Lark Rise – Passive House Plus

Preliminary Energy Performance Evaluation Report

December 2017

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1 Introduction And Overview

1.1 Background

In 1975, Brenda and Robert Vale published The Autonomous House (Vale, 1975), 'offering solutions to the problems of living in a way that does not despoil the earth.' The Vales proposed: 'a house that is independent of the mains services of gas, water, electricity and drainage, and uses instead the 'income' of sun, wind and rain to service itself and process its own waste.' The overall aim was to 'spend income, not capital.'

Just over 40 year later, a house in Buckinghamshire, called Lark Rise, has become one of the closest embodiments to date of the Vales' vision of the Autonomous House. It demonstrates some of the most advanced design and engineering technologies available from around the world, including the UK, Germany, Austria and the USA. By adopting intelligent Passive House design protocols at scale, Lark Rise demonstrates how advanced-technology housing can provide heating and all other household needs including purification of its own waste products, while at the same time releasing existing grid electricity capacity and exporting excess energy for the mass-electrification of motor vehicles.

As such, Lark Rise demonstrates the potential for the UK government to drive policy initiatives that will save money that will otherwise be required for power stations to supply the alternative business-led scenario. Gentle nudging of market forces can provide a new focus for UK industry to facilitate a joined-up plan to enable the emerging microgrid vision to materialise smoothly – in short, to provide the stimuli needed to create a new Green Technology Revolution.

Intelligent design requires new multi-disciplinary skills and these need to be taught by professionals at the 'cutting edge' of change. With investment in the correct form of education and with long-term investment incentives and appropriate pollution regulation, it will be possible to generate 'green' growth in the UK economy for domestic benefit and export. This is the kind of investment that brings financial, environmental and health returns by cleaning up the environment and creating a deep reduction in the UK's carbon emissions; by providing warm, comfortable and healthy homes that will enhance the health of the population; and by reducing pressures on many other areas of public expenditure, from the health services to the public power-supply infrastructure.

1.2 Research objectives

Lark Rise has been designed and built to rigorously test the viability of the following concepts in a North European climate:

1. The concept of 'house as power station'.
    a. Without interaction of an electric car.
    b. With interaction of an electric car.
2. Based on the actual performance results of a single 'house as power station', to establish the potential for a cluster of similar houses to act as a smoothly operating and resilient organism by connecting them to a local microgrid for their mutual benefit and to reduce or to avoid altogether the requirement for this organism to draw down energy from the National Grid. The purpose of this is to find out if we can demonstrate the potential for a low carbon transition plan that avoids demand shocks in the National Grid. Reducing the need for household heating and electricity in this way will reduce the demand on the National Grid, releasing supply capacity for the electrification of cars and for the move towards heat pumps to decarbonise the heating of buildings.

We are alert to the fact that claims are easily and frequently made for the above concepts, but rarely followed through to proof-of-concept. As such, many of the claims about microgrid communities are little better than wishful thinking. Our intention is to provide disclosure of monitoring data and to establish a new UK benchmark establishing to what extent it is possible to reduce the impact upon the grid of a domestic house, or indeed to what extent an intelligently designed, 'fabric-first' house can provide useful and reliable energy supply to the National Grid. This will enable other designers to use proven data in preparing scenarios for national and community energy modelling.

The in-use data from this project will also feed into bere:architect's fledgling UK National Energy Model which aims to provide ideas to address the national (and global) need to switch the heating and cooling of buildings from fossil fuel to renewable energy, and the transportation of people and goods from fossil fuel to renewable energy. Our hypothesis is that it will not be possible to achieve decarbonisation of the grid without first using a combination of smart controls and energy efficiency to cut the energy demand of our buildings by 80-90%. The open question at this time is how much can be achieved at what cost? In other words, how much can be achieved by smart controls such as time shifting, and what is the minimum amount of effort and expenditure necessary for the fundamental job of energy efficiency to reduce energy demand, especially heat?

1.3 Description of the house

Lark Rise is an ultra-low-energy, contemporary and healthy home. It is a detached two-storey, two-bedroom dwelling located on a North West facing slope on the edge of the Chiltern Hills in Buckinghamshire. The main entrance is on the upper floor, facing towards a sheltered entrance forecourt to the South East, bounded by deciduous trees. The main views are to the North West from the upper floor reception spaces, and from the bedrooms on the lower floor. The garden consists of a level lawn, overlooking a small orchard and rolling farmland that extends as far as the eye can see. The upper floor contains an entrance area, cloakroom, and open-plan kitchen/living space, and the lower floor contains two bedrooms, two bathrooms, a boot room, and a utility room.

The main garden façade faces North West and is entirely glazed, with large windows and a terrace. Solar gains are limited because most of the glazing faces to the North West. The northerly orientation helps avoid Summer overheating, and the high thermal mass of the building, although not essential, certainly helps to maintain stable and comfortable temperatures in Summer and Winter.

As with all Passive House homes in colder climates, intelligent design protocols use weather data applicable to the site to determine the technologies used in the homes. This means that to provide equitable living conditions, a house designed for the South of England must have a different specification to one designed for the North of England; a fact completely overlooked by the UK Building Regulations, UK housebuilders and modular construction companies working across the UK.

At Lark Rise to keep the interiors warm in winter with hardly any energy use the basic strategy consists of (1) an extremely detailed design energy model, (2) very good insulation without any cold-bridges, (2) draught-free construction, and (3) high-performance triple glazing. Occupants enjoy steady, comfortable conditions throughout the year, and benefit from a fresh air ventilation system with heat recovery. An air source heat pump supplies the domestic hot water (DHW) at 49 degrees C (hot but providing safety from scalding), and it also supplies the tiny amount of underfloor heating required to maintain optimal conditions in the coldest of weather spells. The roof area is 108m^2 and this provides space for 62m^2 of solar PV generator surface from 38 modules with an output of 12.43kWp. Site-produced energy is entirely from this source. There is no wind-energy generation. There is a small log-burner in the living room, but it is used infrequently, on social occasions.

1.4 Performance objectives

Lark Rise is an all-electric, two-bedroom dwelling house that is designed to produce at least twice as much energy in a year as it requires, while maintaining a very high level of comfort in summer and winter. Energy monitoring shows (figure 13) that after battery storage is installed in spring 2018, the house could become almost autonomous. What is without doubt at this stage is that with the battery storage, the house will not need to import more than a very small proportion of its energy needs, even in winter, without in any way compromising the indoor conditions of extremely high comfort and convenience for the occupants. It would be very interesting to test what small compromises would be required to achieve full autonomy. The small import requirement shown in figure 13 would be confined to November, December and January.

Lark Rise does not rely on optimal solar orientation to achieve this level of performance, so the house demonstrates the concept of 'any-orientation Passivhaus', first proposed by bere:architects (Bere Architects with the Prince's Foundation for the Built Environment , 2011).

Lark Rise is certified to the Passivhaus-Plus standard, which means that it is designed to support a future scenario of a world where solely renewable energy sources are used, and to enable occupants to act as renewable energy prosumers, rather than simply consumers. In other words, we hope that this house will demonstrate precisely how to deliver the elusive 'house as power station' concept that is widely talked about, but (despite claims) rarely achieved.

1.5 Executive summary (interim)

The local infrastructure of the National Grid at Lark Rise is old and unable to accept the significant excess power generated by the 12.4kWp PV array on a sunny day. This means that the National Grid cannot be used as a 'virtual battery store'. So, until battery storage is installed, power generation is capped at 3.8kW.

From spring 2018, an integral 13kWh battery will store excess daytime energy production for night time use. This will soak up most of the excess energy generation, generally avoiding the need to shut down the solar generation to avoid overloading the local infrastructure of the National Grid.

Lark Rise demonstrates how an all-electric Passive House, with an unrestricted 12.4kWP PV array and a 13kWh battery, can be expected to act as a small power station for the electricity grid, producing roughly twice as much energy as it needs in a year, including the power-socket energy needs of its occupants and all other miscellaneous loads. After battery storage has been installed in Spring 2018, allowing the restriction on PV generation to be lifted, Lark Rise is expected to draw 97% less energy from the National Grid than the average UK house, and be a net exporter to the National Grid of over 6000kWh of electrical energy per year.

Once the battery has been installed, we will be able to assess how much excess solar-generated energy is available to power an electric car and when the excess power is available for this, and to assess the potential for an electric car to store energy not just for its own use, but for the benefit of the house and its occupants' needs.

At the same time as removing peak supply spikes from the grid, the battery will also help eliminate peak demand spikes from the grid. This is important because national peak demand (the 'triad' scenarios) is mainly what sets the national power station capacity requirement. So, deeply reducing the size of peak demand spikes caused by aggregated simultaneous patterns of behaviour, can save the massive infrastructure investment costs of new power stations. Our hypothesis is that Lark Rise demonstrates a cheaper, longer-lasting, safer and more reliable means of maintaining a balance between supply and demand, than constructing new low-carbon generation to supply un-checked demand, such as nuclear power stations costing more than £20billion each, excluding the cost of decommissioning.

One of the biggest factors in attacking the power demand spikes for this house is, as far as possible, the meeting of all or most of its energy needs in Winter, when most buildings – even CSH Code 6 houses - have been found to have a large winter-gap, which represents a significant shortfall of on-site generation compared to demand.

After an initial monitoring period without the benefit of battery storage, the house will be connected to a 13kWh battery store in Spring 2018. This will allow the solar panels to operate at full capacity rather than being 'throttled back' as shown in the graphs in this report. This will allow greater utilisation of the power generated from the panels on the roof of the house, and it will reduce the need for grid-supplied energy after dark and on overcast winter days. The control and monitoring equipment for the new battery is already installed. The new battery that we have selected will be available in the UK from Spring or early Summer 2018.

PHPP design engineers, Energelio, produced a self-consumption report (Energelio , 2016) to study the feasibility of a 100% photovoltaic self-consumption system at Lark Rise and to optimise the size of battery considering the demand and supply factors of the house. This will be included in the appendices of the final report. The actual PV generation is also analysed in section 3 of this report.

The monitoring of the building has been made possible by sub-meters on the power circuits of the house. By this means, the energy consumption of power sockets, MVHR, cooking, miscellaneous and lighting have been collected over 2 years, from the date when the first tenants moved in (October 2015) to the most recent meter readings of the second tenants' usage, taken in October 2017. The heating and DHW consumption data have been take from the records contained in the controller of the Viessman 242S air source heat pump. This data is only available for the last year; in other words, we only have data since September 2016. Overall energy consumption was taken from the smart meter supplied by the electricity supply company which was cross-checked (and verified) against the duplicated data contained in the PV control system, which also records detailed import and export data.

This highly energy-efficient, all-electric house was designed by bere:architects with mechanical and electrical services design by Alan Clarke, ventilation detailed design by Green Building Store, and structural design by Techniker. Darke and Taylor designed and installed the PV solar array, and data monitoring control equipment, and have downloaded some of the data used to compile this report. Energelio carried out the self-consumption energy study which determined the optimal battery size for the house, determined the benefits of this approach and helped tune the design for Passive House Plus certification. Passivhaus Plus certification was granted by the Passive House Institute, Darmstadt, Germany, in November 2017. The certifying agent was Kym Mead of Mead Consulting.

2 Data and Monitoring Methodology

2.1 Data and Monitoring of Lark Rise

Sub-meter readings have been recorded from time to time by bere:architects since completion of the building contract. Monitoring has included the control panels for PV production, usage and export, and heat pump energy use. Post-occupancy advice has been given to the tenants. Some data analysis has been done in response to some questions from the current tenants about their bills, and advice has been provided on how to reduce their energy costs.

The key findings and messages for the client, owner and tenants as well as wider lessons taken from this Building Performance Evaluation study are summarized in section 4 of this report.

Electric submeters were installed in the main distribution board for MVHR, power, cooking, lighting and miscellaneous circuits. There was also installed one submeter for the heat pump compressor and controls and one for the boost heaters in the heat pump board and a main electricity meter and PV production meter installed by Dark and Taylor.

1. There have been five sub-meter readings recorded from the main distribution board submeters in this period:

- 06/12/2015 by Justin Bere at bere:architects
- 23/02/2016 by Justin Bere at bere:architects
- 27/04/2016 by Alex Whitcroft at Bere Architects
- 06/09/2017 by Ian Jones, second tenant at Lark Rise
- 17/09/2017 by Justin Bere and Alex Hewitson at bere:architects

2. Heat pump meter readings for heating and DHW were carried out on the 17/09/2017 and read the electric demand (kWh) of the last 52 weeks (1 year) prior to this date. Heat pump heating curves were previously adjusted on the 17/03/2017 by Justin Bere to perform better with a low-temperature heating system as the UFH installed on site. Also, DHW temperature was also adjusted from 54°C to 48°C in order to improve heat pump efficiency and reduce consumption.

3. PV production and site energy consumption data has been obtained between Feb-2016 to Nov-2017.

The house was first occupied on October 2015 by the first tenants that lived there for around 5 months until April 2016. Second tenants moved in at the beginning of April 2016 and are still living in the house (Nov-17).

Actual heating, DHW and rest of electricity consumption, and PV production have been analysed for 1-year period between Oct-16 and Sep-17.

2.2 PHPP data

All relevant data of heating, DHW and the rest of electricity demand of lighting, power sockets, cooking, MVHR and miscellaneous circuits, and the PV generation used at the design stages of this project have been compared to the actual data from site in this report.

2.3 Other standard and Passivhaus buildings performance analysis

Lark Rise data has been compared to peer-reviewed data from the article The Side by Side in use Monitored Performance of two Passive and Low Carbon Welsh Houses (Ian Ridley, Ph.D.; Justin Bere; Alan Clarke; Yair Schwartz; Andrew Farr , 2013) and from Building Performance Evaluation Report of the Camden Passive House (Ian Ridley, Bere, Clarke, Schwartz, & Farr, 2014) . These projects were also designed by bere:architects and monitored with the support of academics and funding from the Technology Strategy Board. Projects are listed below.

- Larch house: the UK's first zero carbon (code 6), low cost, Certified Passivhaus, built as prototype social housing and launched at the 2010 National Eisteddfod for Wales. Monitored between May-12 and Apr-14
- Lime House: Certified Passivhaus in Ebbw Vale. Code 5 of the Code for Sustainable Homes. Monitored between May-12 and Apr-14
- Camden House: first certified Passivhaus in London. Monitored between Oct-12 and Sept-13

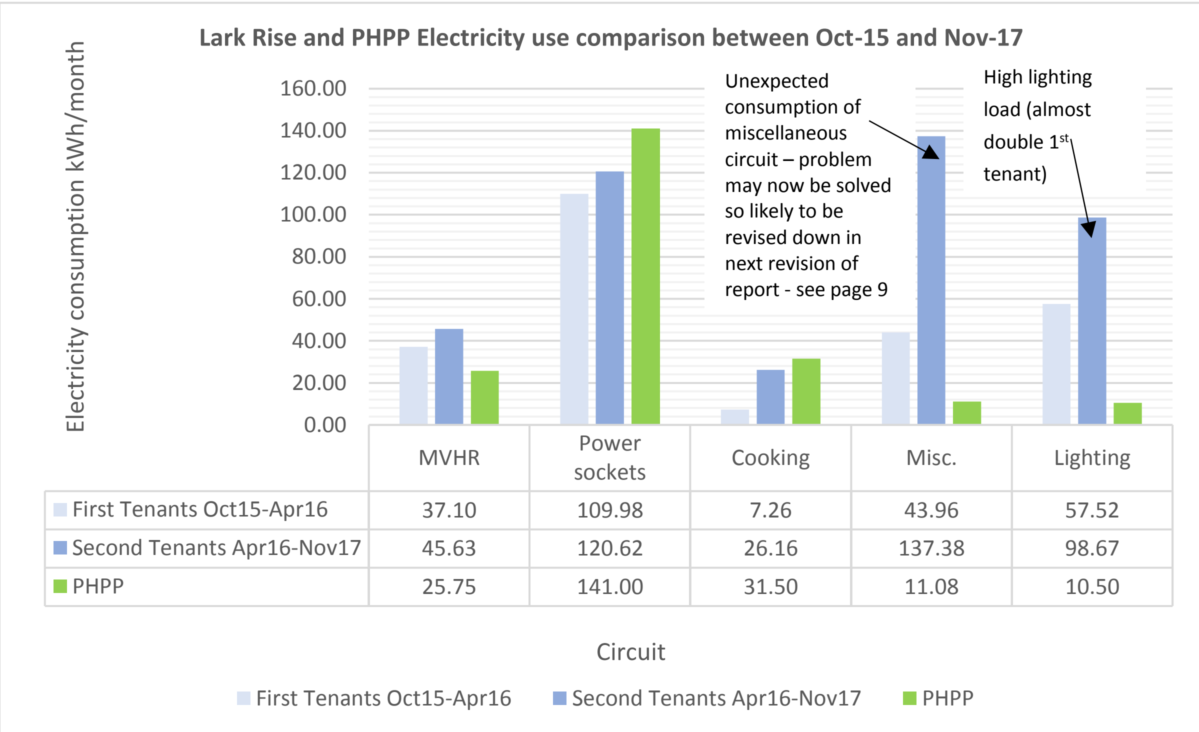
Lark Rise consumption has also been compared to average energy consumption of a UK standard house Sources:

- Total energy average consumption has been taken from Table 3.03 Average domestic gas and electricity consumption, UK, 2011 from ECUK Overall & Domestic Data Tables (DECC, 2017)

- Percentages of by end use have been taken from Figure 3-1 UK of Domestic energy use by fuel type and by end use shown in page 47 of the thesis 'A specification for Measuring Domestic Energy Demand Profiles' (Svehla, 2011) which is based on ECUK tables of 2010 of BEIS.

3 Analysis Of Energy Performance

3.1 Power sockets, lighting, cooking, MVHR & miscellaneous consumptions analysis by tenancy period against PHPP design values



	MVHR	Power sockets	Cooking	Misc.	Lighting
First Tenants Oct15-Apr16	37.10	109.98	7.26	43.96	57.52
Second Tenants Apr16-Nov17	45.63	120.62	26.16	137.38	98.67
PHPP	25.75	141.00	31.50	11.08	10.50

Figure 1 Lark Rise tenants' average monthly electricity consumption from Oct-15 to Nov-17, compared to PHPP design values

Figure 1 shows the average electricity consumption of the sub-metered circuits for MVHR, power sockets, cooking, miscellaneous and lighting over the two tenancy periods of Lark Rise. User preferences can cause variations in the floating demand seen in the cooking and lighting levels in the graph. However, we would expect the miscellaneous circuit to show a relatively constant demand between tenancies because the circuits which are fed by the 'miscellaneous' submeter shouldn't be greatly affected by user preference (Figure 2). At present the cause of the variation in miscellaneous power demand is not known. However, the pump within the septic tank burnt out in November 2017, and it is possible that the increased consumption could be due to this. The septic tank pump has now been replaced and early indications are that miscellaneous consumption has been significantly reduced as explained below. Monitoring will continue before altering the graph in the next revision of this report.

Last meter reading of the miscellaneous circuit taken by the tenants on the 17th of November 2017was 3072.7kWh, just 137kWh higher than previous reading two months earlier on the 17th of September 2017. If we calculate the monthly consumption based on the last 2 months, it is 68.75kWh/month, which is more in line with the monthly consumption of the first tenancy period when it is believed the pump performed correctly. A site visit to check all circuits connected to miscellaneous submeter plus further submeter readings will be need in order get a more precise and realistic consumption.

Initially, on the assumption that the miscellaneous energy consumption of the second tenancy is due to an error, the average annual electricity consumption quoted in this preliminary report includes miscellaneous energy use during the first tenancy period.

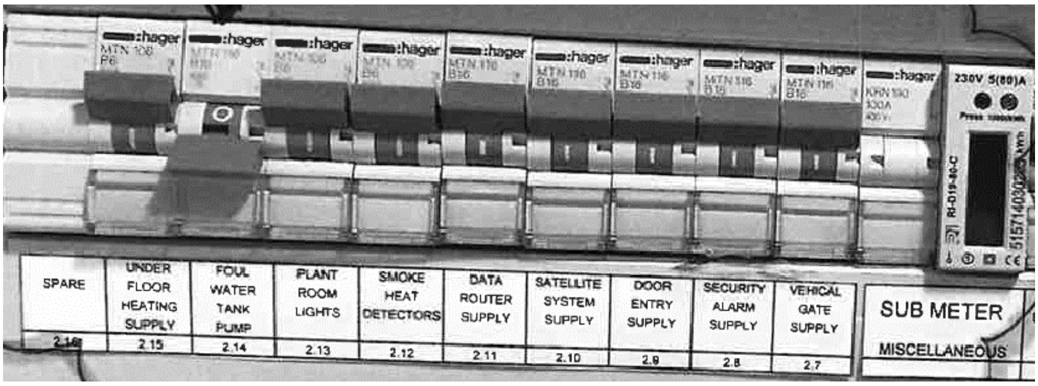


Figure 2 Miscellaneous circuit from main distribution board at Lark Rise

Electricity demand from power sockets, MVHR and cooking circuits in Figure 1 are part of the constant and floating demands and are closely aligned with the PHPP design values. MVHR demand of the second tenancy period might have increased slightly due to extremely dirty filters. They were changed sometime between 20th and 23th of October 2017, a meter reading of MVHR circuit has been requested to current tenants on November 2017 in order to check if this hypothesis is correct.

The average lighting demand in Figure 1 is around 5 times the PHPP value in the first tenancy period and around 10 times in the second. PHPP lighting annual demand is estimated by a factor of occupancy and lighting efficiency. Lark Rise PHPP calculations are based on a lighting efficiency of 50lm/W, in accordance with PHPP requirements, and the power required for sufficient energy-efficient lighting corresponds to 14.4W. It is assumed that a 14.4W light bulb follows each person when they need light and the time is approximated as 2900 hours/year. As the estimated occupancy of Lark Rise is three occupants, the total lighting demand in the PHPP is: 14.4W*2900 hours/annum= 41760 Wh/annum person, = 41.76kWh/annum person x 3 = 126kWh/annum. As shown in Figure 6, this would be a smaller demand than a normal UK house according to 2011 data from the Office for National Statistics, but in reality, the lighting consumption at Lark Rise is higher than the UK average.

Table 1 below calculates total wattage potential of lighting installed at Lark Rise and the average lighting efficiency weighted by percentage of wattage installed of each lighting type. The average efficiency is 58.9 lm/W which is in line with the PHPP estimations. This indicates that the efficiency of lighting fixtures is not causing the actual increase in lighting demand, but as we shall see, the number of fittings may be a contributing factor.

Lighting Plan Ref	Load (W)	G.Floor No. or length (m)	F.Floor No. or length (m)	Total no.	Total (W	% of total	lumen	Type	lm/W	reduction factor	lm/W weighted	
A (indirect strip light)	3		41.6	41.6	124.8	11.18%	9984	LED	57.00	0.50	**28.50**	3.19
A1 (vanity unit lights)	3	9	4.5	13.5	40.5	3.63%	3240	LED	57.00	0.75	**42.75**	1.55
B	13.5		7	7	94.5	8.46%	866	LED	64.15	1.00	**64.15**	5.43
C	13.5	9	9	18	243	21.76%	866	LED	64.15	1.00	**64.15**	13.96
D	13.5	2		2	27	2.42%	866	LED	64.15	1.00	**64.15**	1.55
F	17		3	3	51	4.57%	1100	LED	64.71	1.00	**64.71**	2.96
H (direct strip light)	15	9.7	3	12.7	190.5	17.06%		LED	56.67	1.00	**56.67**	9.67
P	36	7		7	252	22.57%	2400	LED	66.67	1.00	**66.67**	15.04
S	1.2	7		7	8.4	0.75%	105	LED	87.50	1.00	**87.50**	0.66
V	17	4	1	5	85	7.61%	1100	LED	64.71	1.00	**64.71**	4.93
		Total Wattage installed			**1116.7**				**Weighted average efficiency**			**58.92**

Table 1. Lighting efficiency calculation at Lark Rise by lighting type installed on site.

Room	Wattage (W) Circuit 1	Circuit 2	Circuit 3	Circuit 4	Circuit 5	Total W	Min W	PHPP estimation (W)	Times that Min W exceded 14.4W PHPP estimaton
GF entrance	108					108	108	14	**7.5**
GF staircase hall	27	40.5	15			82.5	15	14	1.0
GF utility room	108					108	108	14	**7.5**
GF master bathroom	78	3.6				81.6	78	14	**5.4**
GF master bedroom	40.5	2.4	17	17	42	118.9	17	14	**1.2**
GF guests bathroom	42	2.4				44.4	42	14	**2.9**
GF guests bedroom	40.5	2.4	17	17	30	106.9	17	14	**1.2**
FF entrance hall	40.5	7.8				48.3	7.8	14	0.5
FF toilet	13.5					13.5	13.5	14	0.9
FF living room	35.4	35.4	35.4	40.5	51	197.7	35.4	14	**2.5**
FF Kitchen/dining	54	67.5	40.5	17		179	17	14	**1.2**
FF staircase lights	27					27	27	14	**1.9**
							485.7	168	2.9

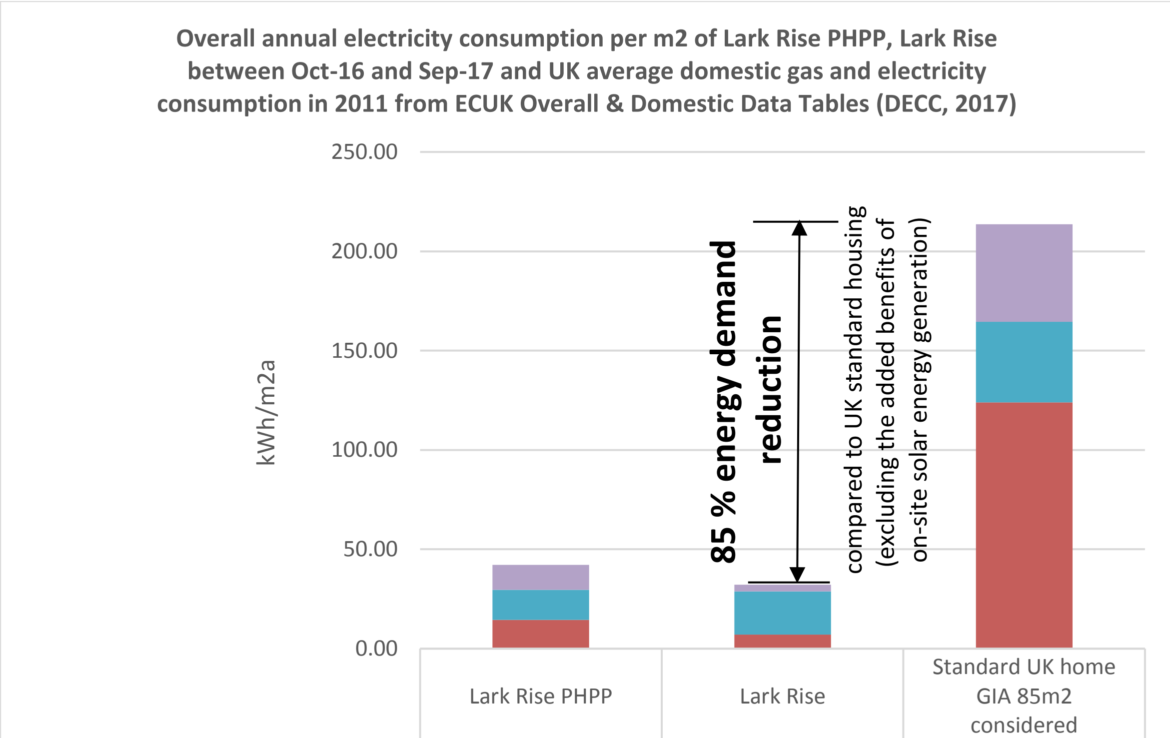
Table 2. Analysis of wattage of lighting circuits installed per room at Lark Rise

Table 2 analyses the cumulative wattage of the lighting circuits installed per room. The result is that the total wattage per room is more than the 14.4W per person estimated in the PHPP. There is more than one lighting circuit in most of the rooms, and in most of the primary spaces, if all the lighting circuits are switched on, the power consumption for the room amounts to around 100W. The green column shows the minimum wattage that can be used by a person operating a single circuit. Bathroom night lights have not been included in this calculation as they don't provide enough light to suit the normal use of the room. The last column to the right shows the number of times that the minimum usable wattage per room exceeds the 14.4W per person estimated in the PHPP. The minimum possible consumption exceeds the PHPP estimate in 9 out of 12 spaces and the total wattage installed is 2.9 times the PHPP design estimate. This analysis indicates that the increase of lighting consumption in the house is partly caused by the number of lights installed per room circuit.

3.2 However, whereas the minimum lighting load per room circuit exceeds the PHPP design estimate by 2.9 times, the actual consumption of the first and second tenancy periods exceed the design estimate by 5 and 10 times respectively. This indicates that a significant factor in the higher than expected lighting

energy demand is the number of hours that lights are switched on in the house. This is likely to be due to one or both of the following factors: (1) lights being switched on during the day (2) lights being left switched on in unoccupied spaces. Overall electricity demand

The overall annual energy demand (kWh/m2/yr) of Lark Rise, analysed from data between Oct-16 and Sep-17, is lower than the PHPP design estimate and more than eight times lower than a standard UK home of just 85m2 (see fig 3). Total consumption of heating and DHW was found to be below the PHPP design estimate (see fig 3), but electricity use for sockets, lighting, cooking etc is higher than the PHPP design estimate. As we have found in other Passive Houses that we have studied, waste heat from higher than expected domestic usage, such as lighting, may contribute noticeably to the very small space heating requirement. However, while the heat produced by lighting and appliances may be regarded as a useful by-product, an excessive amount of lighting will be an expensive way to heat a house, because producing heat from lighting and appliances costs approximately three times more than heating produced by a heat pump. Heating, DHW and other electricity consumption are analysed further in sections 3.3, 3.4 and 3.5 of this report.



	Lark Rise PHPP	Lark Rise	Standard UK home GIA 85m2 considered
DHW	12.51	3.38	49.14
Sockets, lighting, cooking, MVHR & misc	15.04	21.74	40.60
Heating	14.55	7.11	123.93

Figure 3. Lark Rise overall average annual electricity consumption between Oct-16 and Sept-17 compared to the PHPP design estimate and average UK domestic gas and electricity consumption in 2011 from ECUK Overall & Domestic Data Tables (DECC, 2017) (excludes the influence of on-site energy production)

By reference to Figure 4, heating and DHW demands in the PHPP were calculated as 25% and 30% of the total demand of the house, however, they are in fact only 22% and 10% of the total demand of Lark Rise for the period between October 2016 and September 2017. This is a significantly smaller proportion of the total energy use than expected. DHW actual consumption is particularly low as this represents less than one third of the PHPP design value. Heating and DHW will be analysed in the following sections.

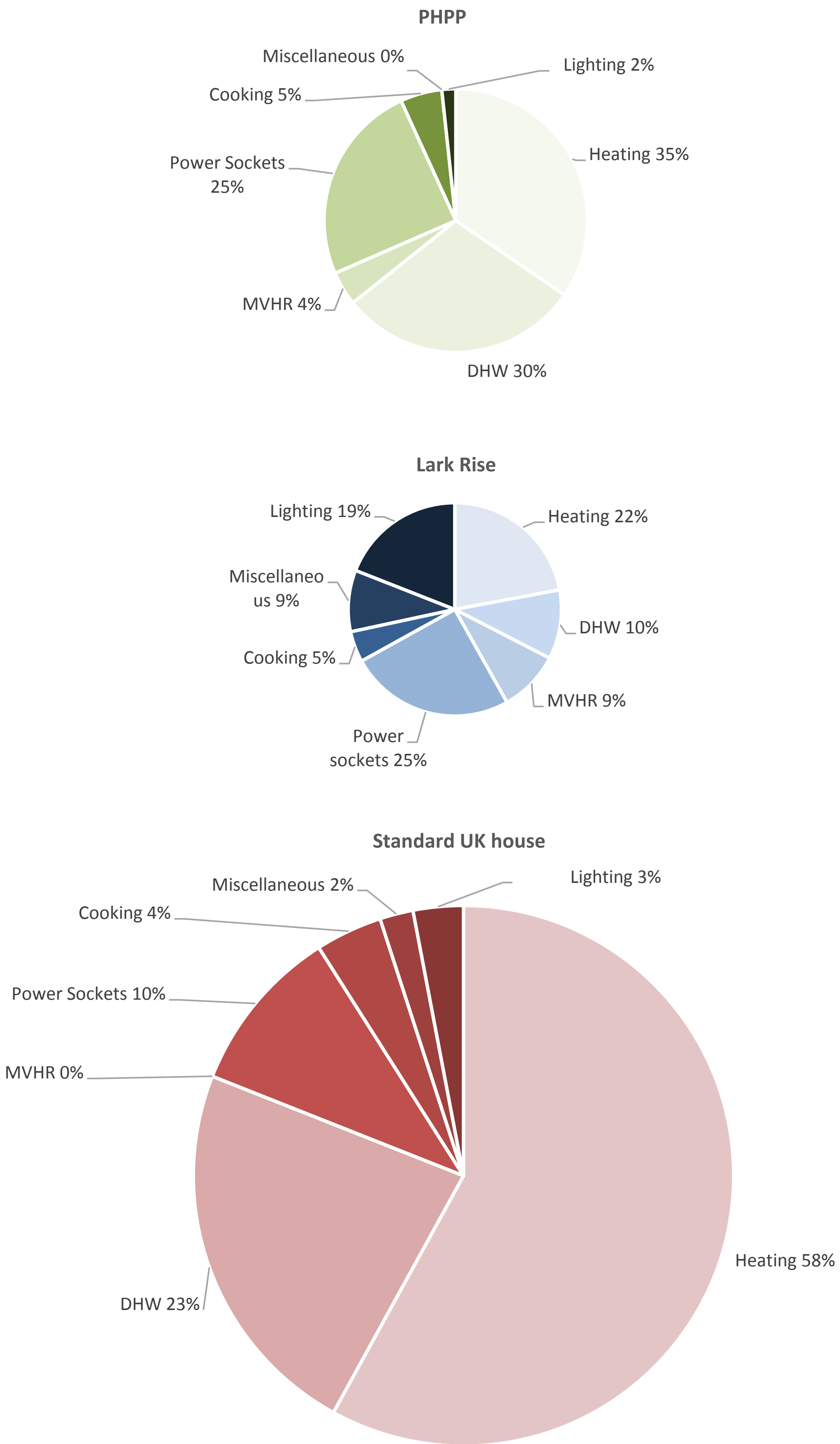


Figure 4. PHPP design estimate, UK standard house and Lark Rise average total final energy consumption, (between Oct-16 and Sept-17). Percentages of by end use of a UK standard home have been taken from Figure 3-1 UK of Domestic energy use by fuel type and by end use shown in page 47 of the thesis 'A specification for Measuring Domestic Energy Demand Profiles' (Svehla, 2011) which is based on ECUK tables of 2010 of BEIS.

The ventilation system's actual consumption (see Figure 4) is 9% at Lark Rise, which is twice as much as the 4% calculated in the PHPP. However, in October 2017 the authors of this report found that the intake and exhaust filters had not been changed since the unit was put into service two years earlier. The filters were extremely clogged up with black particulates in the intake filters (most likely from motor transport pollution) and white in the exhaust (dust from skin flakes etc). The poor state of the filters will certainly have created significant resistance to the flow of air, and this in turn will have significantly increased the fan power requirement. However, the actual consumption of the first tenancy period was also slightly higher (1.5 times) the PHPP design figure. It is thought that this could have been caused by blockage of the exhaust filter at an early stage, caused by dust in the air from decorating works. The authors of this report had specified that ducts were to be stopped up until after completion, however in practice this instruction was not properly complied with by the contractor. It will be interesting to see if the next 6 months see the design target being met.
In Figure 4, average consumption of power sockets and cooking (25% and 5%) represent a similar percentage of the total demand to the PHPP design figures (23% and 5%).

Also from Figure 4, miscellaneous demand (9%) is high compared to the PHPP design figure (2%). Miscellaneous circuit performance of Lark Rise and other PH projects will be compared in the next section.

Lighting overall average demand, as shown in Figure 4, represents 19% of the total demand of the house, this is quite high compared to the 2% design estimate in the PHPP. Actual lighting design of the house (number of internal lights and quality) can affect this figure, but lighting consumption is also part of the floating demand of the house and therefore it can be affected by the lifestyle of the occupants. Lighting performance of Lark Rise and other PH projects will be compared in the next section.

3.3 Power sockets, lighting, cooking, MVHR & miscellaneous demand

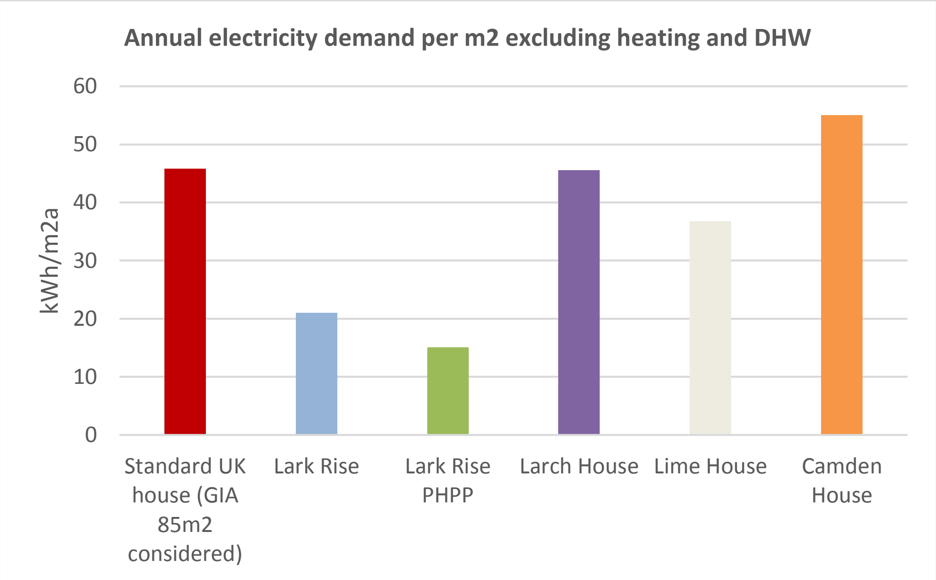
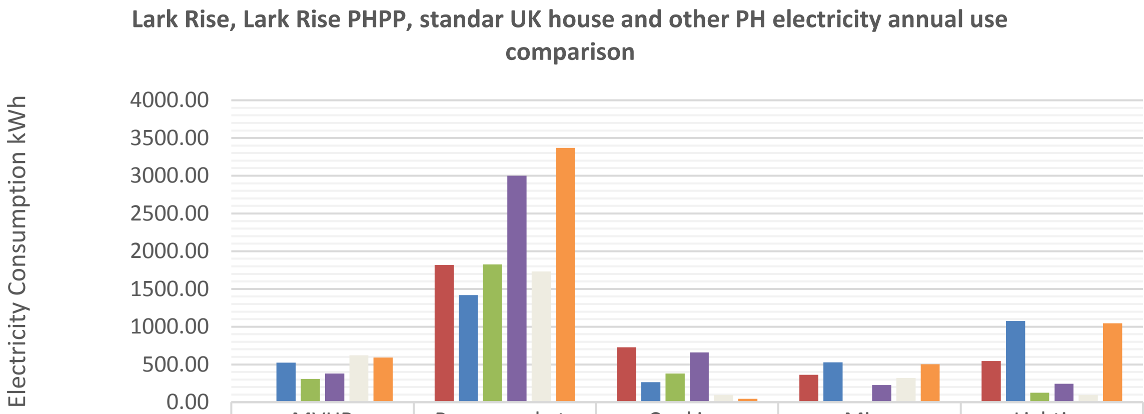


Figure 5. Annual electricity demand per m2 <u>excluding heating and DHW</u> of Lark Rise PHPP design estimate, UK average domestic household electricity consumption in 2011 from ECUK Overall & Domestic Data Tables (DECC, 2017), Lark Rise (between Oct-16 and Sept-17), Larch and Lime houses (average between May-12 and Apr-14) and Camden house (average between Oct-12 and Sept-13).

Figure 5 compares the total annual electricity demand of the MVHR, power sockets, cooking, miscellaneous and lighting (so excluding heating and hot water). The projects compared are: (1) a standard UK house, (2) Lark

Rise (actual), (3) the design estimate in the Lark Rise PHPP, and (4-6) three other monitored Passivhaus projects. The total electricity demand of Lark Rise, excluding heating and DHW and excluding the PV power generated, is lower than any of the other houses but a little higher than the PHPP design estimate.



	MVHR	Power sockets	Cooking	Misc.	Lighting
Standard UK home	0.00	1816.17	726.47	363.23	544.85
Lark Rise	525.29	1419.65	264.57	527.52	1076.66
Lark Rise PHPP	309.00	1825.00	378.00	0.00	126.00
Larch House	380	3002	660	225	245
Lime House	623.00	1731.00	96.00	321.00	96.00
Camden House	591	3371Circuit	43	504	1046

Figure 6. Annual electricity demand per use excluding heating and DHW of UK average domestic household electricity consumption in 2011 from ECUK Overall & Domestic Data Tables (DECC, 2017), Lark Rise (between Oct-16 and Sept-17) Lark Rise PHPP design estimate, Larch and Lime houses (average between May-12 and Apr-14) and Camden house (average between Oct-12 and Sept-13)

Figure 6 compares the electricity breakdown, excluding heating and hot water, of the same house types as figure 5. All houses perform similarly on ventilation, cooking and miscellaneous consumptions

Regarding lighting consumption in Figure 6 there is clear difference between the private houses (Lark Rise and Camden House) and the social housing (Larch House and Lime House). This is partly caused by the high specification of lighting for 'mood effect' that has been installed in the private housing, which has offset the benefits of increased lighting efficiency. The social housing lighting schemes have far fewer light fittings, and fittings generally consist of a single pendant light fitting, which is more economical in terms of both capital and running costs. But as discussed earlier, the other significant factor is the number of hours that the lights are on, and it would appear from the monitored results of the social housing units that the tenants may be less likely to leave lights switched on when they are not needed.

3.4 Heating demand

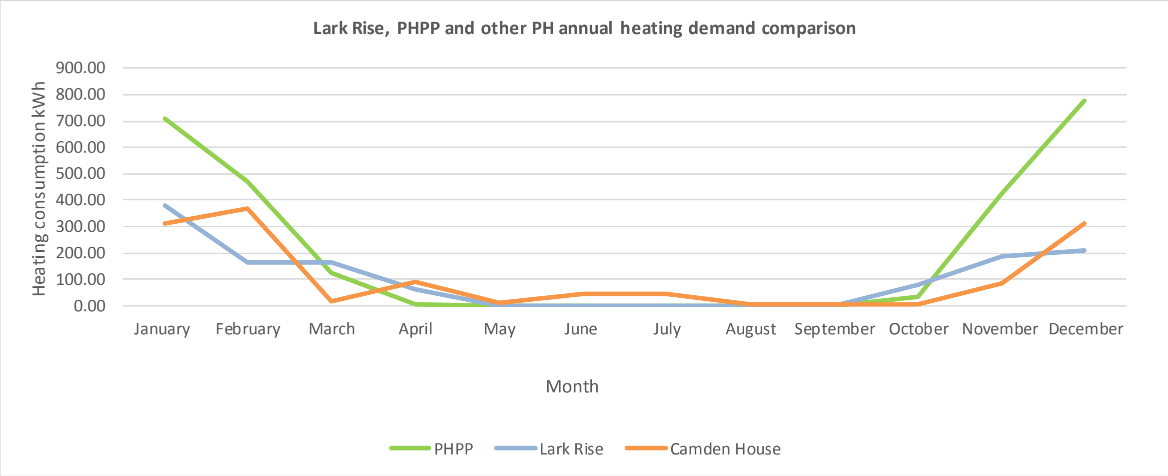


Figure 7. Lark Rise average heating consumption (between Oct-16 and Sept-17) compared to PHPP and Camden House (between Oct-12 and Sept-13)

As shown in the graph above, actual heating consumption of Lark Rise from Oct-16 to Sep-17 performs better than expected in the PHPP. During the winter period the actual usage was less than half the design figures for November, December, January and February. Actual demand is just slightly above design figures in March and September.

The chart below shows the external weather conditions taken from the closest weather station at Princess Risborough during the period analysed and the year before:

YEAR 1	Temp. ºC	YEAR 2	Temp. ºC	PHPP	Temp. ºC
Oct-15	11.5	Oct-16	11.3	October	10.8
Nov-15	10.3	Nov-16	6.2	November	7.1
Dec-15	10.6	Dec-16	8.3	December	4.8
Jan-16	6.3	Jan-17	5.3	January	4.7
Feb-16	6.1	Feb-17	8.1	February	5
Mar-16	6.2	Mar-17	10	March	6.6
Apr-16	8.7	Apr-17	10.3	April	8.5
May-16	13.5	May-17	15.4	May	11.8
Jun-16	16	Jun-17	20.9	June	14.9
Jul-16	18.2	Jul-17	18.9	July	16.6
Aug-16	18.5	Aug-17	17.3	August	17
Sep-16	17.3	Sep-17	15	September	14.5
Year avrg	**11.9**		**12.3**		**10.2**

Table 3. Average monthly and annual temperatures at Back Garden Weather Station in Princes Risborough from Oct-15 to Sept-16 against PHPP design temperatures.

The external climate data has been taken from Back Garden Weather Station from Weather Underground. (Back garden IENGLAND 955 PWS) at Woodfield Road in Princes Risborough, 1.9 miles away from site.

The Year 1 average annual temperature was 11.93C, 1.75°C, warmer than the climate file used in the PHPP design calculation. The Year 2 average annual temperature, 12.5°C, was 2°C, warmer than the PHPP design climate file, and the winter period analysed was particularly much warmer than the PHPP estimated as shown in the table.

External weather conditions must have some influence on the even lower than expected heating consumption, however, these results are also reassuring evidence of a good level of thermal insulation and good thermal design to reduce cold bridges. The results may also be indicative of the excellent performance of a very efficient heat pump. One of the best German heat pumps that money can buy has been specified, the Viessmann model VITOCAL 242-S.

3.5 Domestic Hot Water demand

As shown in the Figure 8 below, Lark Rise DHW consumption is very low compared to other Passivhaus or standard houses and has even performed better that the PHPP calculations. The consumption of the other Passivhaus projects is slightly lower than a standard house, this reduction can be caused by the pipework insulation applied to these Passivhaus projects to avoid distribution thermal losses. However, the Lark Rise figures might also be explained by the very efficient Viessmann heat pump and integral water tank. The other projects that are compared to Lark Rise all use gas boilers in various configurations for heating and DHW. Lark Rise is evidence that all-electric houses with efficient heat pumps can have very low DHW energy consumption.

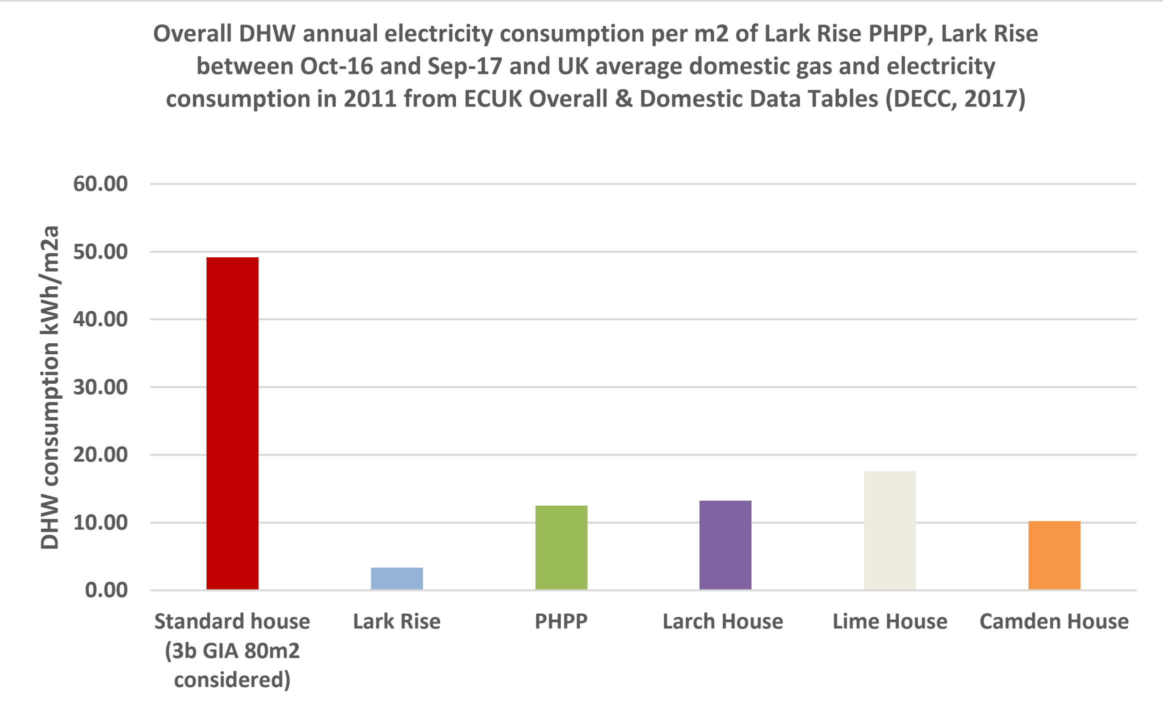


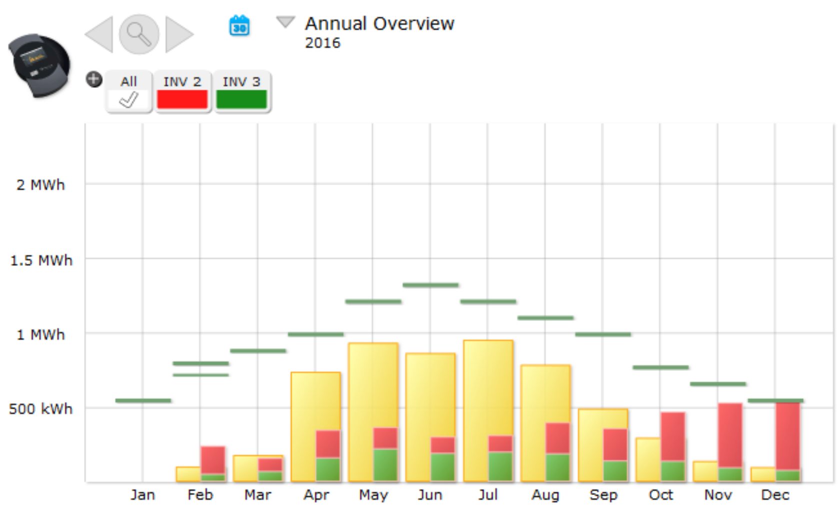
Figure 8. Average DHW annual/m2 consumption of Lark Rise from Oct-16 to Sept-17 compared to annual /m2 consumptions, Larch and Lime houses (average between May-12 and Apr-14), Camden house (average between Oct-12 and Sept-13) and a UK average domestic household DHW consumption in 2011 from ECUK Overall & Domestic Data Tables (DECC, 2017)

3.6 PV generation (this section is compiled with data downloaded and provided by Darke and Taylor)

The roof area of the house is 108m^2 and this provides space for 62m^2 of solar PV generator surface. The photovoltaic system of Lark Rise is designed to generate 12.4 kWp by means of 38 solar panel modules. The panels are made by SunPower and are installed at a 10-degree angle to the horizontal.

The local energy supply company has imposed a 4kW energy export limit to the local grid. For this reason, until a battery has been installed, an automatic control limit has been set up on the PV system to throttle back and finally stop the energy production when the export reaches 3.8 kW. The battery system hasn't been installed on site at present (as of November 2017), but this is planned for Spring 2018. It is expected that the total production of the PV panels will increase significantly when the battery storage system is installed, and the control limit is switched off. (This is discussed further below and graphed in Figure 13).

The yellow bars of Figure 9 below show the total PV electricity generation in this throttled back mode, each month from the date that the PV installation was commissioned on site in February 2016 to 10th of November 2017. For reasons explained above, it does not reflect the true potential of the PV array, which can only be realised once a substantial battery storage facility has been installed. The graphs were downloaded for this report from the internet-connected solar logger. Red and green bars show the total electricity demand of this all-electric house for the same period. The green part of the bars represents the electricity that has been supplied by the PV generation and the red part of the bars shows the electricity consumed from the local grid.



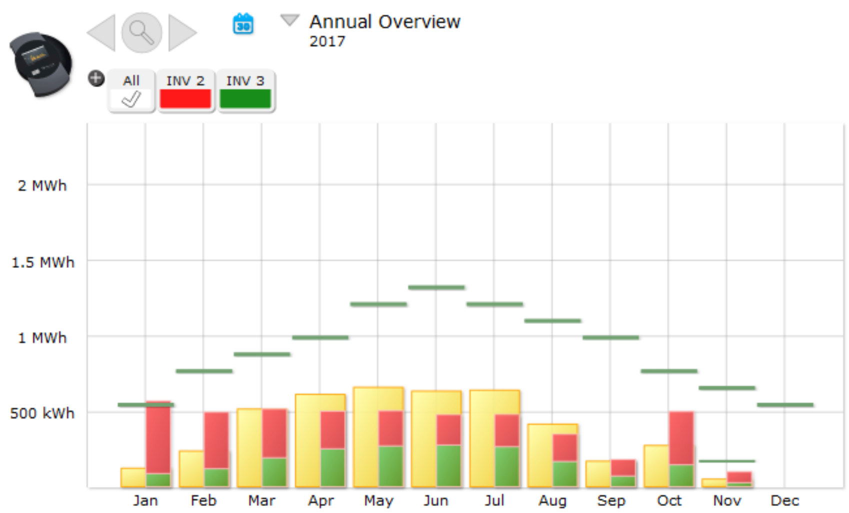


Figure 9. Annual PV electricity generation and total electricity demand of Lark Rise from February 2016 to October 2017 (Courtesy of Darke and Taylor)

By comparing the 2016 and 2017 graphs shown in Figure 9, the total PV electricity production was higher in 2016 than in 2017. Even throttled back, the PV production of both years could have covered the total energy demand of the house between March and September. However, as the green and red parts of each bar indicate, not all the electricity demand during these periods was covered by PV generation. This is since some energy is needed during the evening, and the fact that the batteries have not yet been installed to store the excess electricity generated by the PVs during the day.

Figure 10 shows electricity generated by the PV installation on a summer day in 2017 and the total energy demand on the same day. Again, as in Figure 9, the yellow area represents the energy yield on that day. Green area is the electricity generated by the PV installation that has been used on site, and red area is the energy consumed from the local grid. Peaks on the graph represent the moments of higher demand of the day, that normally occur early in the morning before leaving to work, at lunch time if the occupants come home for lunch or in the evening when occupants are back home after work. As shown in the figure 10, even the peak demands between 08:00 and 10:00 and between 12:00 and 14:00 hours have been met with electricity generated by the PV installation, whereas peak demands in the morning between 6:00 and 8:00 and after 20:00 are almost entirely outside the PV generation hours and therefore met by the National Grid. This analysis indicates that, a priori, installing batteries will help to cover peak demands on hours of low or no PV production.

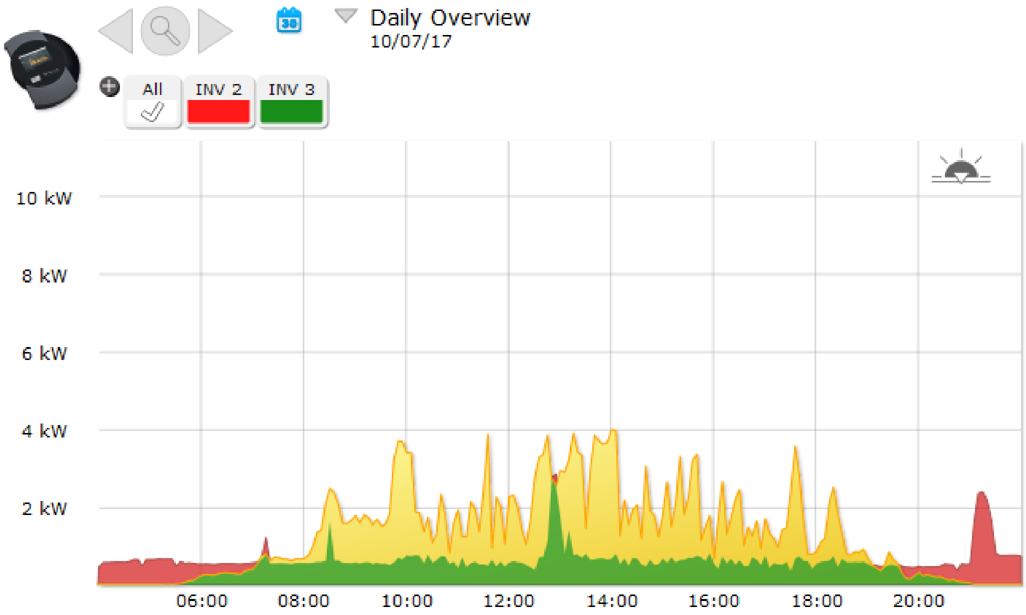


Figure 10. Daily PV electricity generation and total electricity demand of Lark Rise on the 10th of July 2017

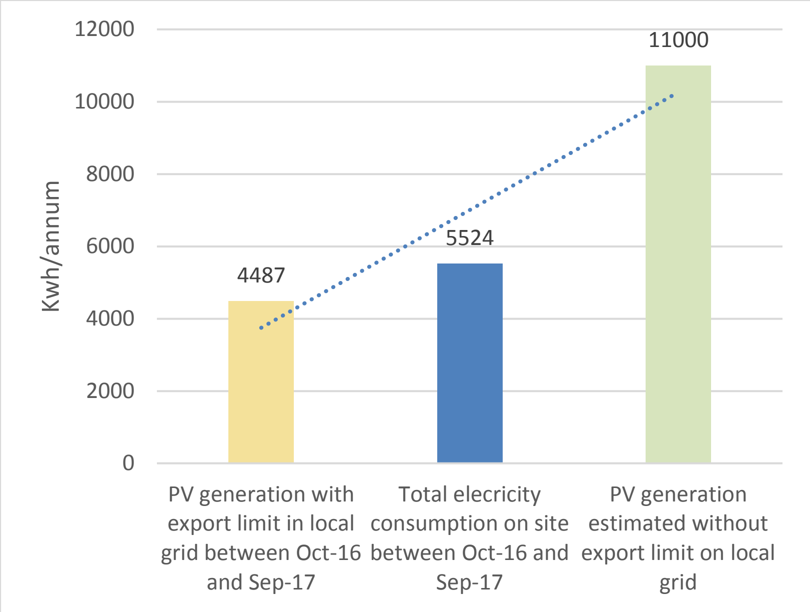


Figure 11. Actual total annual PV generation a Lark Rise between Oct-16 and sep-17 (in temporary throttled-down mode to limit export below 3.8kW) against actual demand on the same period and PV generation estimate by Energelio (once full PV generation capacity can be enabled) in their Self-consumption report of 29th of April 2016

Figure 11 compares annual electricity consumption on site between Oct-16 and Sep-17 with the recorded PV production (in throttled-down mode to limit export to the grid to 3.8kW) in the same months and to the annual PV production estimation by Energelio (once full PV generation capacity can be enabled) in their self-consumption report of 29th of April 2016 included in the appendices of this report. Due to the export limiting control on the PV panels, the total electricity generated on site during this period is not enough to cover the house total demand. As explained previously, the reduction in the energy generation is due to export limits that were imposed to avoid overloading the local grid infrastructure. However, according to Energelio's report, PV generation by the installed 12.4kWp system can produce twice as much energy as the annual demand, and this will be tested once the battery store is installed.

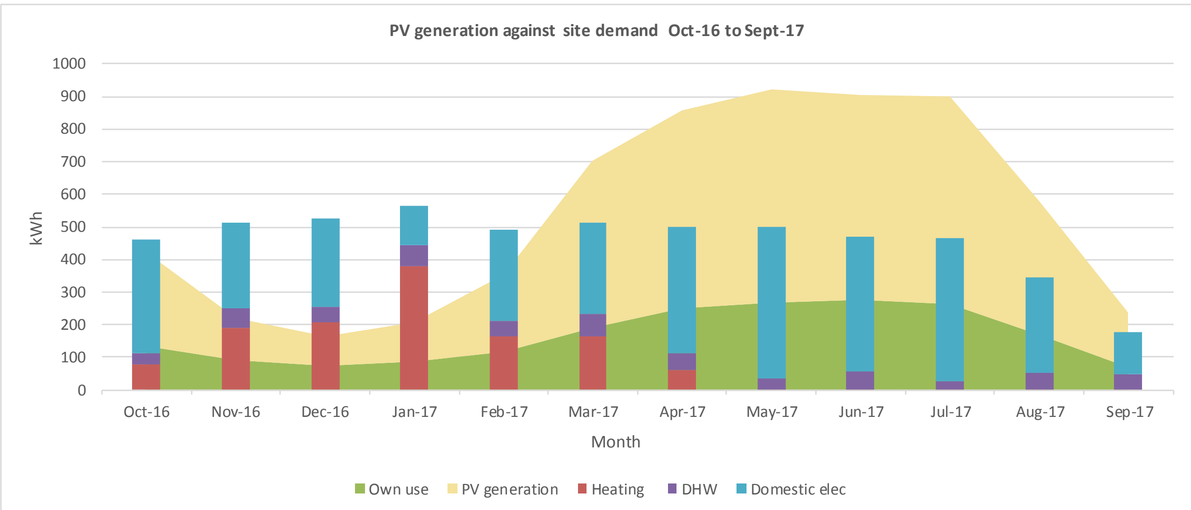


Figure 12. Showing PV electricity generation (ramped down pending battery storage, to avoid overloading the grid) and total electricity demand of Lark Rise between Oct-16 to Sep-17

Figure 12 shows PV electricity production against total electricity demand between Oct-16 and Sept-17. As in previous graphs, yellow area indicates total PV electricity generation on site and green area is the electricity generated by the PV installation that has been used on site and the vertical bars represent the total electricity demand of the house each month of this period. Total electricity demand has been split into heating, DHW and the rest of the 'domestic' electricity consumption of the house (sockets, lighting, MVHR, cooking and miscellaneous). The graph shows that with generation limited to 3.8kW, PV generation could potentially cover total electricity demand of 7 months out of 12, from March to September if a battery was installed. (Note this is not to say that a 3.8kWp installation would achieve the same result, since a smaller installation would produce a different generation curve to a larger installation which is capped). Due to the batteries not being installed on site yet, the self-consumption ratio in the year analysed was 44.4 %, calculated as the total energy used on site from the PV installation divided by the total energy generated on site. However, SCR estimated in Energelio's report for after installation of a 13kWh battery capacity is 78.6%.. In fact, PV generation could potentially cover almost all winter heating consumption (red part of vertical bars) once the batteries are installed on site (figure 13).

Figure 12 shows some odd results during the full year analysed, as the total electricity consumption of the blue 'domestic' category (power sockets, MVHR, lighting, cooking and miscellaneous) increases considerably during the summer months from April to October, keeping the total electricity consumption constant almost the whole year, between 400 and 500 kWh each month. By contrast, we would have expected a reduction of the total electricity consumption during these months as daytime is longer and the weather is warmer the lights would be turned on less hours a day. Also cooking habits may change to cold lunches and dinners and people tend to spend more time out of the house.

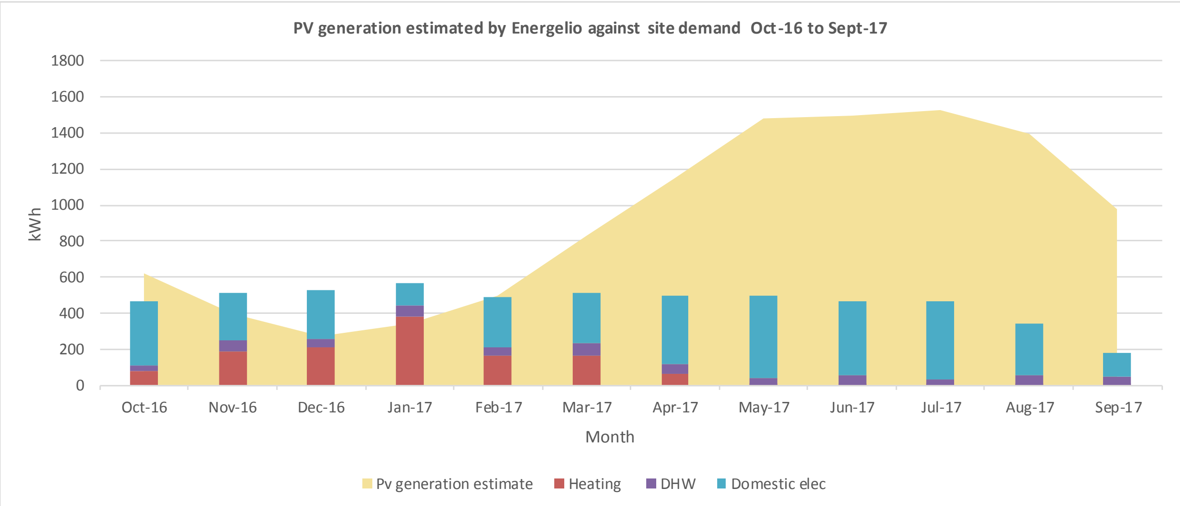


Figure 13. PV annual electricity production estimated by Energelio in their Self-consumption report of 29th of April 2016 against actual annual consumption at Lark Rise between Oct-16 and Sep-17. The house produces more than twice its own energy needs and is almost autonomous in Winter. Battery storage is required to allow the PV panels to avoid overloading the grid, so that they can perform as shown in this graph.

Figure 13 shows, in the columns, the energy demand pattern at Lark Rise from October 2016 to September 2017. Coloured yellow in the background, is the estimated un-throttled annual PV generation based on Energelio's self-consumption study (Energelio , 2016).

Figure 13 shows that once the 13kWh battery store is installed, the PV panels can be un-throttled with the following results:

1. On an annual basis, the building is likely to generate more than twice as much energy from its solar panels as its occupants consume in a year.
2. Monthly, the building is likely to be completely autonomous for 9 or 10 months of the year.

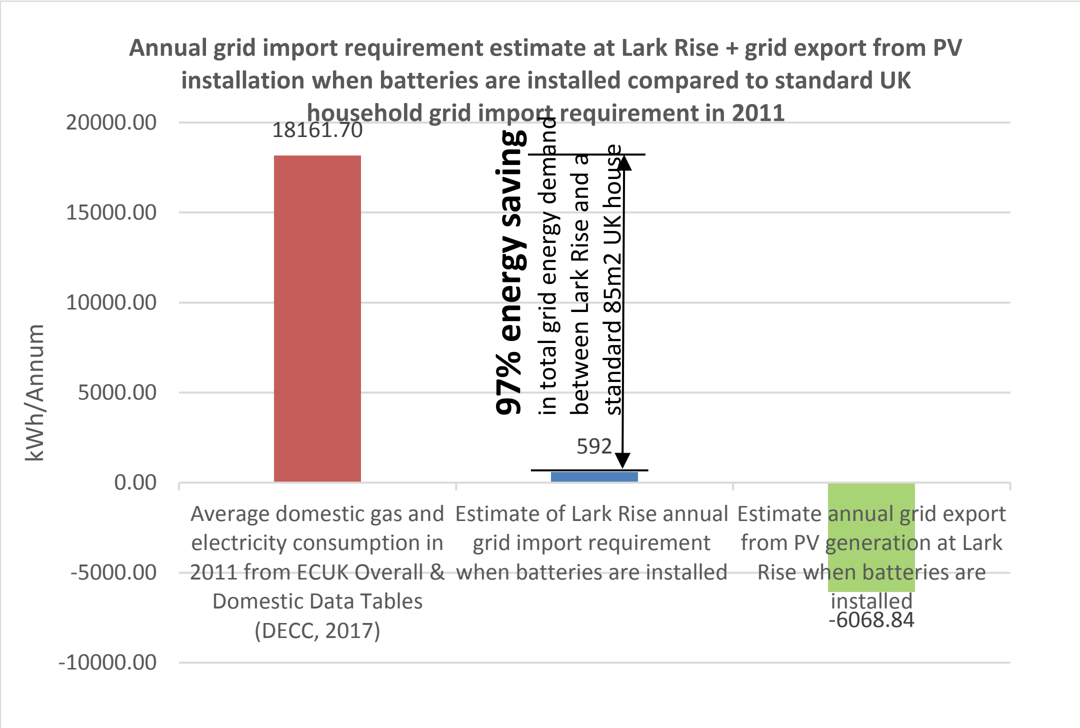


Figure 14. Grid energy requirements – UK average domestic gas and electricity consumption in 2011 from ECUK Overall & Domestic Data Tables (DECC, 2017) and Lark Rise compared. Figure 15 (below) as above but shown per square metre.

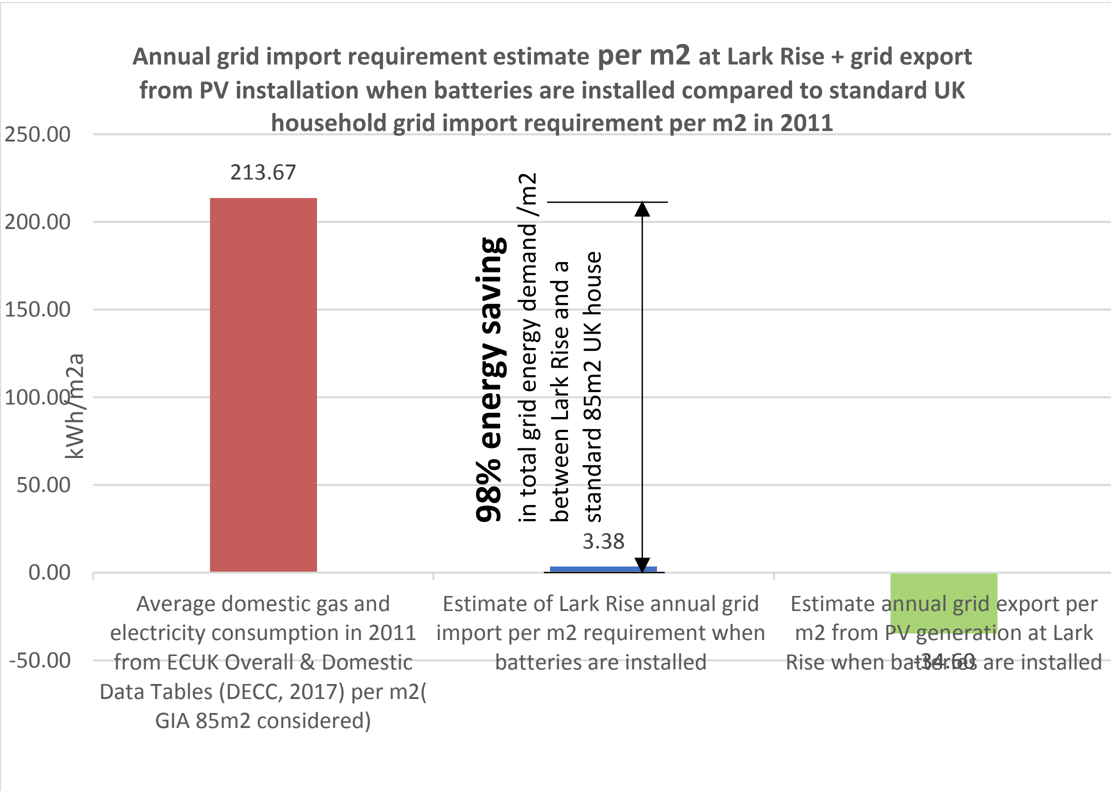


Figure 14 shows a comparison of the total energy draw-down from the National Grid between a standard UK house in 2011 (DECC, 2017) and the fully-operational Lark Rise. When the battery store is installed, Lark Rise is expected to achieve a 97% saving in grid energy demand when compared to the standard UK household annual energy requirements. Figure 15 shows, that when the battery store is installed, Lark Rise is expected to achieve a 98% saving in grid energy demand per square meter, when compared to the standard UK household annual energy requirements (DECC, 2017).

4 Conclusions

1. Figure 3 shows that without taking account of rooftop energy production, Lark Rise has delivered 85% reduction in post-occupancy total annual energy consumption compared to a standard UK house.
2. Figures 14 & 15 show that the fully operational Lark Rise (with battery store and un-throttled 12.4kWp PV production) is expected to deliver a 97% reduction in post-occupancy grid-load compared to a standard UK house of 85m2 and a 98% reduction on a per square metre basis.
3. The annual total in-use grid import of Lark Rise (with battery store and un-throttled PV 12.4kWp production) is estimated to cost 592kWh x £0.182 = £107.74 for all uses (Nottingham Energy Partnership, Nov 2017).
4. The annual total in-use grid export of Lark Rise (with battery store and un-throttled PV 12.4kWp production) is estimated to earn 6069kWh x £0.04/kW = £242.76.
5. Lark Rise (with battery store and un-throttled PV 12.4kWp production) could potentially be fully autonomous if the indoor temperature was allowed to drop a little in November, December and January, such as might call for a pullover, combined with a big effort to cut lighting and miscellaneous power consumption. It would be interesting to test this hypothesis.
6. Alternatively, Lark Rise could be fully autonomous if 141kg of seasoned logs were burnt in the living room log burner during November, December and January (an average of 1.5kg per day). (Nottingham Energy Partnership, Nov 2017). To purchase these, according to the same source, would cost £29.31. Alternatively, it would be interesting to consider how much woodland would be needed to sustainably harvest 141kg of seasoned logs per year, returning the ash to the ground to help fertilise the re-growth of timber.
7. Alternatively, Lark Rise could benefit from a form of renewable energy that could reliably close the small winter gap, such as wind or tidal power.
8. Once the battery has been installed, we will be able to assess how much excess solar-generated energy is available to power an electric car and when sufficient excess power is available for this, and to assess the potential for an electric car to usefully store energy not just for its own use, but for the benefit of the house and its occupants' needs. It should be clear, however from figure 13 that even such a high performance plus-energy building as Lark Rise, will not have sufficient excess energy to power an electric motor vehicle from November to January, regardless of whether the house is connected to a microgrid of similar houses. To achieve this, some additional winter-optimised renewable energy needs to be fed into the microgrid to reliably close the small winter gap. This could be achieved by wind or tidal power. Microgrid designers should take note.

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