: Graphic by author.

Table 5. Average annual carbon intensity data for UK grid: 2014–2018.

Year	UK Electricity Generation g CO_2e/kWh
2013	467
2014	425
2015	380
2016	294
2017	264
2018	250
2019	228

Source: Table by author, adapted from European Environment Agency (2020).

Daily carbon intensity data from 12 September 2017 (Electricity Info n.d.) can be used to produce monthly average figures. Average monthly data since January 2018 are shown in Table 6. The average annual data for 2018 and 2019 are observed to approximate to the annual data in Table 5. The year 2020 saw a significant drop in the industrial and service sectors' electricity consumption compared to previous years. This reduced the requirement for carbon-intensive electricity generation (Department for Business, Energy & Industrial Strategy 2021).

Table 6. Average monthly carbon intensity data for UK grid: January 2018–March 2021.

Period	**Carbon Intensity of UK Electricity Supply g CO_2/kWh**			
	2018	**2019**	**2020**	**2021**
January	254	281	209	191
February	293	217	176	179
March	319	197	189	185
April	228	213	168	-
May	216	210	142	-
June	238	215	172	-
July	248	223	185	-
August	219	188	204	-
September	223	178	194	-
Octorber	234	202	162	-
November	261	240	177	-
December	390	202	185	-
Annual Average	**260**	**214**	**180**	-

Source: Table by author, adapted from Electricity Info (n.d.).

Half-hourly UK electric grid carbon intensity was calculated. Half-hourly power data detailing the various sources feeding the electricity grid (BMRS n.d.a.) were multiplied by the carbon intensity for each fuel type to calculate the half-hourly carbon emissions for the UK grid electricity. The mean carbon intensity for each fuel type (World Nuclear Association n.d.) is illustrated in Table 7 (Gridwatch n.d.). Finally, the half-hourly carbon emissions for the UK grid electricity were divided by the UK energy demand (BMRS n.d.b.) to obtain the carbon intensity per MW electricity.

Table 7. Mean carbon intensity of fuels used in UK electricity production.

Source	Tonnes CO_2e/GWh
Combined cycle gas turbine	499
Nuclear	29
Biomass	45
Coal	888
Wind	26
Solar	85
Oil	733
Open cycle gas turbine	499
Hydroelectric	26
Pumped hydro	415
Interconnector (import)	273
Other	273

Source: Table by author, adapted from World Nuclear Association (n.d.).

Half-hourly data averaged for each month of 2020 are shown in Figure 3. These data confirm that electricity consumed between approximately 00:30 and 06:00 has a lower carbon intensity than that consumed in the rest of the day.

4. Results

The energy, carbon and financial paybacks of the façade PV system, roof PV system, Tesla Powerwall and EV battery are considered in relation to actual performance since purchase.

4.1. Energy Payback

4.1.1. Façade PV

Up to 31 March 2021, the façade PV system generated 12,209.1 kWh. The average annual generation from 2015 to 2020 was 1881.9 kWh, approximately 18% lower than predicted. The monthly yield is illustrated in Figure 4.

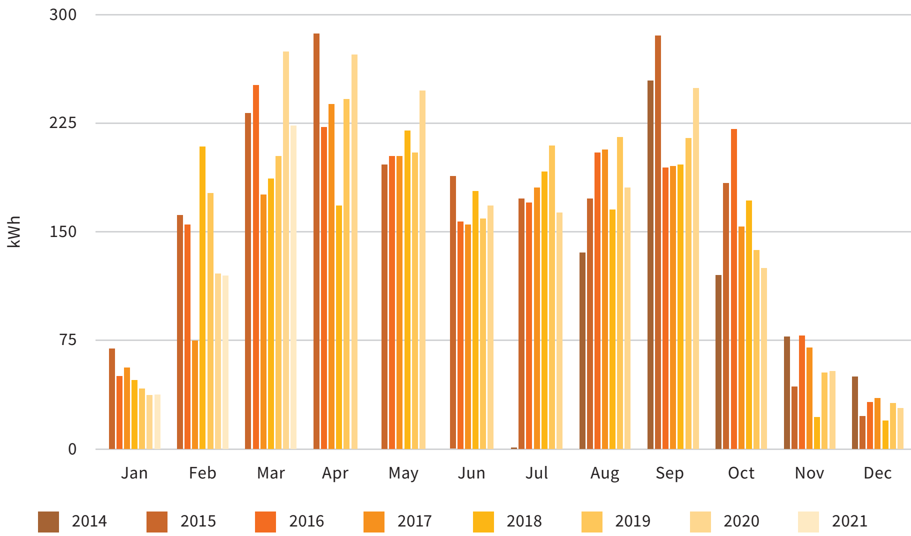

Figure 4. Monthly renewable energy generation of the façade PV system since installation in 2014. Source: Graphic by author.

Based on past energy generation trends, the façade PV system will achieve energy payback between August 2022 and March 2023 depending on weather conditions—at least 8 years to achieve energy payback. Even though this is slower than anticipated based on installer data, it is well within the expected service life of the PV system.

4.1.2. Roof PV

As of 31 March 2021, the roof PV system generated 4156.6 kWh of renewable electricity (illustrated in Figure 5). As the roof PV system was installed in May 2020, there was not a full year of renewable generation data to analyse. Instead, the period 22 June–21 December 2020, which represents a half year between the highest sun availability in summer to the lowest sun availability in winter, was analysed.

Referring to the renewable energy generation of the façade PV system for the period July–December (illustrated in Figure 4), the ranking (best to worst) was 2016, 2015, 2019, 2017, 2020 and then 2018. Table 8 presents the façade PV system's renewable energy generation annually and for the period July–December. For the full year, 2020 ranked third; therefore, the poor performance between July and December can be attributed to weather conditions rather than purely to the expected performance degradation of the façade PV system. As the July–December 2020 period ranks fifth since 2015, the data can be used to predict payback, without being unduly optimistic.

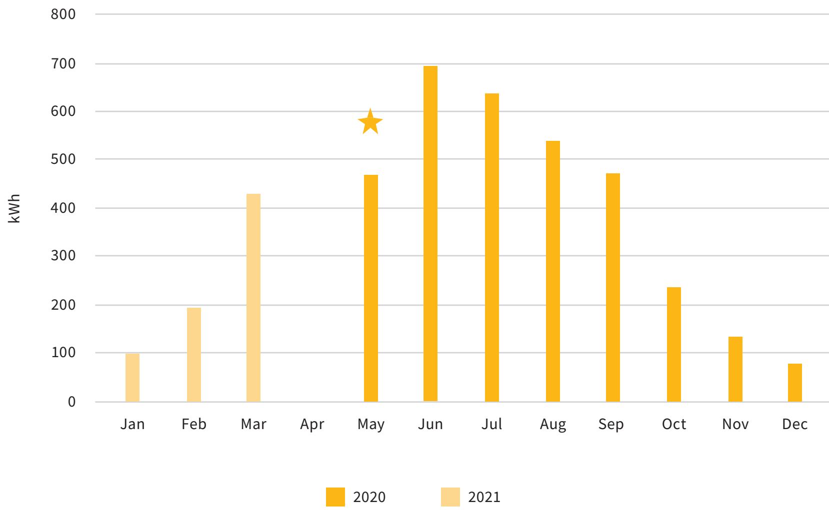

Figure 5. Monthly renewable energy generation of the roof PV system since installation in May 2020. NB: The star highlights that May 2020 data only represents 15 days. Source: Graphic by author.

Table 8. Renewable energy generation of façade PV system (annual and $\frac{1}{2}$ year from July to December).

Year	kWh/year	% Normalised to 2015	Ranking	kWh (½ year)	% Normalised to 2015	Ranking
2015	2021.57	100.0	1	883.58	100.0	2
2016	1945.47	96.2	2	904.05	102.3	1
2017	1751.35	86.6	6	845.44	95.7	4
2018	1752.78	86.7	5	739.57	83.7	6
2019	1893.87	93.7	4	864.57	97.8	3
2020	1926.39	95.3	3	803.49	90.9	5

Source: Table by author.

The roof PV system's generation from 22 June to 21 December 2020 was 2231.2 kWh. To pay back the 25,612 kWh embodied energy of the roof PV system would take 5.6 years. This is close to the expected figure of 5.37 years and well within its service life.

4.1.3. Tesla Powerwall

The energy payback of the Tesla Powerwall is dependent on its ability to capture renewable energy generated by the façade and roof PV systems which would otherwise have been exported or throttled.

There was not a full year of operational data to analyse, and thus the same half-year period as for the roof PV system was analysed. During this period, 21.44 kWh of renewable energy was captured which would otherwise have been exported/throttled (23.26 kWh for the full installation period until 31 March 2021). Based on this, we can assume 42.88 kWh would be captured over a year, resulting in an energy payback in 18.1 years. Although this is beyond the warranty period, the system may still be operating for that period of time. Energy attributed to the Powerwall was not attributed to the roof PV system in order to avoid double counting.

4.2. Carbon Payback

4.2.1. Façade PV

The annual UK electricity grid carbon intensity was taken from Table 5 (European Environment Agency 2020) for 2014–2017, as more detailed data could not be found for this period. For 2018–2021, the monthly data shown in Table 6 (Electricity Info n.d.) were used.

A total of 3.24 tonnes of CO_2 emissions has been avoided by the façade PV system since installation in 2014. The annual CO_2 saving has varied from 768.2 kg CO_2e in 2015 (which combined the highest UK electricity grid carbon intensity with the highest electricity generation) down to 342.2 kg CO_2e in 2020, which had the second highest electricity generation since installation but the lowest electricity grid carbon intensity (as illustrated in Figure 6).

A projection of the future carbon payback based on average energy generation thus far, in combination with an assumed linear progression of the UK grid electricity to 100 g CO_2/kWh by 2030, and then to 10 g CO_2/kWh by 2050, is illustrated in Figure 7. Following this trend, it will take until 2126 to reach a carbon payback of 9216 kg CO_2. This significantly exceeds the expected service life.

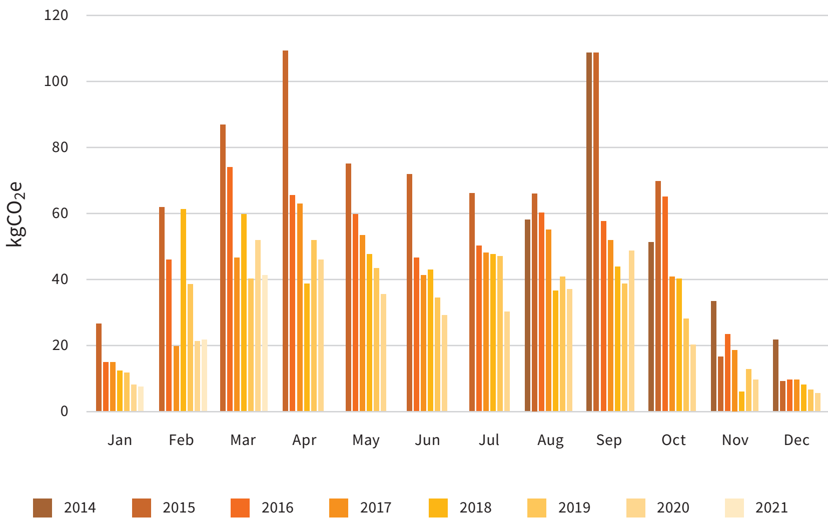

Figure 6. Monthly CO_2 emissions avoided (kg CO_2e) by the façade PV system since installation in 2014. Source: Graphic by author.

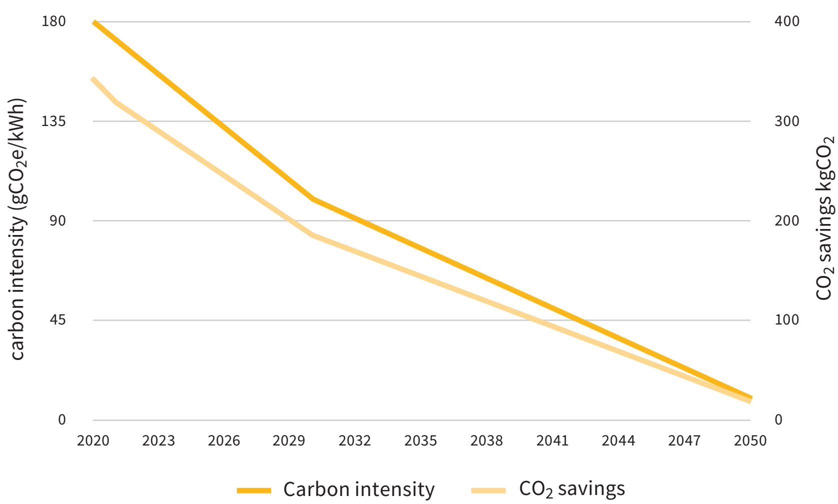

Figure 7. Projected UK electricity grid carbon intensity and annual façade PV system carbon savings until 2050. Source: Graphic by author.

4.2.2. Roof PV

The monthly UK electricity grid carbon intensity was taken from Table 6 (Electricity Info n.d.). The CO_2 emissions avoided by the roof PV system since installation equal 0.71 tonnes CO_2e.

Using the projection of the UK grid carbon intensity illustrated in Figure 7, and assuming annual renewable energy generation by the roof PV system of 4562.4 kWh, it will take until 2036 to reach a carbon payback of 9216 kg CO_2. The carbon payback period has been extended significantly due to sharing the CO_2 saving with the Tesla Powerwall in the first few years when the electricity carbon intensity is higher. Despite this, the roof PV system achieves carbon payback in its expected service lifetime.

4.2.3. Tesla Powerwall

The carbon payback of the Tesla Powerwall is dependent on two elements:

1. Its ability to capture renewable energy which exceeds the current demand of the site for use at another time;
2. Its ability to capture grid electricity with a low carbon intensity for use when grid electricity has a higher carbon intensity (load shifting).

By the end of March 2021, 332.5 kg of CO_2 emissions had been avoided by capturing renewable energy for use at another time. However, half of this is attributed to the roof PV system until the Powerwall's payback is achieved (to avoid double counting); thus, based on the half-year data, 211.85 kg of CO_2 emissions will be avoided annually. This indicates that a significant proportion of the renewable energy generated by the roof PV system is not used immediately. After the Powerwall's payback is achieved, the full CO_2 saving is applied to the roof PV system.

On days when significant renewable generation is expected from the façade and roof PV systems, storage of excess renewable energy should take priority over load shifting. However, from November to February, there is a significant drop in excess renewable energy generation, and load shifting can be utilised instead. The Powerwall has settings which allow it to selectively charge at off-peak times and use the stored energy to minimise grid import at peak times. Although these settings are based around electricity costs, the Octopus tariff's off-peak cost period (00:30–04:30) fits within the lower-carbon intensity period illustrated in Figure 3, while the peak period (16:00–19:00) is associated with a higher carbon intensity (Figure 3).

The carbon saving from load shifting is based on the difference between the average carbon intensity between 16:00 and 19:00 and the carbon intensity of the stored energy while allowing for energy loss between storage and return (referred to as round-trip energy efficiency). Table 9 indicates the monthly energy storage in the Powerwall, the resulting round-trip efficiency and the electricity source. Using the half-year data, the average round-trip efficiency was 90.2%. The round-trip efficiency would be lower for a Powerwall located in a colder place (e.g., outdoors).

Table 9. Energy stored in the Powerwall, round-trip efficiency and electricity source.

Date	From Powerwall (kWh)	Round-Trip Energy Efficiency (%)	Electricity Source
29 April–15 May 2020	11.6	30.1	Façade PV
16–25 May 2020	122.7	86.2	Façade PV + Roof PV
26 May–30 June 2020	492.6	91.1	Façade PV + Roof PV + Off-peak grid
July 2020	422.4	90.0	
August 2020	405.5	88.4	
September 2020	520.7	91.7	
October 2020	497.1	90.3	
November 2020	389.7	89.3	
December 2020	418.1	89.3	Façade PV + Roof PV + Off-peak grid (minimising peak rate import)
January 2021	415.9	89.1	
$\frac{1}{2}$ year (22 June–21 December 2020)	2567 [1]	90.2	-

[1] Data used for calculation. Source: Table by author.

By the end of March 2021, 157.2 kg of CO_2 emissions had been avoided by load shifting off-peak energy for use at another time. Based on the half-year data, 166.4 kg of CO_2 emissions will be avoided annually. However, care should be taken to avoid using load shifting at periods when there is less than a 10% difference in the carbon intensity of off-peak and peak electricity, as the carbon reduction benefit will be outweighed by the energy loss during storage and release.

Combining both elements of carbon saving from the Powerwall results in 378.3 kg CO_2e savings per year. Even allowing for the decreasing carbon intensity of grid electricity in the future, the carbon payback of the Powerwall will be achieved by 2025.

4.3. Financial Payback

4.3.1. Façade PV

There are three elements contributing to the financial payback of the façade PV system:

1. The FiT was 14.9 p/kWh at installation. Retained FiT statements show that the rate was 15.78 p/kWh in 2018, 16.2 p/kWh in 2019 and 16.56 p/kWh in 2020. The UK Retail Prices Index (RPI) (Office for National Statistics n.d.) was used to determine the approximate tariff for 2015–2017.
2. The export payment—5.5 p/kWh for an assumed 50% export.
3. Saving on electricity payments. Retained electricity bills show that the rate (excluding service charge) was as follows:

a.	September 2017–April 2018	12.45 p/kWh + 5% VAT
b.	May–June 2018	12.48 p/kWh + 5% VAT
c.	July–October 2018	13.62 p/kWh + 5% VAT
d.	October 2018–April 2020	13.63 p/kWh + 5% VAT
e.	May–October 2020	13.35 p/kWh + 5% VAT

Prior to 2017, electricity rates were derived based on the Consumer Price Index for electricity (Statista n.d.) relative to the 2017 tariff. At the time of calculation, no evidence could be found of an anticipated increase in electricity costs, meaning the average of 2015–2020 was used for future years.

Financial savings since installation total GBP 3719.38 (approximately GBP 598/year), and this equates to a payback period of 18 years. The expected payback was affected by the lower than expected energy generation. The proportional contributions are as follows: FiT 49.5%, export 8.7% and electricity cost savings 41.8%.

4.3.2. Roof PV

The only contribution to the financial payback of the roof PV system is the saving on electricity payments. Retained electricity bills show that the rate (excluding service charge) was 13.35 p/kWh + 5% VAT. Financial savings since installation total GBP 557.73. Based on the half-year data, the assumed annual renewable energy generation will be 4476 kWh. Relating this to the current electricity tariff, annual savings will be GBP 639.53; however, GBP 105.86 annually is attributed to the Powerwall, resulting in a financial payback of GBP 7803 within 15.4 years.

4.3.3. Tesla Powerwall

As with the carbon payback, the financial payback of the Tesla Powerwall is dependent on two elements:

1. Its ability to capture renewable energy which exceeds the current demand of the site for use at another time;
2. Its ability to capture grid electricity with a low cost (and carbon intensity) for use when grid electricity has a higher cost (and carbon intensity) known as "load shifting".

The renewable energy element of the cost saving is shared equally between the Powerwall and the roof PV system until the roof PV system's payback is achieved, whereon the full cost saving applies to the Powerwall. By the end of March 2021, a GBP 174.00 saving had been made based on storing the roof PV system's generation for later use. Based on the half-year period, the annual cost saving will be GBP 211.71, which will be equally shared between the Powerwall and the roof PV system.

The cost saving from load shifting is based on the Octopus Go tariff which has an off-peak period (00:30–04:30). Accounting for the average 9.8% energy loss during storage and return, the cost saving up to 31 March 2021 was GBP 192.27. Based on the half-year period, the annual cost saving will be GBP 296.29.

Combining both elements of the cost saving from the Powerwall results in GBP 402.15 savings per year, achieving a financial payback of GBP 8040 by 2039.

4.4. Electric Vehicle

The electric vehicle has a 35.5 kWh battery which has an embodied carbon value of 3550 kg CO_2 assuming 100 kg CO_2/kWh (Hausfather 2019).

The monthly distance travelled by the EV, along with average energy efficiency, electricity consumption and carbon emissions, for the period is presented in Table 10, along with a comparison of the carbon emissions which would have resulted from the replaced diesel vehicle (Figure 8).

Table 10. Electric vehicle monthly distance travelled, energy efficiency, electricity consumption and carbon emissions.

Month	Distance (km)	Energy Efficiency (km/kWh)	Electricity Consumption (kWh)	EV Carbon Emissions (kg CO_2) [1]	Diesel Carbon Emissions for Same Distance (kg CO_2)
October 2020	850	4.82	176.2	28.5	92.6
November 2020	1379	4.67	295.5	52.3	150.3
December 2020	1447	4.50	321.2	59.4	157.7
January 2021	780	4.34	179.4	34.3	85.0
February 2021	943	4.50	209.4	37.5	102.8
March 2021	1337	4.83	276.9	51.2	145.7

[1] Carbon emissions are based on the monthly average for the UK electricity grid. Source: Table by author, adapted from Electricity Info (n.d.).

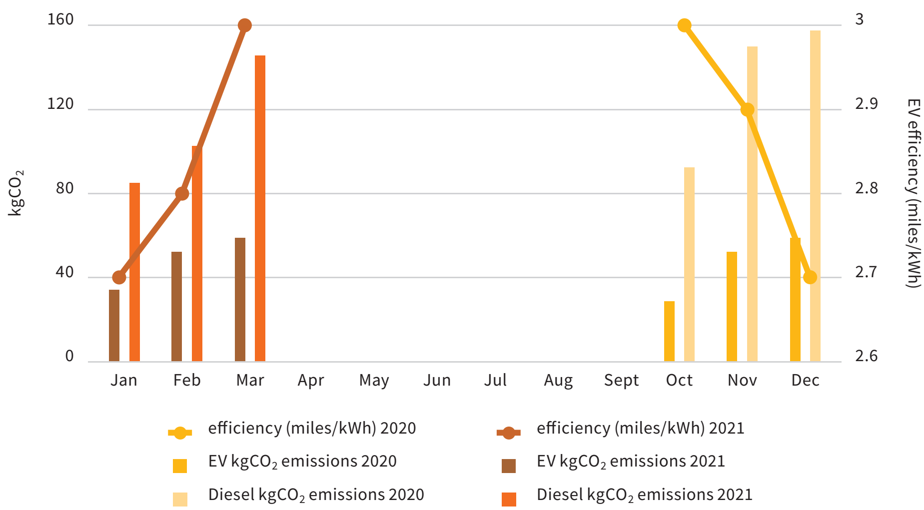

Figure 8. Carbon emission comparison between electric vehicle and diesel vehicle, plus electric vehicle efficiency. Source: Graphic by author.

Based on monthly UK electricity carbon emissions (Table 6), the EV saved 471 kg of CO_2 in six months of operation in comparison to the diesel car it replaced. On this basis, the electric vehicle batteries will achieve carbon payback within 7.5 years.

Cost payback has not been considered as it is difficult to assess how much more expensive the EV is than a comparable diesel car, although it is acknowledged that electric variants are generally more expensive than their diesel equivalents. Energy payback is not considered as the car consumes energy.

5. Discussion

The calculated energy, carbon and financial paybacks of each part of the renewable generation and storage system are summarized in Table 11.

Table 11. Calculated energy, carbon and financial paybacks of façade PV system, roof PV system, Tesla Powerwall and EV battery.

Element	Energy Payback (y)	Carbon Payback (y)	Financial Payback (y)
Façade PV	8.0	132.0	18.0
Roof PV	5.6	16.0	15.4
Tesla Powerwall	18.1	5.0	19.0
EV Battery	N/A	7.5	N/A

Source: Table by author.

5.1. Energy Payback

The energy payback of both PV systems is well within the expected service lifetime. The energy payback of the Tesla Powerwall is more complex as its ability to facilitate energy payback relies on the specification of the renewable generation it is partnered with. In this case, the energy payback is 18.1 years, which is significantly beyond the warranty period, but there is potential for the system to still be operating in that time period. It should be considered that the captured energy would have been higher (and energy payback shorter) if the full 6.8 kWp roof PV system had been permitted.

5.2. Carbon Payback

The carbon payback is less certain than the energy payback because the calculations vary depending on the future potential decarbonisation of the UK electricity grid. The decarbonisation of the grid in recent years has had a noticeable impact on the carbon payback of the façade PV system, which was initially expected to achieve carbon payback within 8.6 years.

Assuming that targets to reach 100 g CO_2/kWh by 2030 and then 10 g CO_2/kWh by 2050 are achieved, the roof PV system will achieve carbon payback within its service life. However, the carbon payback of the façade PV system is much longer.

Some people may argue that the reduced carbon intensity of the electricity grid negates the requirement for renewable energy installation. For this reason, it needs to be acknowledged that the decarbonisation of the electricity grid is only possible if renewable energy generation is increased. Approximately 162 TWh of low-carbon generation is required to meet the 100 g CO_2/kWh target by 2030 while covering the planned retiral of nuclear plants and increased electrification of transport and heating (Evans 2020). It should also be considered that the electricity decarbonisation contributes to reduce embodied carbon of new renewable energy generation systems. This trend is already being observed in the decreasing embodied carbon data for batteries (Hausfather 2019).

The carbon payback of the Tesla Powerwall benefitted from its year-round capability to save carbon. In sunny weather, the maximum carbon saving comes from "saving" solar energy for a higher-carbon intensity period. However, even in low-sun conditions during the winter, it is able to powershift lower-carbon intensity electricity generated overnight to a higher-carbon intensity period. This enables a carbon payback of 5 years which is well within its service life.

Under the 2020 electricity grid carbon intensity, the electric vehicle battery is likely to reach carbon payback in less than 8 years (which is the warranty period for the EV battery). There is potential for this to be even earlier as the data analysed do not consider the following factors:

- EV grid charging was scheduled from 00:30 to 04:30. Analysis of 2020 data (as illustrated in Figure 3) has shown that the carbon intensity during this period is nearly 20% lower than that during the rest of the day (202.239 g CO_2 compared to 249.975 g CO_2).
- Not all of the electricity came from the electricity grid. Periods of solar PV generation being stored directly in the car were observed in October 2020, and February, March and April 2021. Unfortunately, the amount could not be logged with the current equipment.
- The period analysed was during cold months which are known to adversely affect vehicle energy efficiency.
- As decarbonisation of the electricity grid improves, the carbon emissions of the electric vehicle will reduce further.

5.3. Financial Payback

The financial payback of the façade PV system will be reached within its service life due to the FiT contribution. The roof PV system was a simpler installation and will reach financial payback within its service life without any subsidy. However, the roof PV system can only reach financial payback in tandem with the Tesla Powerwall; otherwise, much of the energy generated would be exported to the grid with no benefit to the owner. This is why its financial benefit has been shared with the Tesla Powerwall. Even with the payback contribution from the PV system, the Tesla Powerwall will not achieve financial payback within its expected service life. This agrees with the findings in the literature (Zakeri et al. 2021; Sheha and Powell 2018; Gardiner et al. 2020; Dong et al. 2020).

There is an element of uncertainty in the financial payback calculations—particularly over an extended period. There is potential for fluctuation in electricity prices which could significantly extend or reduce the payback period.

5.4. Behaviour

Visual displays were used to ensure that the status of solar generation and the battery can be considered when scheduling use of appliances such as the washing machine in order to minimise grid electricity imports.

6. Conclusions

Although the façade PV system's financial payback was only made viable by the FiT contribution, this subsidy had wider benefits as it transformed the UK market and established PV as a viable renewable energy generation technology in the UK.

The energy, carbon and financial payback for simple roof-installed PV generation covering the base load is clear.

The installation of PV generation beyond the base load can be justified as long as suitable storage capability is also installed to reduce stress on the grid and maximise benefit to the owner. However, this can impact on financial payback, as previously indicated in the literature (Zakeri et al. 2021; Sheha and Powell 2018; Gardiner et al. 2020; Dong et al. 2020). It should be noted that the main benefits of storage installed with PV are to the electricity grid (Zakeri et al. 2021; Sheha and Powell 2018; Jankowiak et al. 2020; Koskela et al. 2019; Gardiner et al. 2020; Dong et al. 2020); however, owners of the storage are not currently rewarded for providing these benefits. In fact, the payback of this system has been adversely affected by the reduction in the intended PV installation from 6.8 to 6.12 kWp (as required by Western Power). The literature has indicated that policy changes which monetise the benefits offered by energy storage to the grid will outperform subsidies (Gardiner et al. 2020).

The ability of a PV system to achieve carbon payback through its own generation will vary depending on the solar efficiency of its installation and future electricity grid decarbonisation. As renewable generation is contributing to decarbonisation of the electricity grid—which, in turn, reduces the embodied carbon of the equipment produced in future—it is important that solar-efficient installations continue.

The carbon payback of the electric vehicle battery is clear and will benefit from future electric grid decarbonisation.

The combination of renewable generation, energy storage and swapping to an electric vehicle is likely to avoid 1655.6 kg CO_2 per year operational emissions at the 2020 UK electric grid carbon intensity. Obviously, this is a small decrease on the national scale, but there is potential to replicate this approach in other buildings.

This study has been limited by a relatively short monitoring period. Future work to review the data after an extended period would be beneficial.

Funding: This research received no external funding.

Acknowledgments: I would like to express my eternal gratitude to my husband, Andrew Earp, for co-funding the PV systems, the Tesla Powerwall and the electric vehicle, as well as for managing the monitoring equipment and prototyping the visual displays. I would like to acknowledge the loan of sensors by HWM.

Conflicts of Interest: The author declares no conflict of interest.

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