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Assessing The Potential For Demand-Side Storage To Buffer The Differential Between Real-Time Demand and Renewable Energy Supply in Orkney

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Abstract

Increasingly frequent curtailment of renewable energy generation in Orkney due to grid constraint, both within the Orkney Islands and between Orkney and the UK mainland, has prevented the county from maximising its renewable energy generation potential. Behind-the-meter battery storage is one solution proposed to alleviate grid congestion by changing the energy demand profiles of individual properties throughout Orkney, attempting to buffer the gap between generation and demand, and reducing the carbon intensity of the energy consumed in the county as a consequence. By using energy consumption data collected from five individual properties in Orkney in addition to Orkney-wide demand and generation data, an Excel model was created in order to determine by how much the demand profiles of these properties could be altered using a 14kWh battery installed behind the meter in such a way that energy demand could be increased during periods of high renewable generation, and decreased otherwise. The results suggested that the most effective way to maximise renewable energy consumption and to reduce associated CO_2 emissions was to use behind-the-meter storage combined with solar panels, with behind-the-meter storage used in isolation having a more modest effect. Based on the model created and calculations performed, behind-the-meter battery storage does appear to be a solution to grid constraint worthy of further research, but more detailed and rigorous models and calculations, along with an assessment of financial feasibility, are required before a definitive conclusion can be made.

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In memory of Gareth Woodruff, my diving buddy, friend, and fellow Orkney enthusiast who recently passed away. He will be sorely missed.

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1 Introduction

1.1 Motivation

Scotland is a nation in a unique position to take advantage of plentiful natural resources for the generation of renewable energy, owing both to its windy climate (Früh, 2013) and extensive coastline (Neill *et al.*, 2017), allowing the exploitation of wind as well as wave and tidal power. The Orkney Islands in particular, located off the north coast of Caithness, have the potential to be a powerful example of what can be achieved when renewable energy is embraced, accelerating the process of decarbonising the local electricity supply as well as offering a potential stimulus to the local economy (Coon *et al.*, 2015).

Orkney is an archipelago of over 70 islands and skerries*, 20 of which are permanently inhabited. According to the 2011 census (Scotlandscensus.gov.uk, 2017), there are just over 21,000 people living in Orkney. The City of Kirkwall is the largest settlement on the island and its administrative centre. The primary industries on Orkney have historically been farming and fishing, although tourism is now the largest sector of the local economy, and renewable energy has also grown to be a significant contribution (Hie.co.uk, 2017).

In 2013, it was reported that Orkney could now produce 103% of its electricity needs from renewable generation (Engineering.com, 2016), which is a significant achievement for a county that had almost no renewable energy 10 years ago. However, this statistic oversimplifies the complex energy supply and demand dynamic which exists in Orkney. The reality is that, while the progress made up to this point is commendable, there is a significant amount of further development required if Orkney is to take full advantage of the huge natural resources available to it, and finding the best way to achieve that is one of the key motivations for this research.

Orkney is currently connected to the UK mainland grid via two 33kV sub-sea cables (SSEPD, 2017). Before the second cable was connected in the late 1990s, Orkney relied on a diesel power station located in Kirkwall for its energy generation, with the sub-sea cable acting as a backup in case the power station failed. However, since the installation of the second cable, the power station became an emergency backup, and all of Orkney's energy was imported from the UK grid.

This began to change in the early 2000s when the first onshore wind farms were commissioned to provide a basic amount of indigenous generation capacity for Orkney. Since then, there has been a dramatic increase in both wind and solar generation, with wind constituting the most significant generation capacity. Over 6MW of generation capacity from small-scale wind† has been granted planning permission (Aquatera, 2014), with planning applications peaking sharply around 2012 as a result of the reduction of feed-in tariffs, and large-scale wind farms‡ have an installed capacity of just over 43MW, with an additional 17MW having been granted planning permission as of 2014. There has also been a limited amount of tidal and wave power connected to the grid, but at the time of writing these technologies are still in the early stages of deployment. The total annual energy generation exceeds the demand within Orkney, and the subsea cables which were originally installed to import energy to Orkney are now net exporters from Orkney to the UK mainland. However, while this is an

*A skerry is defined as a small rocky island or reef, typically too small for human habitation.

†Wind turbines with a generation capacity of 50kW or less.

‡Wind turbines each with generation capacity greater than 50kW.

Figure 1: Map of Orkney (Google.co.uk, 2017)

accurate macro level description of the Orkney grid, it is not so simple when energy usage and generation is tracked at a smaller time scale.

As is the case for most of the distribution grid across the UK, the grid in Orkney was built to allow the distribution of power away from a centralised source—in this case the diesel power station in Kirkwall—to power the extremities of the islands. However, with the advent of wide-spread wind turbine construction across the county, often in relatively remote locations, the grid now has to withstand large amounts of electricity generation at the edges of the grid, predominantly distributing it back into the more densely populated areas of Kirkwall and Stromness, where the majority of the energy demand is located. This increase in local generation capacity has exposed the limits of what the Orkney grid can do in its present form. As shown below, the grid is arranged into zones, and between each zone there is a "pinch point", a location where the grid converges and the amount of power that can be transmitted is limited.

The primary consequence of this is that much of the energy generation capacity installed on Orkney cannot always be utilised at any given time, even if there is sufficient demand throughout the county for the energy. Due to the physical limitations of the grid infrastruc-

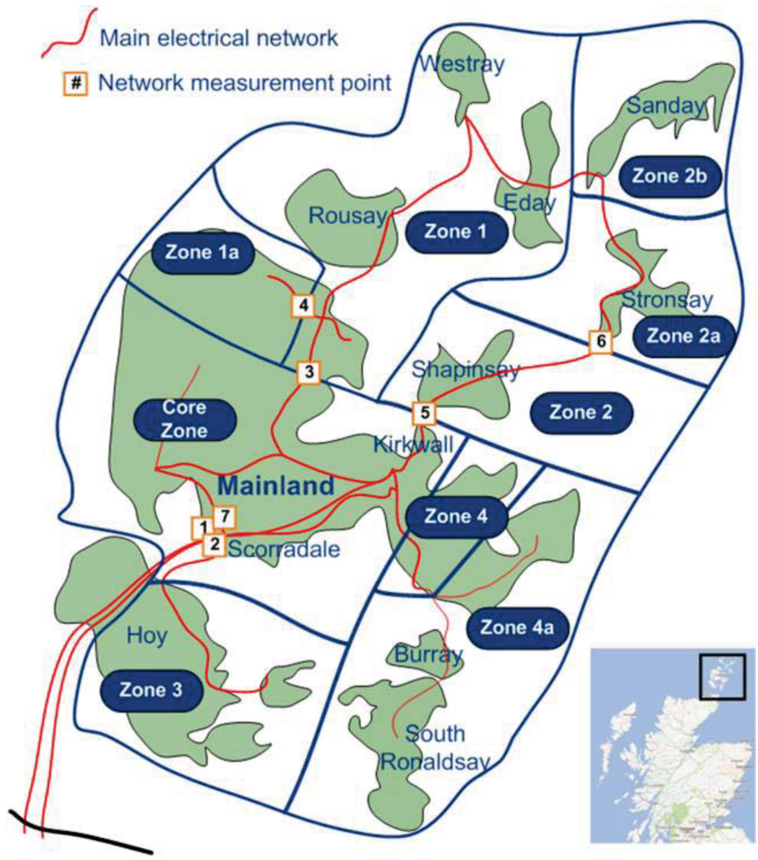

Figure 2: Map showing the different grid zones in Orkney (Aquatera, 2014)

ture, there is a cap on the amount of energy that can be safely transmitted from generators in one zone to consumers in another. In order to prevent an overloading of the grid, an Active Network Management (ANM) system (Kane and Ault, 2015) was installed on the Orkney grid in 2009. Real time information is fed into the system from a selection of network measurement points located in between the different grid zones and when the specified capacity limit is reached at those points, the management system will reduce the output from the New-Non-Firm Generation* (NNFG) wind turbines in order to balance the grid. While unavoidable at present, this curtailment of wind power is clearly undesirable, as it wastes a perfectly good natural resource with which to generate electricity by preventing the use of wind turbines which have already been installed and financed. There is a clear desire to find a solution to this problem, so that current owners of wind turbines can maximise the return on their investment, and also so that others who wish to purchase a wind turbine for electricity generation can do so. As of 2012, with the exception of the smallest generators at 3.6kW per phase or less, no new turbines can currently be built due to a moratorium imposed by SSEPD amid fears of overloading the grid (Aquatera, 2014).

*New-Non-Firm Generators are those which are allowed to connect to the grid on the condition that they agree to cease generation at times of reduced demand and/or excessive generation.

1.2 Solutions To Curtailment

In addition to the ANM system as described above, a wide variety of solutions have been proposed at different times and by different sectors to attempt to resolve the issue of grid constraint and generation curtailment within Orkney. One solution proposed is to expand the uses of electricity across the county in order to increase demand. By doing so, particularly in zones which regularly experience generation curtailment, there would be a reduced need to curtail generation because there would now be an additional, immediate demand for it. Examples of demand increase include electric vehicles, ground-source and marine-source heat pumps, and hydrogen and fertiliser production (Aquatera, 2014). Each of these options has varying degrees of economic feasibility and practicality, but all would offer an additional productive use for energy which would otherwise not be generated, and would displace more carbon-intensive alternatives, such as petrol for internal combustion engine vehicles and oil for heating properties.

Another solution to help alleviate grid congestion on Orkney is energy storage. This is something which has been widely acknowledged (Waterson, 2017) to be necessary in any situation where renewable forms of generation are to be the primary energy suppliers due to the inherent intermittency associated with almost all forms of renewable generation. If in Orkney it were possible to store some of the energy produced at times of peak generation in order to then use it when generation decreases, such as when the wind stops blowing for wind turbines, then this would reduce the need to import more carbon-intensive electricity from the UK grid, reducing the need to curtail electricity generation at times of low demand. There are a number of different options available to store energy, in terms of both the technology used and the location at which the storage takes place.

One option for energy storage is to use excess energy not required by the grid to power an electrolyser which, when applied to water, could produce hydrogen gas (Ancona *et al.*, 2016). This hydrogen could then be stored and converted back to electricity, either with a fuel cell or a modified internal combustion engine (Vliet *et al.*, 2010), in order to meet local grid demand for energy when generation is low. Other uses could include powering hydrogen cars and ferries, or fertiliser production for agriculture (Garcia, 2017). There are a number of advantages to using hydrogen as an energy storage system, including the fact that it is easily transferable for some applications, such as when filling a hydrogen vehicle compared to charging an electric one (Lane, Shaffer and Samuelsen, 2017). However, in applications where electricity is the only required output of the hydrogen after production, as opposed to also requiring heat, the efficiency of using hydrogen as an energy storage method is fundamentally limited (Kotowicz *et al.*, 2017), and different options for energy storage may be more suitable for applications in Orkney.

A method that is widely used across the UK is Pumped Storage Hydro (Gils *et al.*, 2017), where excess electricity is used to pump water up to a reservoir at a higher elevation, converting the electrical energy to gravitational potential energy. When electricity demand increases, the water is allowed to flow back down to the lower reservoir, operating an electricity generator as it does and creating electricity to go back into the grid. While widely used across the UK, the efficiency for this process is moderate at best (Black and Strbac, 2006), and regardless would be entirely inappropriate for Orkney due to the local topography.

A third approach to energy storage which is more suited to the specific situation in Orkney is small-scale storage. Many different options are available in terms of storage technologies, chemical battery based or otherwise, but Lithium-Ion batteries appear to be one of the more attractive options in terms of cost and efficiency, and it is the technology that this research will be centred around. Battery technology has progressed significantly over recent years, and many of the previous issues with different battery technologies such as battery life, charging times and memory are becoming less and less significant (Langridge and Edwards, 2017). For this reason, combined with the fact that current Lithium-Ion batteries can store energy with almost perfect efficiency (Batteryuniversity.com, 2017), it is unlikely that any future energy storage pathway would not include batteries of a similar form in one way or another.

Energy storage using batteries has the advantage that, as well as being more efficient than hydrogen electrolysis, the batteries can either be concentrated in one central storage bank, or they can be distributed all over the grid. This is in contrast to hydrogen storage, which generally can only be implemented at a small number of centralised locations due to the cost and size of the equipment necessary (Gahleitner, 2013). This means that there is the flexibility to either store the energy at the point of generation (supply-side), or alternatively at the point of use (demand-side). While there are potential benefits of either approach, the modularity and added flexibility of demand-side storage mean that this is the area which this project is going to investigate.

1.3 Research Focus

The purpose of this research is to attempt to determine the feasibility of utilising demand-side storage in Orkney using Tesla Powerwall Lithium-Ion batteries (Tesla.com, 2017) installed behind the meter in private domestic and commercial properties. This system of energy storage is currently being trialled by Solo Energy Ltd (Solo Energy, 2017), which has provided the majority of the data for this research. While alternative Lithium-Ion batteries are available, the Powerwall unit was chosen predominantly for the association with the Tesla brand. Tesla has been a world leader in the fields of electric vehicles and renewable technology (Davis, 2017), and it was felt that it was a healthy brand association to have with the services that Solo Energy Ltd offer. This is in addition to the relatively compact size and competitive pricing of the battery offered by Tesla.

Both demand-side and supply-side energy storage have become an increasingly important area of research and investment in the UK (Energy.stanford.edu, 2017). Consumer based, behind-the-meter storage is one example, and there are now several companies including Tesla (Tesla.com, 2017) and Sonnen (Sonnenbatterie.de, 2017) that offer, or plan to offer, battery units for installation in properties, allowing energy consumers to take advantage of the benefits of energy storage. Such is the momentum behind this approach that the UK government recently announced an investment of £246M to fund innovation and research in battery technology (Ambrose, 2017). The benefits that battery storage could bring include the ability to maximise the output from behind-the-meter solar panels attached to a particular property, or it could be used to take advantage of cheaper electricity if the consumer is on a multi-level tariff (Lord, 2017). These are advantages which this form of energy storage can provide to consumers throughout the UK, but the nature of the grid constraint taking place in Orkney means that such technology has the potential to be particularly useful.

The initial motivation for Solo Energy Ltd to install Powerwall batteries in properties on Orkney was to allow new-build properties to maximise their consumption of solar power generation from behind-the-meter solar panels attached to their roofs. Due to the grid constraint on Orkney, the Distribution Network Operator (DNO), SSEPD, have stated that they will not allow any new solar generation to connect to the grid until at least 2025. This means that if solar power were to be used at all in these new properties, it could only be for consumption by the property to which the panels were attached, rather than also having the option to feed in to the grid when there was excess generation available. Without battery storage, this would result in a significant waste of solar generation potential, particularly in the summer months when generation will typically be high, but energy demand for lighting and heating will be comparatively low. Therefore, the installation of the Powerwall batteries would allow any additional energy generated to be stored for consumption at a later time. However, while this is often promoted as the primary purpose for such energy storage products, grid constraint in Orkney provides an additional use for battery storage beyond maximising solar consumption, and determining to what extent this could be the case is the purpose of this research. The concept is to use the batteries to make the local grid more dynamic and ease constraint within the county by adjusting the demand of each household according to the energy generation available at a given time. An idealised version of the practical use of the battery units would consist of charging from the grid at times of low demand and/or high generation, and discharging its energy at times of high demand and/or low generation. The discharged energy could remain behind the meter to be used in the household, or sold back into the grid for a feed-in tariff if the household does not have enough demand of its own. To facilitate this, all batteries would be connected to a cloud-based grid controller (Ellis and Breathnach, 2016) which could then optimise the charging patterns of the batteries. This additional use for the batteries will be especially advantageous during the winter months, when solar generation will be very low and household energy demand is likely to be higher. In this situation the batteries would have very limited functionality, and so introducing the additional purpose of grid balancing allows the batteries to continue to serve a purpose when solar power is no longer prominent.

The intended consequences of this are three-fold. Firstly, once operational maturity has been reached, households should be able to reduce their energy bills by being able to change much of their energy demand from high to low price times. Assuming that consumers are on a multi-level energy tariff, they would now have the capability to increase their demand, i.e. charge their battery, at a time of day when the electricity price is low, and to discharge their battery back into the grid when the price is higher, selling it back at a higher price, assuming the stored energy is not required for consumption within the property itself. Secondly, by helping to ease grid congestion at peak generation times, it should be possible to allow more renewable generation capacity to connect to the grid (Aquatera, 2014). As previously mentioned, there is a moratorium on the construction of any new wind turbines in Orkney barring the very smallest, a result of the inflexibility of electricity demand and the variable nature of wind generation. If energy demand can be made more flexible to better match generation then this will provide a significant benefit to the DNO, and there will be a stronger argument for lifting the moratorium and increasing the renewable energy generation capacity of Orkney. Thirdly, this will help to reduce the carbon intensity of the electricity consumed on Orkney. At present, when local generation is greater than real demand on Orkney, the excess energy is exported to the UK mainland grid as there is currently no ability to store it for later use in the county. Equally, when demand exceeds local renewable generation, the differential must be balanced by importing energy from the UK grid—energy that has not come solely from renewable sources as local generation on Orkney generally has. By making demand more dynamic and opening up the option for energy storage on Orkney, the energy which currently has to be exported due to low demand could instead be stored and used at a later time, when energy would have to otherwise be imported from the more carbon-intensive UK grid.

The final point mentioned above is particularly significant, and is the motivation for pursuing an additional goal for this research. This is to calculate what the carbon footprint of the electricity used in Orkney is at present, and then to subsequently determine what this could be reduced to with the utilisation of demand-side storage. The carbon intensity of the local grid has particular significance for the construction industry where energy efficiency ratings are an important part of evaluating the quality of a building. At present, the definitions used in the energy efficiency standards assume that all electricity used has a carbon intensity equal to that of the average value of the UK grid (Gov.scot, 2017). Given that a significantly greater proportion of electricity used on Orkney is generated from renewable energy than is the case in the rest of the UK (Aquatera, 2014), this has resulted in misleadingly poor energy efficiency ratings of residential properties. It is hoped that it may be possible to begin the process of reviewing the standards for special cases such as Orkney if it can be convincingly shown that the carbon intensity of electricity used there is significantly lower than the UK average.

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2 Methodology

2.1 Data Collection

The data which was used for this research is varied and was gathered from several different sources. The primary data which was previously unavailable consists of the energy consumption information from five different properties on Orkney. These properties were fitted with OWL Intuition (Theowl.com, 2017) energy monitoring units; these can record the power consumption of a property to a resolution of as little as 12 seconds. Due to differences in property specification—one of them has solar panels fitted whereas the others do not—and variations in the time periods for which the data for each property was recorded, the properties were split into three different groups. From this point onwards, what will be referred to as property group A should be taken to mean the collection of properties 1, 2, 3 and 4, the energy consumption data for which was available from 08/10/16 13:33 until 31/10/16 23:59. Property group B consists of properties 1, 2 and 4, data for which was available from 03/06/17 02:05 to 30/06/17 17:04. Finally, property group C consists of property 5 only, although for uniformity of language it will still be referred to as property group C. This is the only group which utilises solar power and a limited amount of battery storage. The battery is used to maximise solar power consumption by storing additional solar-generated energy which would otherwise have been wasted, but at no point does the battery charge itself from the Orkney grid. This is an important distinction to remember, and its significance is something which is investigated later in this report. The demand and solar generation data for group C was available from 06/07/17 17:45 to 01/08/17 00:00. For groups A, B and C, the periods for which their data was available will be referred to as October, June and July respectively. While none of these datasets include any month in its entirety, it removes an unnecessary layer of linguistic complexity to simplify the terms in this way. The data collected for each of these groups was available to download from the monitors in the form of a CSV file, which could subsequently be manipulated using Microsoft Excel.

The data detailing the total energy generation and demand for Orkney was kindly provided by Aquatera Ltd as an Excel file, allowing for easy manipulation and comparison alongside the OWL Intuition energy consumption data. The data was available for the entire year of 2016, as well as for the first seven months of 2017. This data was available at a resolution of 1-minute intervals, allowing for high precision in any calculations performed involving the two datasets. Other data utilised such as the 2016 UK Government figures for the carbon intensity of the national grid were sourced from the UK Government website (Gov.uk, 2017).

2.2 Data Analysis

2.2.1 Mapping Demand and Generation

The first piece of analysis carried out was to make a general comparison between the energy demand and indigenous power generation on Orkney. Demand data in this case was sourced from both the individual demand profiles of the property groups mentioned in the data collection section and from the county-wide data provided by Aquatera. All renewable generation data was taken from the same Aquatera dataset.

All analysis was carried out and all graphs were produced using Microsoft Excel. The

"VLOOKUP" function was initially used to combine the datasets into one spreadsheet, taking the relevant data from separate Excel sheets and combining them together so that the same time intervals were defined for all datasets. This allowed the creation of a spreadsheet containing the individual demand profiles for different properties in each group, Orkney-wide power demand and Orkney-wide power generation. The demand profiles of the constituent properties for each group were combined together to create one overall demand profile per group using the basic mathematical function "SUM". The following information was then able to be calculated, using methods as described:

- Total energy generation and demand for Orkney as a whole. This is the information provided by Aquatera, therefore no significant manipulation was necessary.
- Total energy usage of each property group. These values were calculated by taking the sum of the total power demand figures, which are in watts, and dividing the sum by 60,000 to produce a result in kilowatt-hours, given that the uniform time interval for the power data was 60 seconds.
- Multiple graphical depictions of the trends present in the power demand and generation data. These graphs were created using the scatter graph plot function in Excel.

2.2.2 Calculating Carbon Intensity

The purpose of this section was to calculate what the "effective" carbon intensity was of the energy used throughout Orkney as a whole, and specifically by the different property groups. In order to perform the calculation, a number of assumptions were made:

1. That all power consumed when Orkney-wide demand was less than indigenous generation was generated entirely by renewable energy. While there is a small amount of power that is generated from non-renewable sources at the Flotta oil terminal and Kirkwall power station (Aquatera, 2014), these contributions were discounted. The power generated on Flotta was estimated to be no more than 0.49GWh annually as of 2014, and this power is intended only for the use within the oil terminal itself; the Kirkwall power station only generates to test its functionality on a monthly basis, and its contribution was so small as to not be worth including in the 2014 energy audit of Orkney (Aquatera, 2014).
2. That energy generated renewably on Orkney at times of high generation and low demand will not result in "negative emissions" if that energy is exported and fed into the UK mainland grid. While it may be tempting to claim that such a scenario results in the "saving" of emissions by displacing energy in the UK which would otherwise have been generated from fossil fuels, it essentially allows one to dodge the primary issue with renewable generation. As stated in the introduction, there are claims that Orkney can now produce over 100% of its energy needs (Engineering.com, 2016), but the fact that there is still the regular need to import energy into Orkney from the UK mainland shows that this is not strictly true. While that may be the case in terms of the total annual quantity of energy required for the islands, the timing of the generation is just as important as the quantity. By allowing surplus renewable energy exported to the UK grid to count towards the target amount of energy generation required to

power Orkney, one ignores the fact that, if the rest of the UK were at the same stage of renewable energy implementation as Orkney, there may not be a use for that exported energy. The only reason why Orkney is able to export its surplus energy is because the UK mainland is not yet in a position to generate sufficient renewable energy on its own. If that is to change, then the underlying issue of intermittency of renewable energy needs to be addressed, and allowing credit for "negative emissions" will only serve to inhibit the pursuit of a solution.

3. That the carbon intensity of renewably generated electricity is zero. This is generally true in terms of associated *operational* carbon emissions as no fossil fuels are required to rotate the blades of a wind turbine, but it is important to note that there is a non-zero amount of embodied carbon within each turbine, a life-cycle analysis for which could be calculated and then converted into an emissions factor for each unit of energy produced by the turbine. However, it is beyond the scope of this project to take account of additional factors such as these. The assumption will be that there are no associated emissions with renewable energy generation, primarily because the purpose of the carbon intensity calculation in this project is to demonstrate the magnitude of the difference in energy carbon intensity that could be achieved by utilising demand-side storage, rather than to provide an exact figure with which to perform further detailed calculations. The real carbon intensity of the primary renewable supply on Orkney, onshore wind, is calculated to be less than 5% that of the UK grid as a whole (Thomson and Harrison, 2015; Gov.uk, 2017), and therefore it seems reasonable to discount this to zero for the purposes of simplicity at this stage. Taking account of such additional factors would be a legitimate exercise to undertake, but it is a task requiring more thorough and detailed calculation than what the scope of this project allowed.

4. That at a time when Orkney-wide demand exceeds indigenous generation, and therefore there is a net energy import from the UK grid, the ratio of renewable energy to imported energy that each individual consumer uses is equal to the ratio of total indigenous renewable generation to imported UK energy. For example, if total indigenous generation is equal to 10MW, and Orkney-wide demand is 20MW, then the ratio would be 1:1. Therefore, if a property was consuming 2kW of energy, it would be consuming 1kW of Orkney-generated renewable energy and 1kW of imported energy from the UK grid. The alternative to this would be to assume that, at a time of net energy import into Orkney, the energy that an individual property consumes has come entirely from the UK grid, and would therefore have 100% of the UK grid electricity's carbon intensity. While there is a possible argument to be made for this approach in some circumstances, this clearly becomes incoherent if the principle is applied to every consumer on Orkney, the only logical conclusion of which would be that all of the energy consumed on Orkney originated from the UK mainland, which would be demonstrably false.

Given these assumptions, the carbon intensity of the energy consumed across the whole of Orkney from time t_0 to a time T, $I_{\text{Orkney}}(t_0, T)$, was calculated by the following equation:

$$I_{\text{Orkney}}(t_0, T) = I_{\text{UK}} F_{\text{Orkney}}(t_0, T)$$

given

$$I_{\text{UK}} = \text{Carbon intensity of UK grid}$$

$$F_{\text{Orkney}}(t_0, T) = \text{Fraction of UK energy consumed in Orkney from } t_0 \text{ to } T$$

$F_{\text{Orkney}}(t_0, T)$ was calculated using the following formula:

$$F_{\text{Orkney}}(t_0, T) = \frac{\sum_{t=t_0}^{T} D(t)B(t)H_{\text{Orkney}}(t)}{\sum_{t=t_0}^{T} D(t)}$$

given

$$H_{\text{Orkney}}(t) = \text{Fraction of consumed energy on Orkney at time } t \text{ imported from UK grid}$$

$$D(t) = \text{Orkney-wide power demand at time } t$$

$$B(t) = \text{Binary factor; 1 if net energy import to Orkney at time } t\text{, 0 otherwise.}$$

The value used for I_{UK} is 0.44932kg CO_2e/kWh.

$D(t)$ was provided in the Orkney-wide demand and generation data from Aquatera, from which $H_{\text{Orkney}}(t)$ and $B(t)$* were also calculated.

$$H_{\text{Orkney}}(t) = \frac{D(t) - G(t)}{D(t)}$$

and

$$B(t) = \text{IF}\Big(D(t) > G(t), 1, 0\Big)$$

given

$$G(t) = \text{Orkney-wide power generation at time } t$$

The IF function in Excel uses the syntax $\text{IF}\Big(\text{argument}, \text{true}, \text{false}\Big)$, so the formula for $B(t)$ above would read: if $D(t) > G(t)$ then cell value = 1, otherwise = 0.

*This binary factor is to allow for the implementation of assumption 2 as previously described.

Moving on from Orkney as a whole to the energy consumed specifically by each property group, the carbon intensity values of the energy consumed by the property groups from time t_0 to a time T, $I_{\text{Property}}(t_0,T)$, were calculated by the following equation:

$$I_{\text{Property}}(t_0,T) = I_{\text{UK}} F_{\text{Property}}(t_0,T)$$

given previous definitions, and in addition

$$F_{\text{Property}}(t_0,T) = \text{Fraction of UK energy consumed by properties from } t_0 \text{ to } T.$$

$F_{\text{Property}}(t_0,T)$ was calculated using the following formula:

$$F_{\text{Property}}(t_0,T) = \frac{\sum_{t=t_0}^{T} P_{\text{Property}}(t) B(t) H_{\text{Orkney}}(t)}{\sum_{t=t_0}^{T} P_{\text{Property}}(t)}$$

given

$$P_{\text{Property}}(t) = \text{Power demand of the properties at time } t$$

$P_{\text{Property}}(t)$ was provided in the basic data from the OWL monitoring system.

2.2.3 Introducing Battery Storage

The purpose of this section was to model how the energy consumption profiles of the property groups could be changed if battery storage were implemented. The first step was to plot what is to be defined as the "cumulative energy balance". This is effectively the running total of imported and exported energy associated with the properties. It is a plot of $E_{\text{Cumulative}}(t_0,t)$ against time. $E_{\text{Cumulative}}(t_0,t)$ is defined as follows:

$$E_{\text{Cumulative}}(t_0,t) = \text{Energy import consumed/surplus for the properties from } t_0 \text{ to } t.$$

where

$$E_{\text{Cumulative}}(t_0,t) = -\frac{\sum_{t=t_0}^{t} P_{\text{Property}}(t) H_{\text{Orkney}}(t)}{60}$$

The negative sign was introduced to allow the graph to be more intuitive, with a positive value indicating an indigenous energy surplus and a negative value a deficit.

Imported energy has a negative sign, and is calculated in accordance with assumption 4 from the previous section. Exported energy has a positive sign, and in this case is defined as the surplus indigenous generation which the properties would be "entitled" to consume in proportion to their current power demand, without requiring additional energy to then have to be imported from the UK grid. This is the same concept as explained in assumption 4 of the previous section, but instead of applying to how much of the imported energy the property must take responsibility for, it is instead a measure of how much additional energy the property could use at times of net export, without exceeding total indigenous generation if every consumer on Orkney were to increase their consumption by the same proportion.

The result of plotting this is to demonstrate for how much of the relevant time period for each property group that the properties could solely rely on indigenous renewable generation, assuming it was possible to store some of the energy for later use. A negative point on the graph denotes a time when the energy demand of the property from the beginning of the plot up to that point has exceeded what indigenous generation could provide. Similarly, a positive point on the plot denotes a time when, if the timing and capacity of energy storage was unlimitedly flexible, there would in principle be no need to use any imported energy from the UK mainland. It is important to remember that this is a plot of cumulative energy, not of instantaneous energy use. Therefore, a positive gradient on the graph indicates a net instantaneous energy export from Orkney, i.e. an excess of indigenous generation that could be otherwise utilised, and a negative gradient indicates a time of net instantaneous import, when indigenous generation is proportionately insufficient at that point in time to match the demand of the properties. Therefore, if energy storage could be utilised with a hypothetically unlimited capacity, then any point on the graph which was positive would denote a time when no UK import energy would be required, whereas without storage, only the points on the graph with a positive *gradient* indicate no need for energy import.

Following on from this, a model can be created to simulate what the energy demand profile of each property group would have been in their relevant time period if they had Tesla Powerwall batteries installed in each property. In order to do this, a number of assumptions were made:

1. That all of the batteries used are 100% efficient in their charge and discharge cycles. In reality this is not currently the case, and it would be entirely possible to include an efficiency factor in the model, but for the purpose of this initial simulation it was decided that it was not a factor significant enough to outweigh the other uncertainties and variables in the rest of the data. The overall trend change for energy consumption will still have been essentially the same.

2. That the constituent properties combined in each property group are treated as one single property, with one single battery that is shared by all of them. Therefore, with each Powerwall unit having a capacity of 14kWh, the four properties in group A combined were modelled as if there were a single 56kWh battery, and similarly for the other groups. It is possible that the final result may have been marginally different if each property were modelled individually due to differences in energy consumption patterns between them, but this did not seem to be particularly relevant when assessing the effectiveness of a system to be implemented on any significant scale.

3. That the battery would charge at a time when there was a net export of energy from Orkney until full, and discharge at a time of net import until empty. Furthermore, the charging rate at time t would be equal to, and no higher than, $-P_{\text{Property}}(t)H_{\text{Orkney}}(t)$, assuming net energy export on Orkney and the battery is not yet full. This is because, while a much higher charging rate could be utilised when it is only a small number of properties which would be taking advantage of energy storage, it is the maximum

rate at which every consumer on Orkney could increase their energy demand and not require energy to be imported from the UK grid. This makes the use of the battery relatively conservative at this point, but it demonstrates the role that batteries could play in a scalable manner if implemented county-wide.

4. That there is no additional tactical use of battery storage which might involve discharging back into the Orkney grid instead of being used solely to power the properties. While this could prove to be an attractive option to take advantage of in the future, it is beyond the scope of this project to explore.

Given these assumptions, the following methods were used to create the models in Excel. Due to the addition of solar power for property group C, an additional level of complexity was required for the model, and the details of that follow those of the model used for groups A and B.

Property Groups A and B Firstly, a model for the battery storage level at a time t, $S(t)$, had to be created. Each cell was defined using a two-level "IF" function, using the same syntax as explained previously. The Excel formula would read as follows, using property group A as an example where group-specific values such as battery capacity are required:

$$S(t) = \text{IF}\left(H_{\text{Orkney}}(t) < 0, W(t), X(t) \right)$$

where $W(t)$ and $X(t)$ are the "IF" functions:

$$W(t) = \text{IF}\left(S(t-1) < 56, S(t-1) - \frac{P_{\text{Property}}(t) H_{\text{Orkney}}(t)}{60}, S(t-1) \right)$$

$$X(t) = \text{IF}\left(S(t-1) > 0, S(t-1) - \frac{P_{\text{Property}}(t)}{60}, S(t-1) \right)$$

A description of this model in words would go as follows. If there is a net energy surplus in Orkney, $H_{\text{Orkney}}(t) < 0$, then, if the battery is not yet full, $S(t-1) < 56$, then the battery will charge from the grid by an amount equal to $\frac{-P_{\text{Property}}(t) H_{\text{Orkney}}(t)}{60}$*, the current surplus divided by 60 to give a value in kWh, otherwise if the battery is full, then it would remain at its previous charge level, $S(t-1)$. If there is a net energy import into Orkney, $H_{\text{Orkney}}(t) > 0$, then, if the battery is not empty, $S(t-1) > 0$, then the battery will discharge to provide power to the property by an amount equal to the energy demand for the property for 1 minute (as the time step from one cell to another is 1 minute), $\frac{P_{\text{Property}}(t)}{60}$, otherwise the battery is empty and it remains at its previous charge level, $S(t-1)$.

Next, by utilising the $S(t)$ battery function as defined above, the adjusted grid demand at time t, $A(t)$, can now be calculated, from which the total energy consumption, carbon

*Note that when there is a net energy surplus in Orkney, H_{Orkney} has a negative value, hence the negative sign in this expression to make it positive.

intensity and all other quantities can then be deduced. Also utilising the Excel "IF" function, $A(t)$ is defined as follows:

$$A(t) = \mathrm{IF}\Big(H_{\mathrm{Orkney}}(t) < 0, Y(t), Z(t)\Big)$$

where $Y(t)$ and $Z(t)$ are the "IF" functions:

$$Y(t) = \mathrm{IF}\Big(S(t) < 56, P_{\mathrm{Property}}(t)\Big(1 - H_{\mathrm{Orkney}}(t)\Big), P_{\mathrm{Property}}(t)\Big)$$

$$Z(t) = \mathrm{IF}\Big(S(t) > 0, 0, P_{\mathrm{Property}}(t)\Big)$$

Putting this equation for the new grid demand into words would go as follows. If there is a net energy surplus in Orkney, $H_{\mathrm{Orkney}}(t) < 0$, then, if the present battery level is not full, $S(t) < 56$, then the grid demand will be equal to the property energy demand plus additional demand to charge the battery, $P_{\mathrm{Property}}(t)\Big(1 - H_{\mathrm{Orkney}}(t)\Big)$, otherwise if the battery is full then the grid demand is simply equal to the immediate energy demand of the property, $P_{\mathrm{Property}}(t)$. If there is a net energy import into Orkney, then, as long as the battery is not empty, the grid demand will be 0 because the property is consuming power from the battery to minimise the demand for imported UK grid energy; if the battery is empty then the grid demand is simply equal to the property demand, $P_{\mathrm{Property}}(t)$, as there is no alternative energy source to take advantage of.

This now provides data for what the energy consumption profiles would look like for property groups A and B if each property within them were fitted with a Tesla Powerwall battery and used as described. From this, total energy usage, energy imported from the UK grid, carbon intensity of energy used and graphical consumption patterns are all calculated and produced using the same method as for the original data without battery storage.

Property Group C In addition to those already stated above, extra decisions and assumptions had to be made when creating the model for property group C, owing to the additional complexity introduced by solar panels. Following on from assumptions already stated, these are as follows:

5. That there is no difference in terms of carbon intensity between solar power generated for the property behind-the-meter and energy consumed by the property from the Orkney grid at a time of surplus indigenous generation. While this may not strictly be correct in reality, it seems a reasonable simplification to make for the purposes of this model, given that in both cases the energy will have originated from an entirely renewable source.

6. That at a time of net energy import into Orkney, the energy demand of the property will first be met by solar generation when possible, and when this is not sufficient then it will be supplemented by consumption from the battery. Only if demand is greater than solar generation and if the battery is empty will the property consume energy from the Orkney grid when there is energy being imported from the UK mainland grid.

7. That at a time of net energy export from Orkney, the energy demand of the property will first be met by solar generation, and then supplemented by grid consumption when this is not sufficient. While there may have been a small additional advantage to be gained by allowing all solar generation at such a time to charge the battery and for all immediate demand to be satisfied from the grid, it seemed a more realistic assumption that, in practice, a property fitted with solar panels behind-the-meter will take advantage of solar generation, which would be free of charge at the point of use, before consuming energy from the grid.

Given these additional assumptions, the following model was created for the battery storage level at time t, $S(t)$:

$$S(t) = \text{IF}\Big(H_{\text{Orkney}}(t) < 0, W(t), X(t)\Big)$$

where $W(t)$ and $X(t)$ are the redefined "IF" functions:

$$W(t) = \text{IF}\Big(S(t-1) < 14, K(t), S(t-1)\Big)$$

$$X(t) = \text{IF}\Big(V_{\text{Property}}(t) > P_{\text{Property}}(t), L(t), M(t)\Big)$$

with $K(t)$, $L(t)$ and $M(t)$ being "IF" functions defined as:

$$K(t) = \text{IF}\Bigg(V_{\text{Property}}(t) > P_{\text{Property}}(t), S(t-1) + \frac{V_{\text{Property}}(t) - P_{\text{Property}}(t)\Big(1 + H_{\text{Orkney}}(t)\Big)}{60},$$

$$\text{cont. } S(t-1) - \frac{P_{\text{Property}}(t) H_{\text{Orkney}}(t)}{60}\Bigg)$$

$$L(t) = \text{IF}\Bigg(S(t-1) < 14, S(t-1) + \frac{V_{\text{Property}}(t) - P_{\text{Property}}(t)}{60}, S(t-1)\Bigg)$$

$$M(t) = \text{IF}\Bigg(S(t-1) > 0, S(t-1) - \frac{P_{\text{Property}}(t) - V_{\text{Property}}(t)}{60}, S(t-1)\Bigg)$$

given

$$V_{\text{Property}}(t) = \text{Solar power generation of the property at time } t$$

Putting these equations succinctly into words is challenging. In order to attempt to do so, it will be described in two halves—the first in the case when there is a net energy surplus in Orkney, $H_{\text{Orkney}} < 0$, and the second in the case when there is not. As such, number 1 below is a description of $W(t)$ and number 2 a description of $X(t)$.

1. If the battery is not full, then, if solar generation is greater than the energy demand of the property, $V_{\text{Property}} > P_{\text{Property}}$, the battery will charge at a rate equal to the sum of the additional solar generation beyond the property's requirements and the current surplus available from the grid, $\frac{V_{\text{Property}}(t)-P_{\text{Property}}(t)\left(1+H_{\text{Orkney}}(t)\right)}{60}$, otherwise, if solar generation for the property is less than its energy demand, then the battery will charge at a rate equal to the current surplus only, $\frac{-P_{\text{Property}}(t)H_{\text{Orkney}}(t)}{60}$. If the battery is full, then it remains at its previous charge level, $S(t-1)$.

2. If solar generation is greater than property demand, $V_{\text{Property}}(t) > P_{\text{Property}}(t)$, then, if the battery is not full, $S(t-1) < 14$, the battery will charge at a rate equal to the difference between solar generation and property demand, $\frac{V_{\text{Property}}(t)-P_{\text{Property}}(t)}{60}$, whereas if the battery is full then it remains at its previous value, $S(t-1)$. If solar generation is less than property demand, $V_{\text{Property}}(t) < P_{\text{Property}}(t)$, then, if the battery is not empty, $S(t-1) > 0$, the battery will discharge at a rate equal to the difference between the property demand and solar generation, $\frac{P_{\text{Property}}(t)-V_{\text{Property}}(t)}{60}$, in order to prevent the property from having to consume energy from the grid; otherwise if the battery is empty then it remains at its previous value, $S(t-1)$.

As with groups A and B, by utilising the $S(t)$ battery function as redefined above, the adjusted grid demand at time t, $A(t)$, can now be calculated. $A(t)$ is redefined as follows:

$$A(t) = \text{IF}\left(H_{\text{Orkney}}(t) < 0, Y(t), Z(t)\right)$$

where $Y(t)$ and $Z(t)$ are the redefined "IF" functions:

$$Y(t) = \text{IF}\left(S(t) < 14, N(t) - P_{\text{Property}}(t)H_{\text{Orkney}}(t), N(t)\right)$$

$$Z(t) = \text{IF}\left(S(t) > 0, 0, N(t)\right)$$

where $N(t)$ is the "IF" function:

$$N(t) = \text{IF}\left(P_{\text{Property}}(t) > V_{\text{Property}}(t), P_{\text{Property}}(t) - V_{\text{Property}}(t), 0\right)$$

Putting this into words, the same numbering method as above will be used, where number 1 represents a description of $Y(t)$, the case where there is a net surplus of energy in Orkney, $H_{\text{Orkney}} < 0$, and number 2 a description of $Z(t)$ when there is not.

1. If the battery is not full, then, if property demand is greater than solar generation, $P_{\text{Property}}(t) > V_{\text{Property}}(t)$, the grid demand is equal to the difference between property demand and solar generation, $P_{\text{Property}}(t) - V_{\text{Property}}(t)$, plus the current surplus available from the grid, $-P_{\text{Property}}(t)H_{\text{Orkney}}(t)$, otherwise if solar generation is greater than property demand then the grid demand is just equal to the current surplus, $-P_{\text{Property}}(t)H_{\text{Orkney}}(t)$, because all of the demand from the property for immediate consumption is met by solar generation. If the battery is full, then, if property demand is greater than solar generation, $P_{\text{Property}}(t) > V_{\text{Property}}(t)$, the grid demand is equal to the difference between property demand and solar generation, $P_{\text{Property}}(t) - V_{\text{Property}}(t)$, otherwise if solar generation is greater than property demand then the grid demand is 0.

2. If the battery is not empty, $S(t) > 0$, then the grid demand is 0, because the property will consume stored energy in the battery until either the battery is empty or until there is an energy surplus within Orkney. If the battery is empty, then, if property demand is greater than solar generation, $P_{\text{Property}}(t) > V_{\text{Property}}(t)$, the grid demand is equal to the difference between property demand and solar generation, $P_{\text{Property}}(t) - V_{\text{Property}}(t)$, otherwise it is equal to 0.

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3 Results

3.1 Mapping Demand and Generation

The purpose of this section is to display the various energy demand and generation profiles which will then be used in the calculations and models of subsequent sections. The energy demand profiles collected from the OWL energy monitors for the three different groups of properties as defined in the methodology will be presented, along with the Orkney-wide energy demand and generation profiles that correspond to the periods of time for which the property data was available.

3.1.1 Property Group A

Energy consumption data for property group A was available from 08/10/16 13:33 to 31/10/16 23:59, and it is this time period which will be used for all relevant calculations. However, in order to provide a qualitative understanding of the general form of the energy demand data, a selection of figures has been chosen to display the demand profiles for shorter periods of time during which the profile features appeared particularly interesting. Equivalent figures displaying the demand data for the entire October period are available in the appendices.

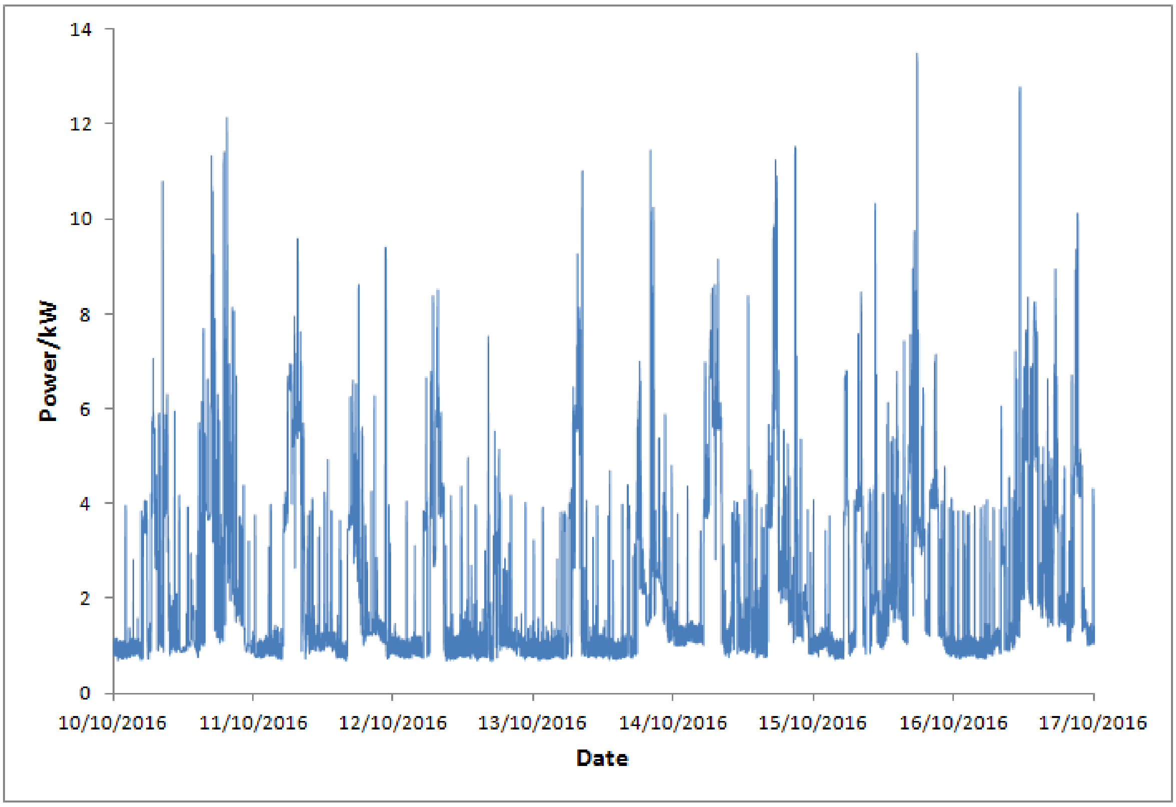

Figure 3: Energy demand for group A from 10/10/16 to 16/10/16.

Figure 3 shows the consumption of property group A from Monday 10/10/16 to Sunday 16/10/16, providing an overview of the typical energy consumption pattern that occurs on a weekly basis. An additional graph showing the energy demand for the October period can be seen in appendix figure A.1.

Figures 4 and 5 also show the power consumption for group A on a typical weekday and weekend day respectively. In these figures, it is easy to recognise certain patterns of energy usage in the households; for example, the spikes in the mornings and evenings are likely to be preparing for and returning from work respectively on the weekday graph, and the regular peaks and troughs are likely to be intermittent consumption from white goods such as fridges and freezers.

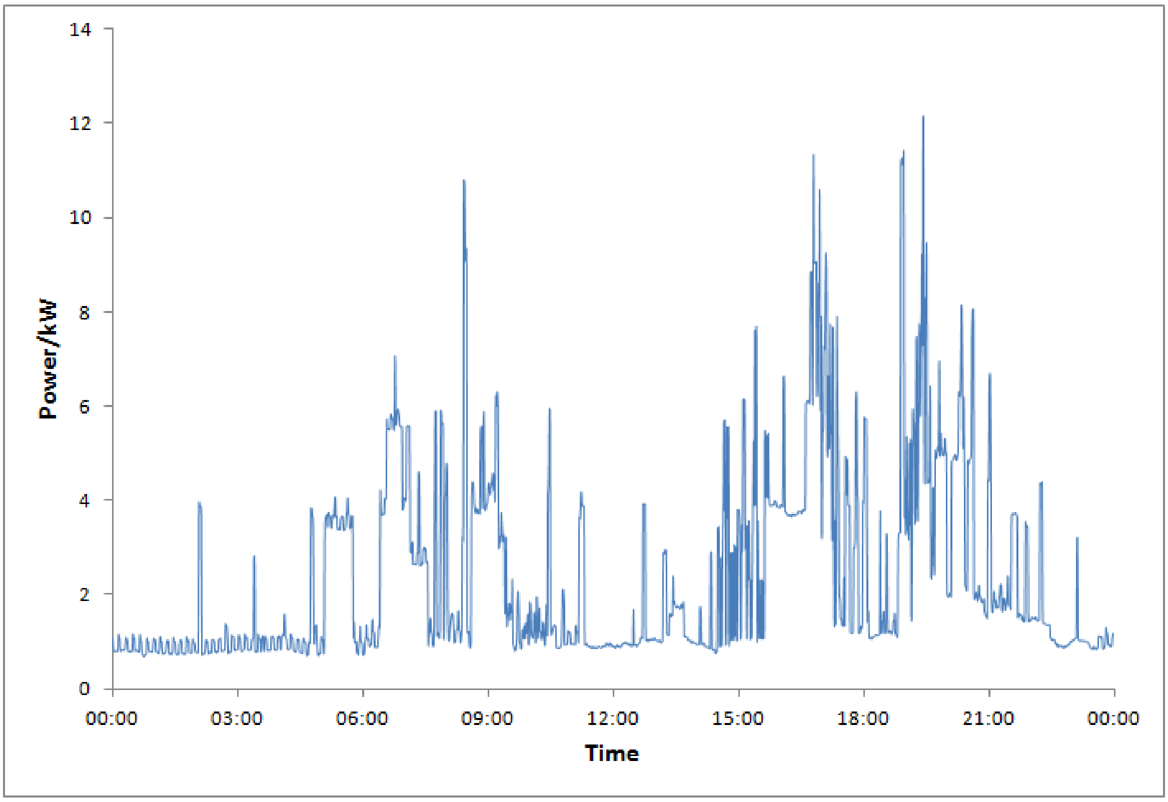

Figure 4: Energy demand for group A on Monday, 10/10/16.

The Orkney demand and generation data for the same week (10/10/16 to 16/10/16) as the OWL monitor data for property group A is displayed in figure 6, with the full range of data for October shown in appendix figure A.2. Figure 6 shows that during the first two days of the week, demand in Orkney was on the whole significantly higher than local generation, and from the middle of the week onwards generation was greater than demand. When the weather records for this week in October 2016 were examined (Timeanddate.com, 2017), there was a notable increase in the average wind speed from the start of the week to the end of the week, averaging only 5 to 7 mph from the Monday to the Wednesday, increasing up to 20 mph by the Thursday. This is consistent with the generation data displayed in figure 6, and is a clear demonstration of the dependency upon favourable weather conditions for renewable generation in situations where storage is not available.

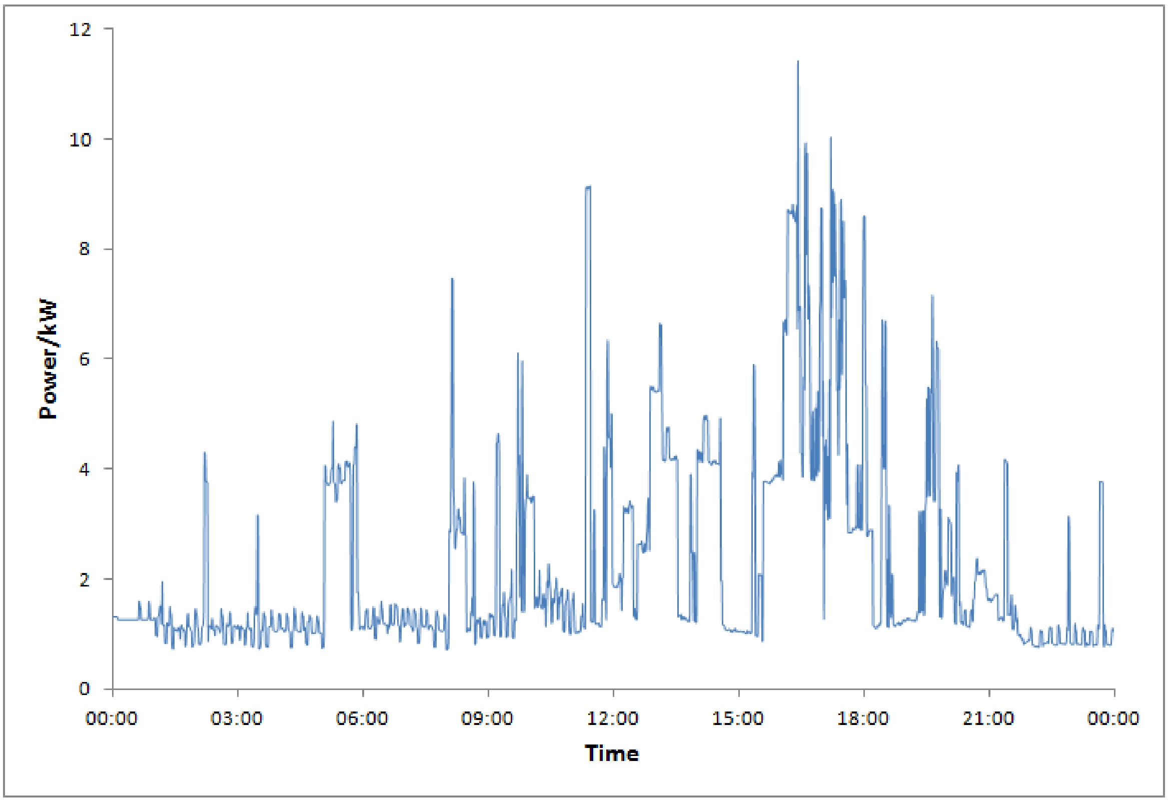

Figure 5: Energy demand for group A on Sunday, 16/10/16.

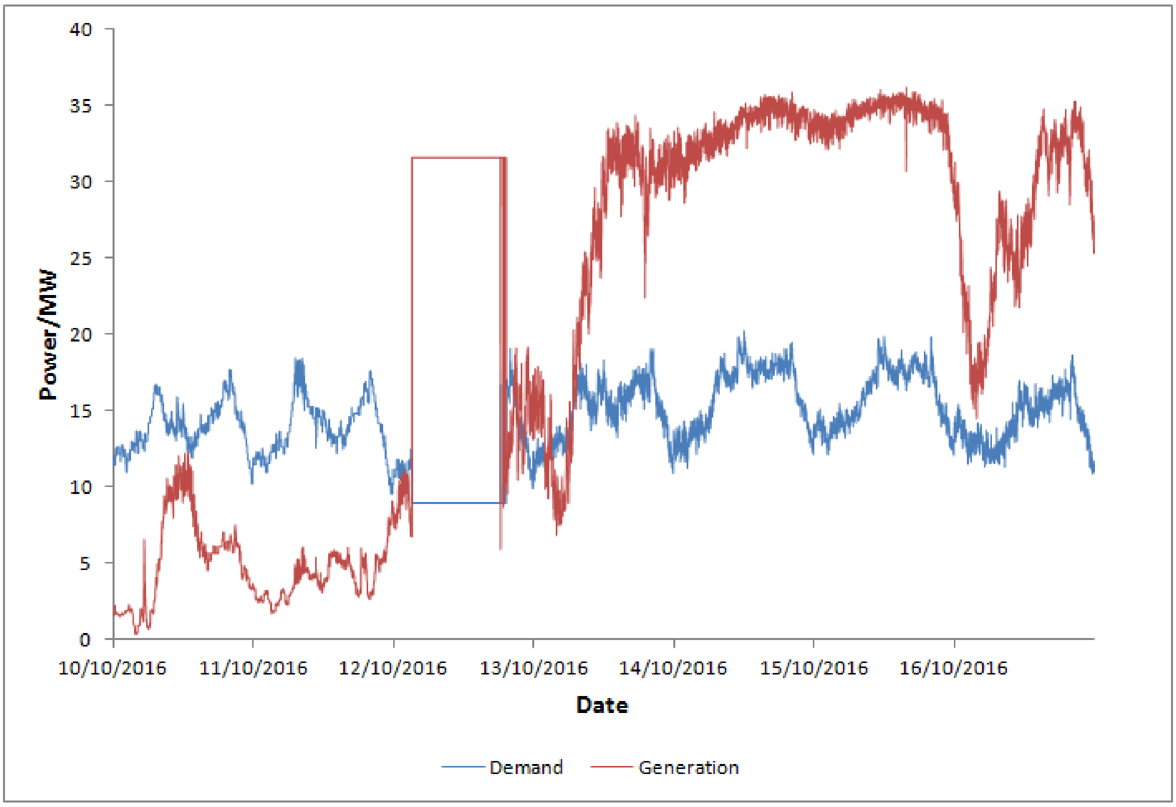

Figure 6: Energy demand and generation for Orkney from 10/10/16 to 16/10/16.

3.1.2 Property Group B

Energy consumption data for property group B was available from 03/06/17 02:05 to 30/06/17 17:04. As with group A, the full range of data available will be used for all calculations to follow, but figures showing a shorter week-long period will be used to allow a comparison between the demand of group A in October and group B in June. Appendix figure A.3 shows the demand profile for group B for the full June period.

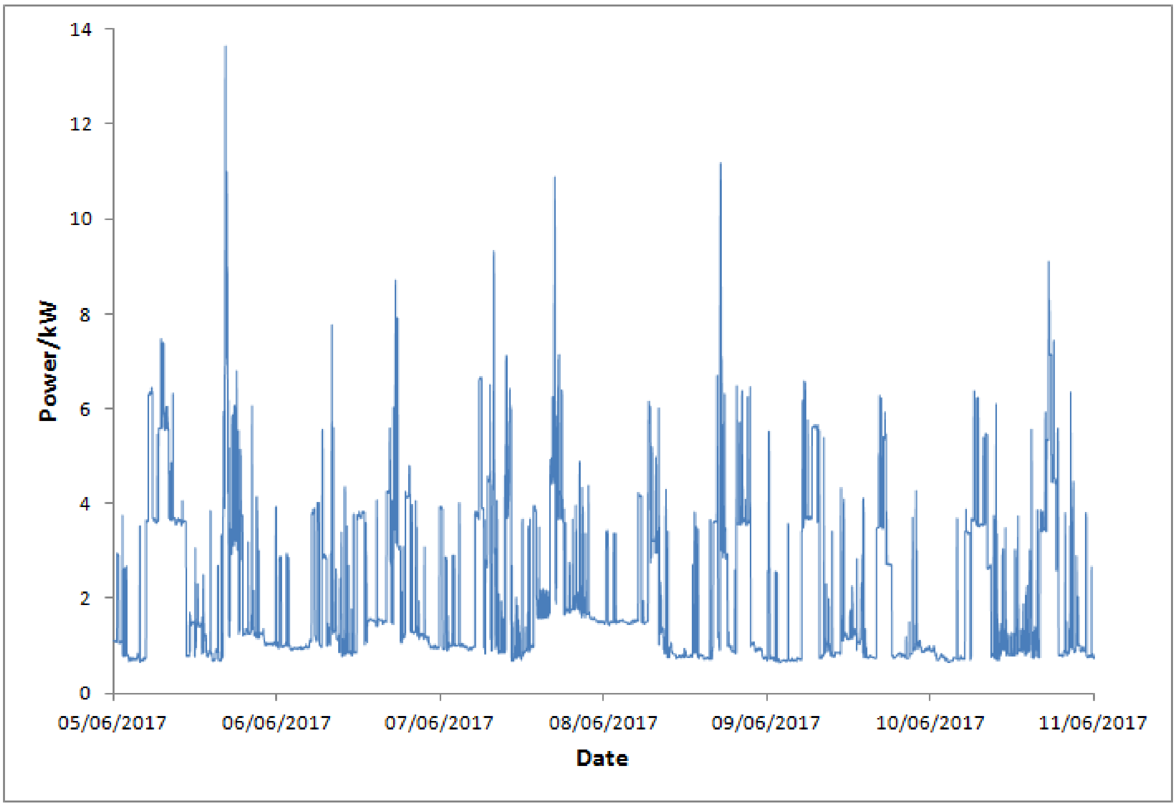

Figure 7: Energy demand for group B from 05/06/17 to 11/06/17.

Figure 7 shows the demand profile for group B starting from 05/06/17 00:00 and ending 11/06/17 23:59, a similar Monday to Sunday period to the one used for group A. Despite the fact that the data for group B is for eight months after the data for group A, the demand profiles are essentially of the same form, as one would likely expect. Figure 8 below shows the Orkney-wide demand and generation data for that same period, providing a clear depiction of when the property group would be consuming energy entirely from Orkney generation, and when it would be consuming energy partly imported from the mainland UK grid. This data for the full June period can be seen in appendix figure A.4. Orkney-wide demand remains relatively consistent and regular, while the generation plot varies dramatically throughout the week. As before, the generation is consistent with the weather records for that time (Timeanddate.com, 2017), bearing in mind that the majority of Orkney-wide generation comes from wind power. Additional graphs showing the property demand profiles for individual days as was done for group A have not been included, as they did not prove to be overly illuminating beyond what can already be seen in the present figures.

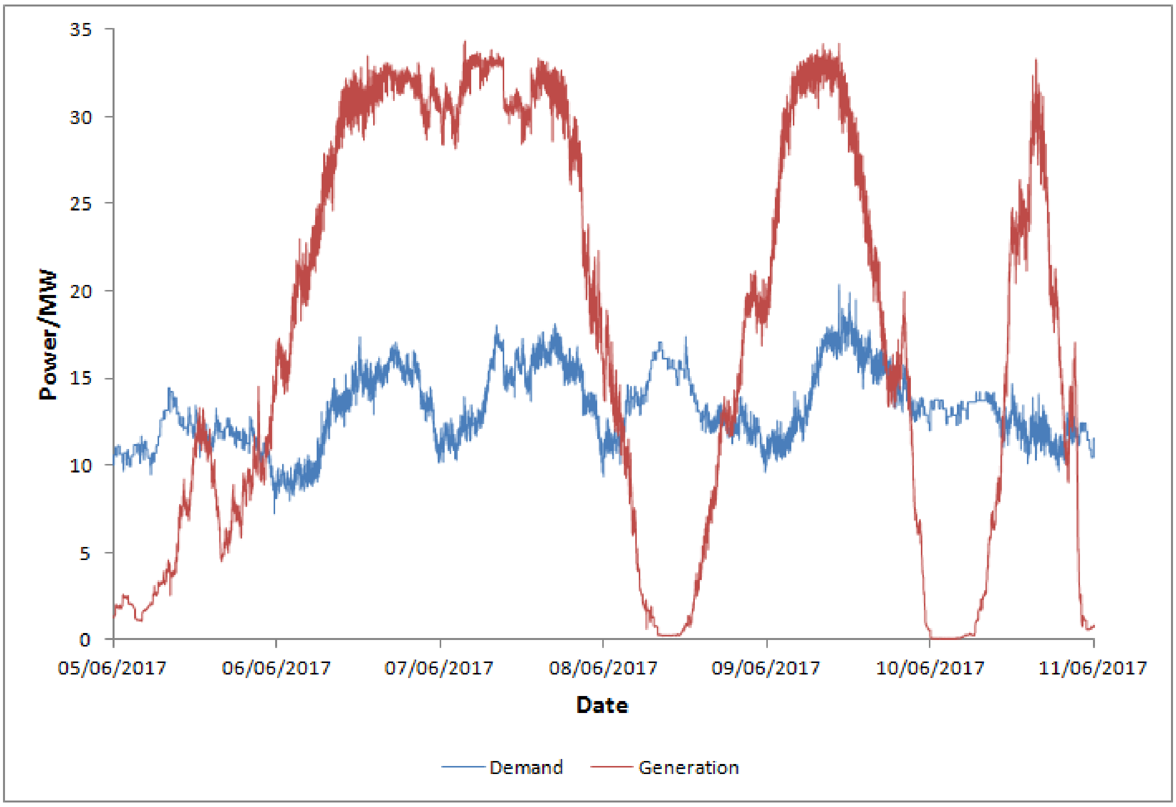

Figure 8: Energy demand and generation for Orkney from 05/06/17 to 11/06/17.

3.1.3 Property Group C

Property group C differs from groups A and B in that it includes the use of solar panels, and already uses battery storage in a limited way to maximise solar power consumption. The demand and solar generation data was available for group C from 06/07/17 17:45 to 01/08/17 00:00, and the full range of data can be seen in appendix figure A.5. The week-long period starting 24/07/17 00:00 and ending 30/07/17 23:59 was chosen as an illustration of how changing solar output can affect the demand for energy from the grid for such a property. Figure 9 shows the total energy demand profile for the group along with the solar generation occurring simultaneously. The energy demand plot is of a similar form to the plots of groups A and B, and the solar generation plot is consistent with an assumption of high levels of sunlight during the day, and low levels during the night. A notable increase in solar generation can also be seen during the second half of the week, and this is consistent with the weather observed during this time period (Timeanddate.com, 2017).

Figure 10 is a plot of the energy from the Orkney grid that group C demanded during this time period, and the full range of data can be seen in appendix figure A.6. It must be noted that this is the data recorded for grid energy consumption given that both direct solar consumption and consumption of stored solar energy were taking place. This is the only instance where the empirical data recorded includes energy storage, although it must be remembered that the storage in this case is only being used in order to maximise solar consumption, and at no point does the battery charge from the grid during periods of excess renewable generation within Orkney. The impact that such behaviour by the battery could have if this were done is addressed later in the report.

Figure 10 shows that, when solar power and limited battery storage are accounted for, the demand for energy from the Orkney grid for group C changes in two notable ways. Firstly, the maximum value for instantaneous demand is significantly lower than in figure 9, registering less than 1kW. Secondly, the consumption patterns throughout the week for figures 9 and 10 do not particularly resemble each other. This is a function of the solar generation and the battery discharge reducing and skewing the demand profile.

Figure 11 displays the Orkney-wide demand and generation data for the same time period, and, as with previous figures showing this data for different time periods, periods of both high and low generation are clearly visible, and it is this profile combined with the timing of the grid energy demand shown in figure 10 that will affect the carbon intensity of the energy consumed by group C, as shown in the next section. The full range of data can be seen in appendix figure A.7.

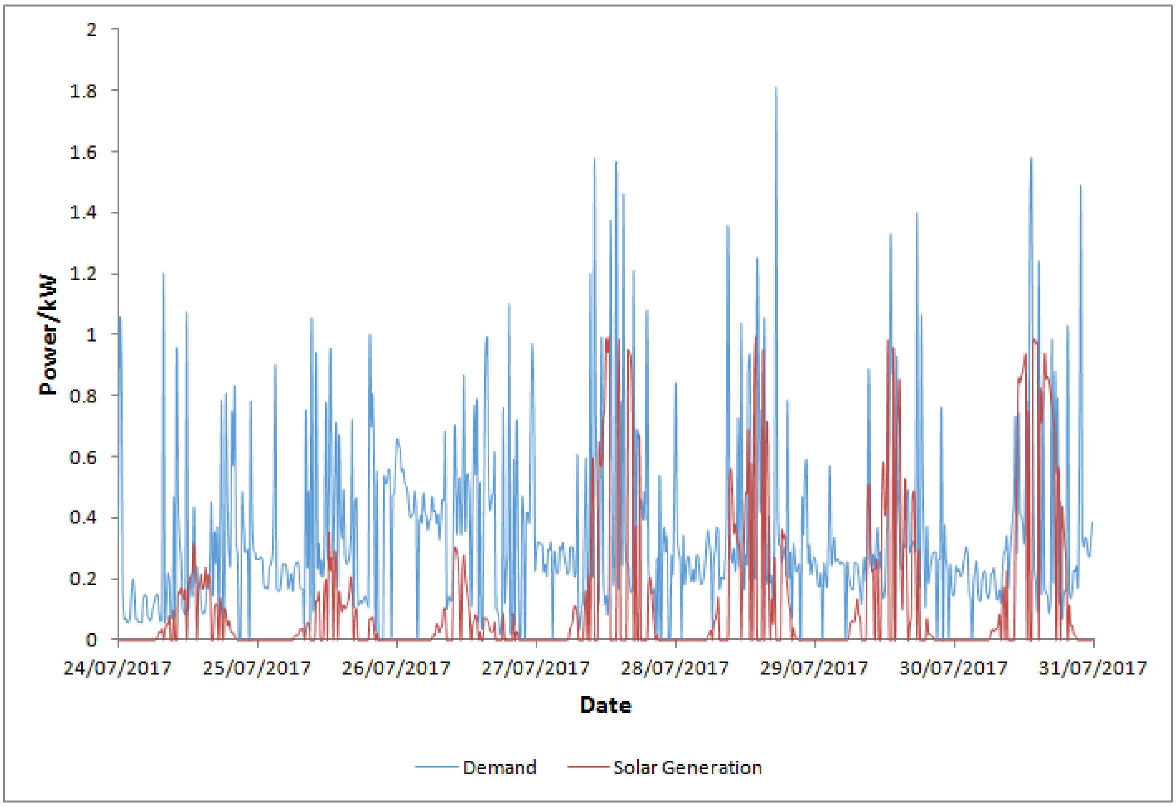

Figure 9: Energy demand and solar generation for group C from 24/07/17 to 30/07/17.

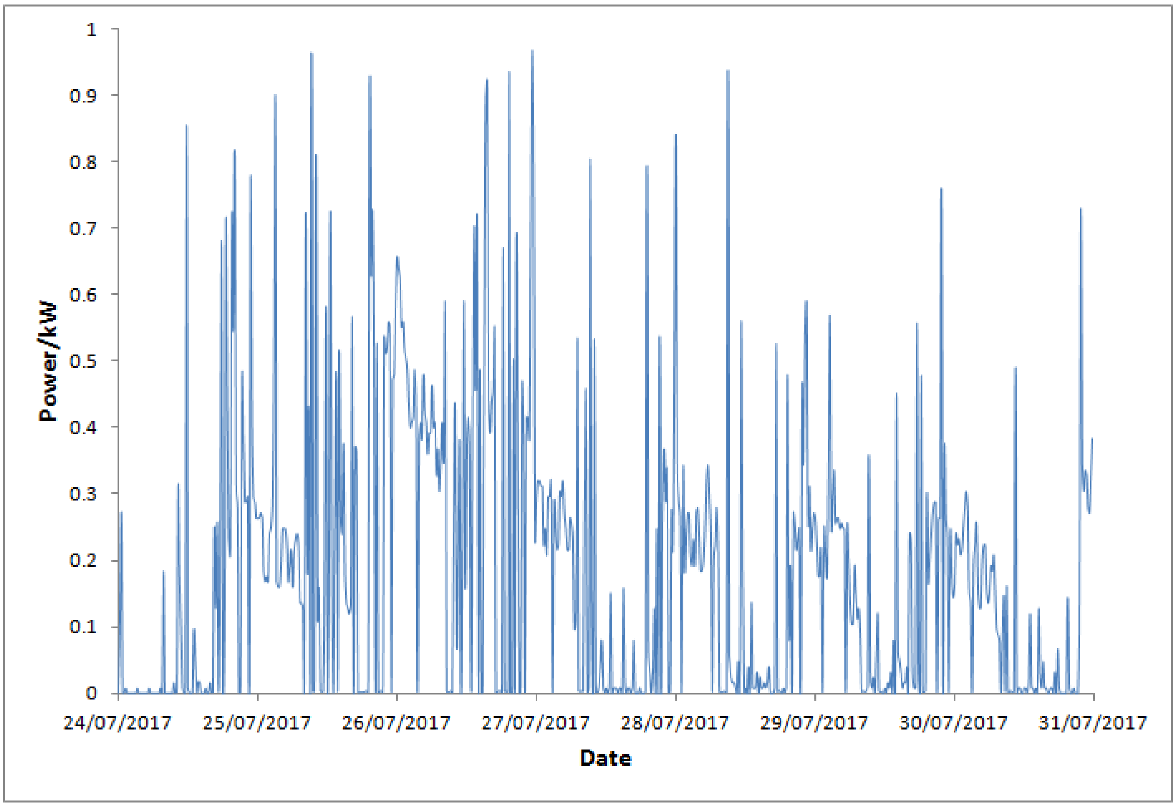

Figure 10: Grid energy demand for group C from 24/07/17 to 30/07/17.

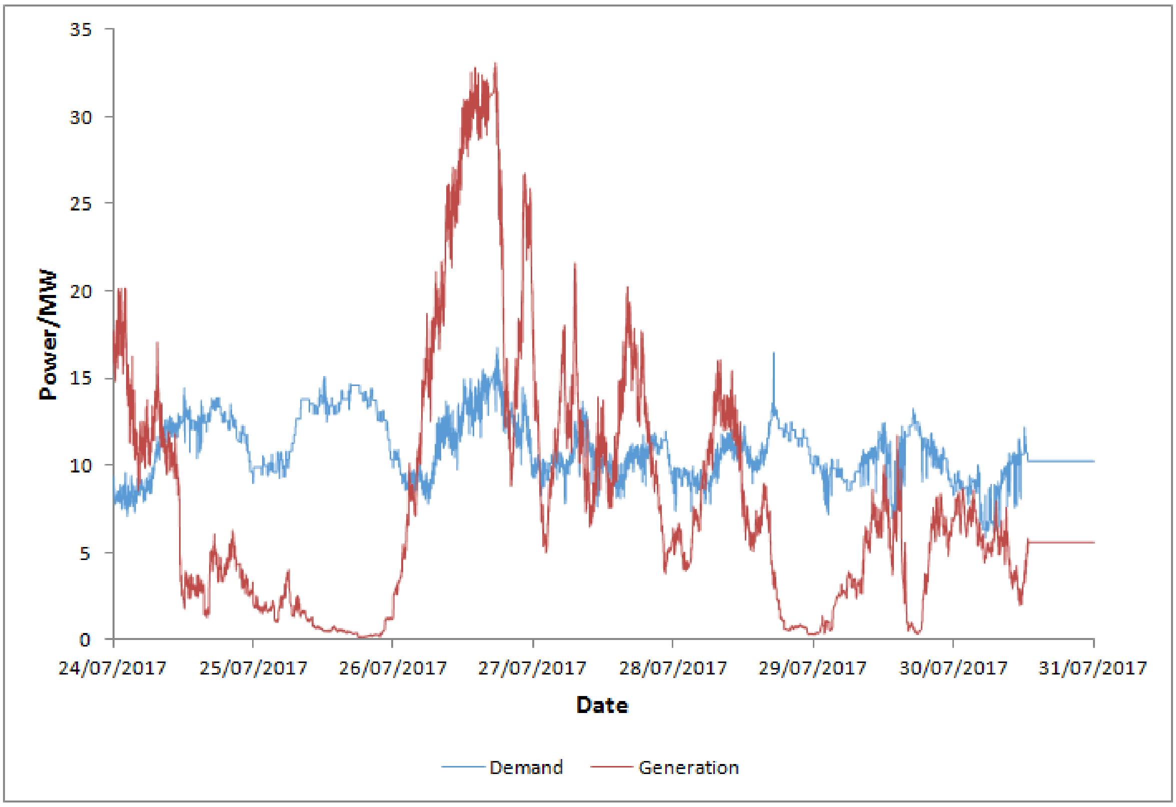

Figure 11: Orkney-wide demand and generation from 24/07/17 to 30/07/17.

3.2 Calculating Carbon Intensity

The purpose of this section is to provide a selection of calculations for the carbon intensity of the energy consumed within Orkney. As with the previous section, data concerning both Orkney as a whole and the individual property groups was used for these calculations.

3.2.1 Orkney-Wide Energy Usage

While the energy consumed by the individual property groups in question will all have unique carbon intensity values due to the differences in their specific consumption patterns, it was possible to calculate the carbon intensity for the Orkney grid as a whole for 2016, and for the period between January and July 2017. Table 1 below shows the total energy consumed within Orkney, the fraction of that energy which was imported from the UK mainland grid, the carbon intensity of the energy consumed within Orkney, and the weighted standard deviation of the monthly carbon intensity values around the periodical weighted mean. The individual monthly values for carbon intensity can be found in appendix table 8.

	Jan–Dec 2016	Jan–July 2016	Jan–July 2017
Total Energy Demand/MWh	122238.4	68791.2	80611.4
UK Import %	28.5	27.8	28.2
Carbon intensity/kg $CO_2e(kWh)^{-1}$	0.128	0.125	0.127
Standard Deviation/kg $CO_2e(kWh)^{-1}$	0.024	0.030	0.029

Table 1: Periodical Orkney-wide energy consumption and carbon intensity data for 2016 and 2017.

The range of calculations for 2017 ended in July as further data had not been collected. However, when the same period of time is compared between 2016 and 2017, it can be seen that the two values for carbon intensity are almost identical to each other, and the standard deviations of the two figures are relatively small.

While this is potentially useful information, the next important step is to calculate the carbon intensity of the energy consumed by the different property groups, and to then evaluate how that can be reduced by the use of battery storage.

3.2.2 Property Group A

Using the Orkney-wide energy demand and generation data, it has been possible to calculate how much of the energy consumed by property group A was the product of indigenous generation, and how much was imported from the mainland UK grid. Figure 12 below shows the energy demand profile for the week when only energy imported from the UK grid is accounted for, and the same profile for the whole month of October can be seen in appendix figure A.8.

Figure 12 clearly emphasises the point that when renewable generation is high as is the case in the second half of the week, there is little to no requirement for energy imported from the mainland UK grid, and the demand from the properties is met solely using local, low carbon energy. The total energy consumption figures for the week in question, and for the month of October as a whole, are shown in table 2 below.

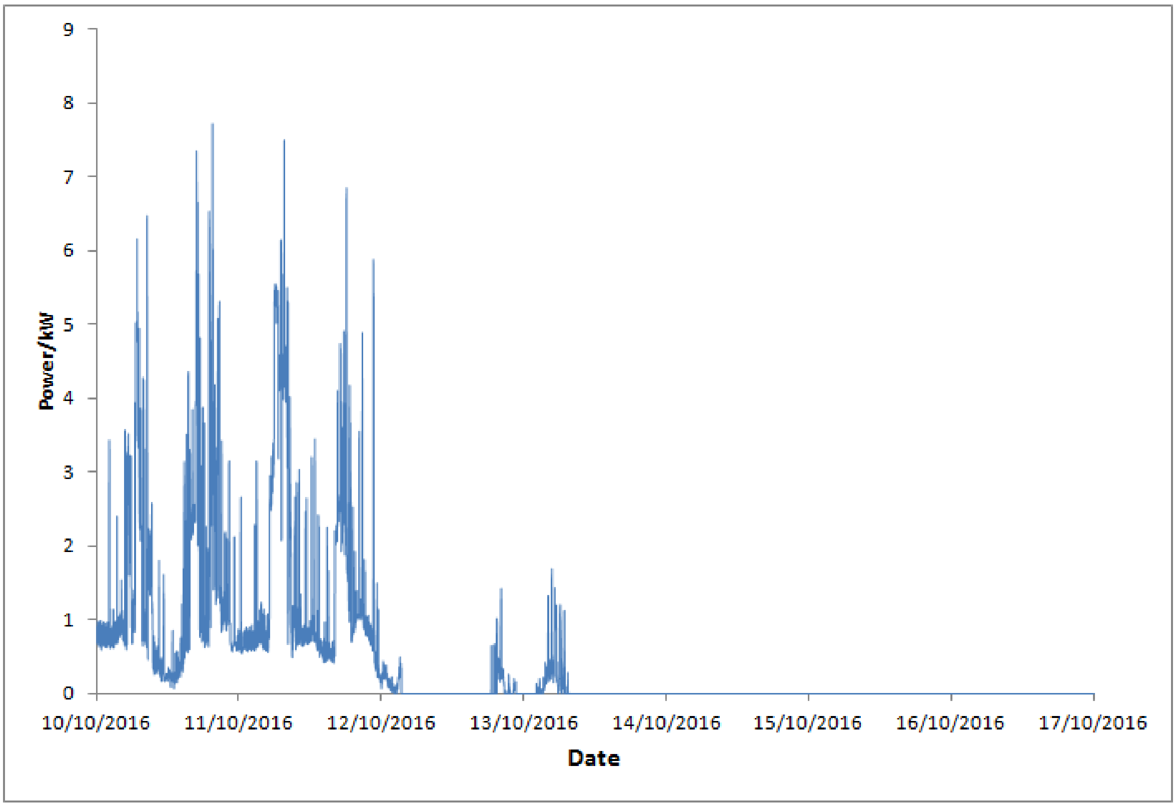

Figure 12: Energy consumption for group A from the UK grid from 10/10/16 to 16/10/16.

	Week	Month
Total Energy Used/kWh	381.89	1342.65
Total UK Grid Energy Imported/kWh	74.89	471.88
UK Import %	19.61	35.15
Carbon Intensity/kg $CO_2e(kWh)^{-1}$	0.088	0.158

Table 2: Energy consumption for group A and energy imported from UK grid for the period between 10/10/16 and 16/10/16, and for the month of October.

These figures show that approximately 80% of the energy consumed by group A in the week-long period was generated from local renewable sources, with this figure reducing to approximately 65% when the date range is expanded to the month of October.

3.2.3 Property Group B

The same calculations which were performed for property group A were then carried out for group B, although it was generally expected that the results would be broadly the same given the similar Orkney-wide carbon intensity values for October 2016 and June 2017 (see appendix table 8) and the similar demand profiles for the two groups as demonstrated previously. Figure 13 below shows the demand for imported energy from the UK grid of property B. The full range of data can be seen in appendix figure A.9. While the shape of the graph is different from figure 12 for property group A, it is another demonstration of the same principle—when Orkney-wide generation is greater than demand, energy import from the UK grid is 0.

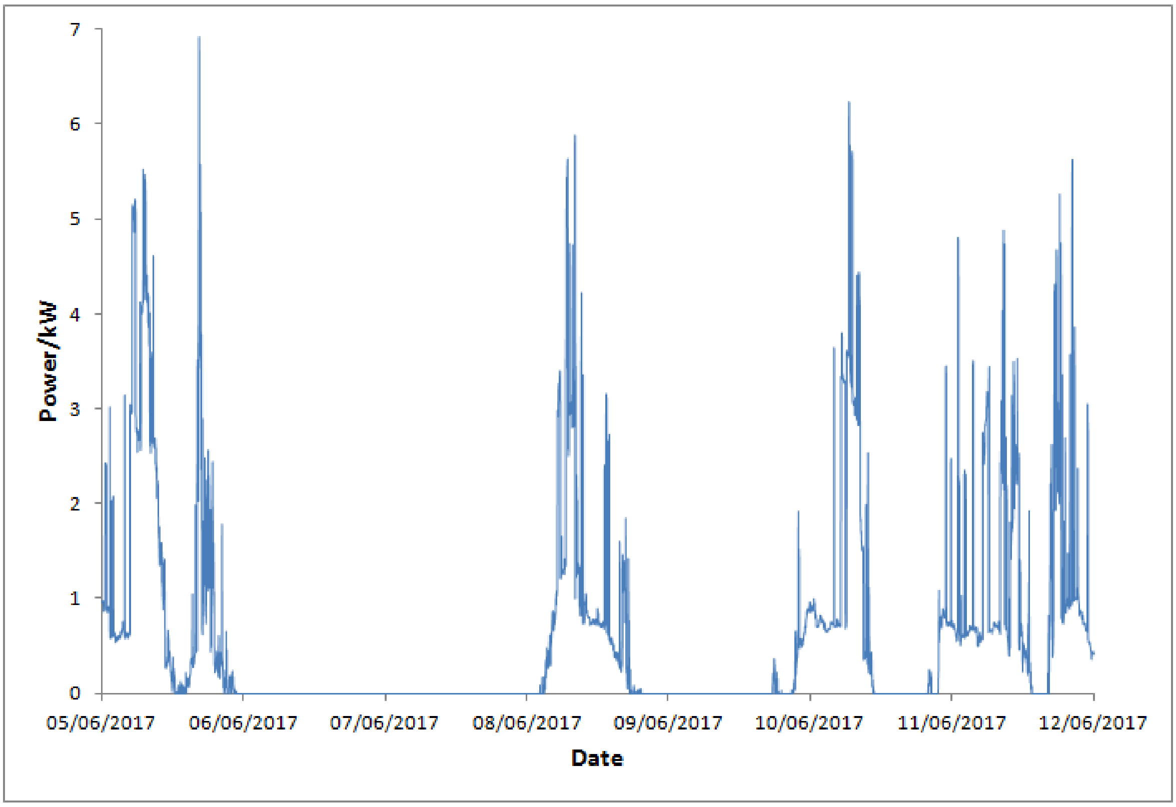

Figure 13: Energy consumption for group B from the UK grid from 05/06/17 to 11/06/17.

Table 3 below displays figures for group B which are similar to those found in table 2 for property group A, although notably more energy was imported from the UK grid to satisfy the energy demand of group A than group B, and this is reflected in the higher value for carbon intensity for group A.

	Week	**Month**
Total Energy Used/kWh	336.02	1309.48
Total UK Grid Energy Imported/kWh	96.56	354.40
UK Import %	28.74	27.06
Carbon Intensity/kg $CO_2e(kWh)^{-1}$	0.129	0.122

Table 3: Energy consumption and energy imported from UK grid for group B for the period between 05/06/17 and 11/06/17, and for the month of June.

3.2.4 Property Group C

While similar figures might be expected for the carbon intensity of the energy consumed by group C if all of its demand were satisfied from the Orkney grid, the presence of behind-the-meter solar panels, combined with the fact that July is typically a rather sunny month, means that the carbon intensity of the energy consumed by the property is likely to be significantly less than for groups A and B. Figure 14 shows what the demand from group C was for imported energy from the UK grid, compared to what it would have been if it had not had solar panels and all of its energy demand had to be met by the Orkney grid. This data for the whole month of July can be found in appendix figure A.10.

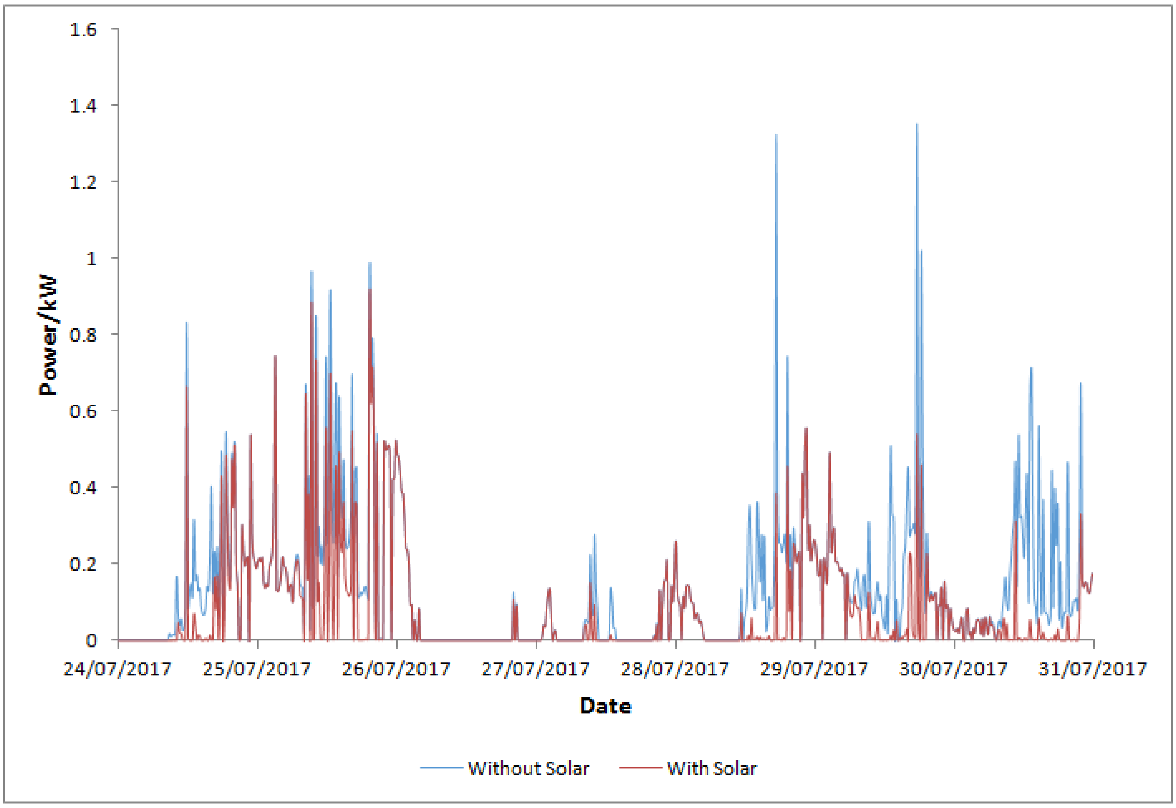

Figure 14: Energy consumption for group C with and without solar from the UK grid from 24/07/17 to 30/07/17.

When comparing the two plots in figure 14, a notable decrease can be seen in the profile with solar when compared to the profile without, and this is a demonstration that, even before battery storage has been utilised to its full potential, solar power combined with behind-the-meter storage provides an opportunity to decrease the carbon intensity of the energy consumed by a property. This is further demonstrated in table 4 where the carbon intensity of the energy consumed by group C during the month of July decreased by approximately 50% when solar power was included.

	With Solar		Without Solar	
	Week	Month	Week	Month
Total Energy Used/kWh	57.41	165.80	57.41	165.80
Total UK Grid Energy Imported/kWh	13.77	28.78	23.34	57.70
UK Import %	23.98	17.36	40.65	34.80
Carbon Intensity/kg $CO_2e(kWh)^{-1}$	0.108	0.078	0.183	0.156

Table 4: Total energy consumption and energy imported from UK grid for group C for the period between 24/07/17 and 30/07/17, and for the month of July.

3.3 Introducing Battery Storage

The purpose of this section is to determine to what extent introducing behind-the-meter battery storage would affect the energy demand profiles for each of the property groups, and the carbon intensity of the energy consumed by them as a result. Given that a long-term ambition for energy storage on Orkney is to eliminate the need to import any energy at all from the UK grid—something which is in principle possible given that Orkney generates more energy than it consumes on an annual basis—this section will first provide figures showing the cumulative energy balance for each property group, followed by the results of the models made to simulate the energy demand profiles of the groups once battery storage is implemented.

3.3.1 Property Group A

Before modelling what impact a battery storage system would have on household energy demand, the cumulative energy balance profile in October 2016 for property group A is shown in figure 15 below.

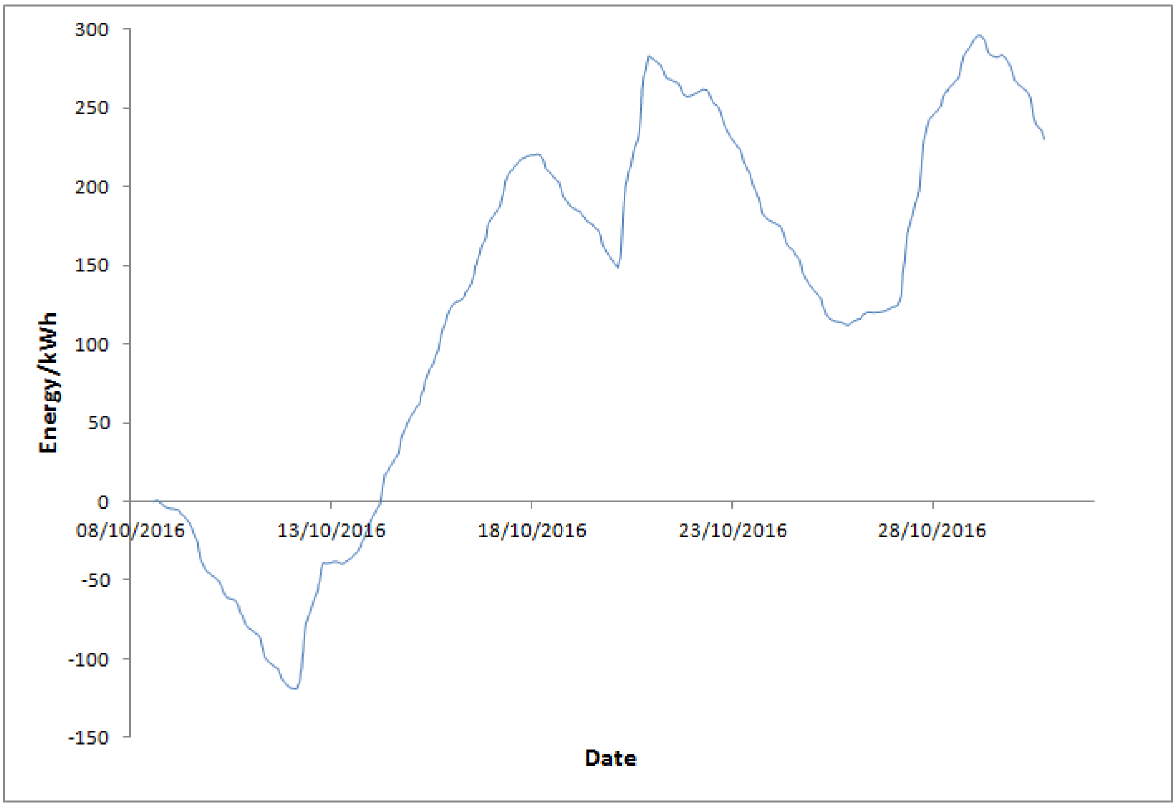

Figure 15: Cumulative energy balance for property group A.

The cumulative energy balance is a way of measuring how much of the energy which has been consumed originated from Orkney, and how much has been imported from the UK grid. A positive value denotes a point in time when there has been more energy exported from Orkney than imported to Orkney since the start of the measuring period, and vice versa for a negative value. Figure 15 therefore shows us that at the beginning of October there was a net import of energy occurring into Orkney, a trend which ends approximately at 12/10/16 when the gradient becomes positive, after which there is a net energy export out of

Orkney. Then at around 14/10/16 the cumulative energy value becomes positive, indicating that the total energy imported into Orkney is now equal to the total energy exported, and the continuing positive gradient until approximately 18/10/16 indicates that up to then there was continuously a case of net energy export from Orkney. While the gradient changes sign several times from then until the end of the month, the cumulative energy balance remains positive the entire time. This shows that the energy generated on Orkney after 14/10/16 is more than sufficient to meet the energy requirements of the county, provided that there could be flexibility in when that demand occurred—that is to say, provided that some form of energy storage was available. Without any such storage, there are still occasions where energy is required to be imported into Orkney at the points on the graph where the cumulative energy balance is positive, but the gradient is negative.

Figure 16 below shows what the impact would be on the power demand of group A for a week-long period in October if battery storage were to be implemented, and figure 17 shows the Orkney-wide energy demand and generation for that same period. Both of these graphs are provided in full for October in appendix figures A.11 and A.2 respectively. This particular period was chosen for display at this point as it highlights particularly well the effect that introducing battery storage can have on the timing of power demand in relation to energy generation.

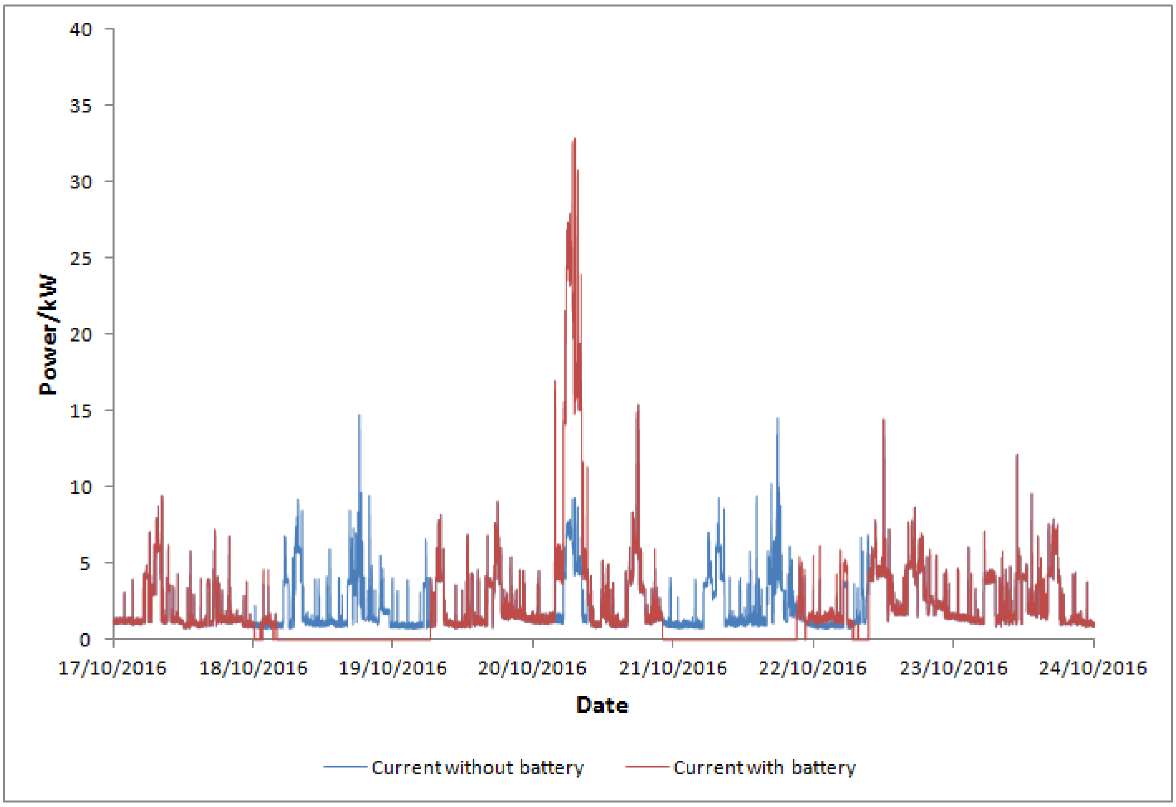

Figure 16: Power demand for property group A from 17/10/16 to 24/10/16 with and without battery storage.

In figure 16, both currents with and without battery are identical until approximately the start of 18/10/16. This is due to a combination of the fact that Orkney-wide generation is greater than demand and there is therefore a net energy export from the county, and the fact

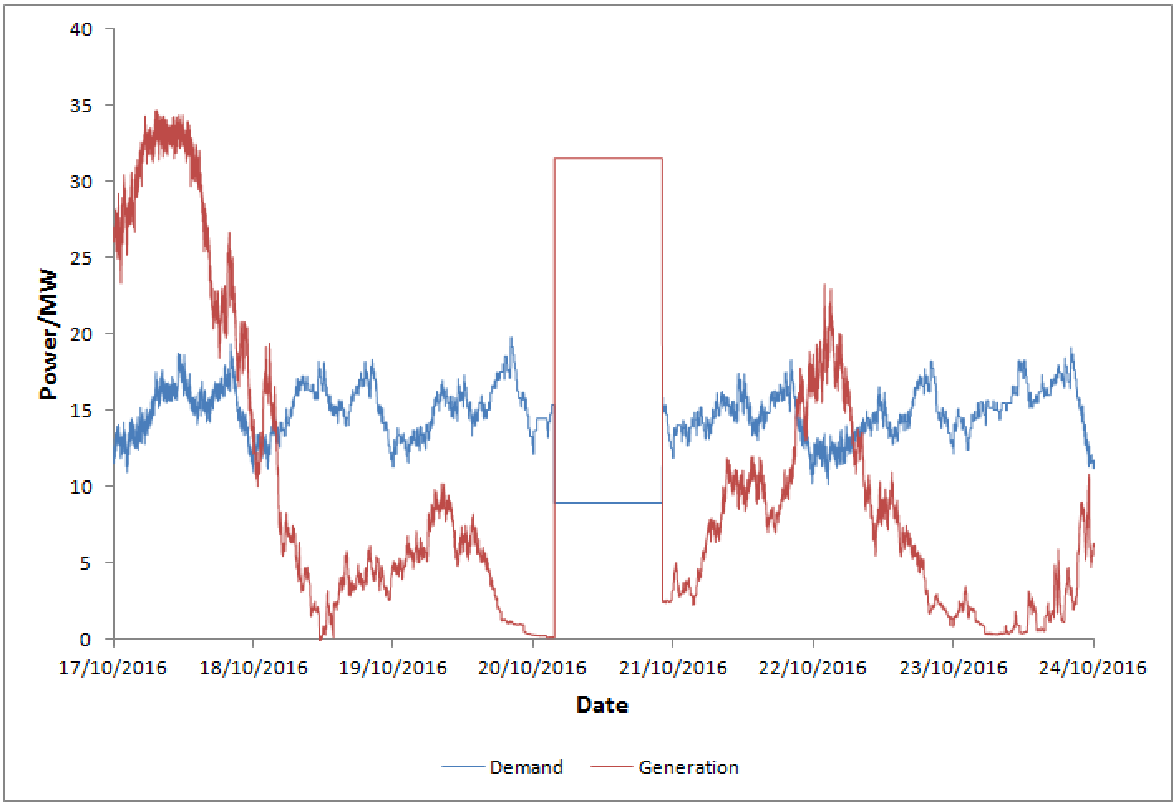

Figure 17: Orkney-wide power demand and generation from 17/10/16 to 24/10/16.

that the battery has already been charged to full capacity at this point due to a sustained period of excess generation prior to 17/10/16. Soon after the start of 18/10/16, the grid demand with battery storage reduces to zero. This is because energy generation decreased below the level of Orkney-wide demand, resulting in a net energy import into the county from the UK mainland grid. As a result, the battery then discharges in order to provide the power that the properties would have otherwise had to consume from the grid at a time of net energy import, and therefore higher carbon intensity. This trend ends and both demand profiles match each other again around 6 hours into 19/10/16—this indicates that the battery is fully discharged, and it will not recharge until there is once again a situation of net energy export from Orkney, i.e. there is a surplus of indigenous generation of which to take advantage. This situation occurs shortly after the start of 20/10/16, when figure 17 shows generation sharply overtaking demand, and figure 16 shows that the power demand of the properties with battery storage is significantly higher than the demand without. The additional current in the former case is a result of the battery being charged. It can then be seen that the difference between the currents with and without battery disappears approximately halfway through 20/10/16, before generation drops below demand again on figure 17. This implies that the battery is once again fully charged, and no additional power beyond the instantaneous needs of the group is required. This pattern then begins to repeat itself, with the battery discharging at times of high demand and low generation, and charging again in the opposite scenario.

Taking into account this new energy demand profile for the properties, table 5 below shows the energy consumed from the UK grid with and without battery storage by the properties in October, along with the calculated effective carbon intensities of the total energy consumed by the properties*. The decrease in UK grid consumption and associated decrease in carbon intensity which has been achieved by introducing battery storage is significant, and the following figures 18 and 19 when compared clearly show the reduction in energy imported from the UK grid when battery storage is utilised.

	Without Battery	With Battery
Total Energy Used/kWh	1342.65	1349.03
Total UK Energy Imported/kWh	471.88	372.79
UK Import %	35.15	27.63
Carbon Intensity/kg $CO_2e(kWh)^{-1}$	0.1579	0.1242

Table 5: Energy consumption and carbon intensity data for group A in October.

*The slight discrepancy between the battery and no battery values for total energy consumed is due to the discrete nature of the data and how the model was created in Excel; higher resolution data with a smaller time step would eliminate this.

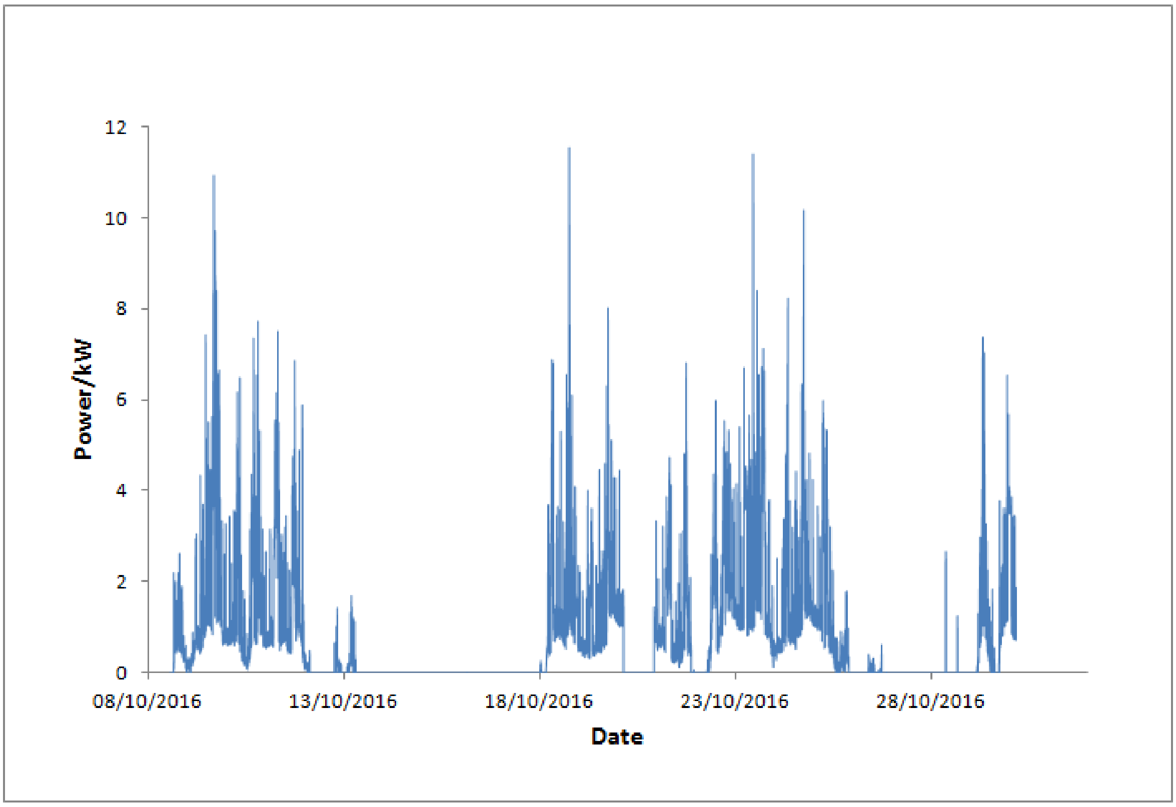

Figure 18: UK grid energy demand of group A without battery storage.

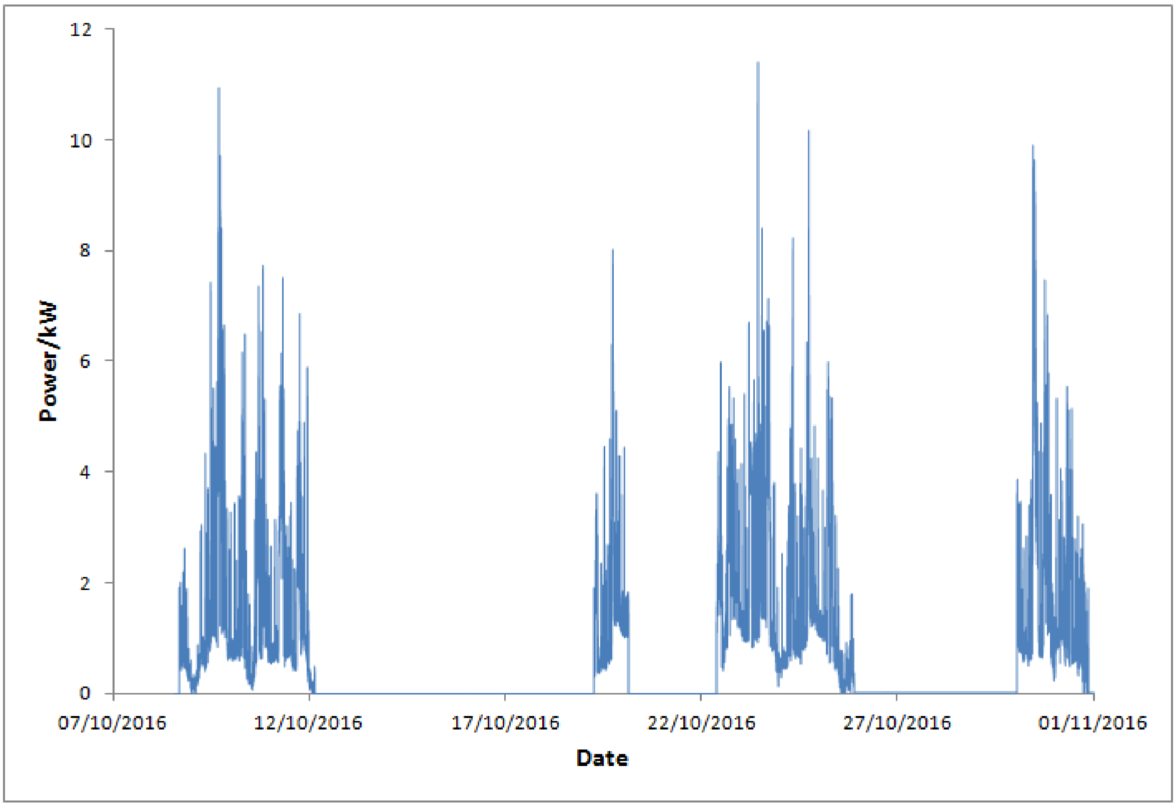

Figure 19: UK grid energy demand of group A with battery storage.

3.3.2 Property Group B

The cumulative energy balance for property group B in the month of June 2017 is shown in figure 20. It is similar in form to the plot for property group A, although it is not until approximately halfway through the month that the energy value remains consistently positive. Nevertheless, this is a demonstration that, provided that a sufficient storage capacity was available, the property group could satisfy its power demand using only energy generated on Orkney provided that storage began no later than 18/06/17.

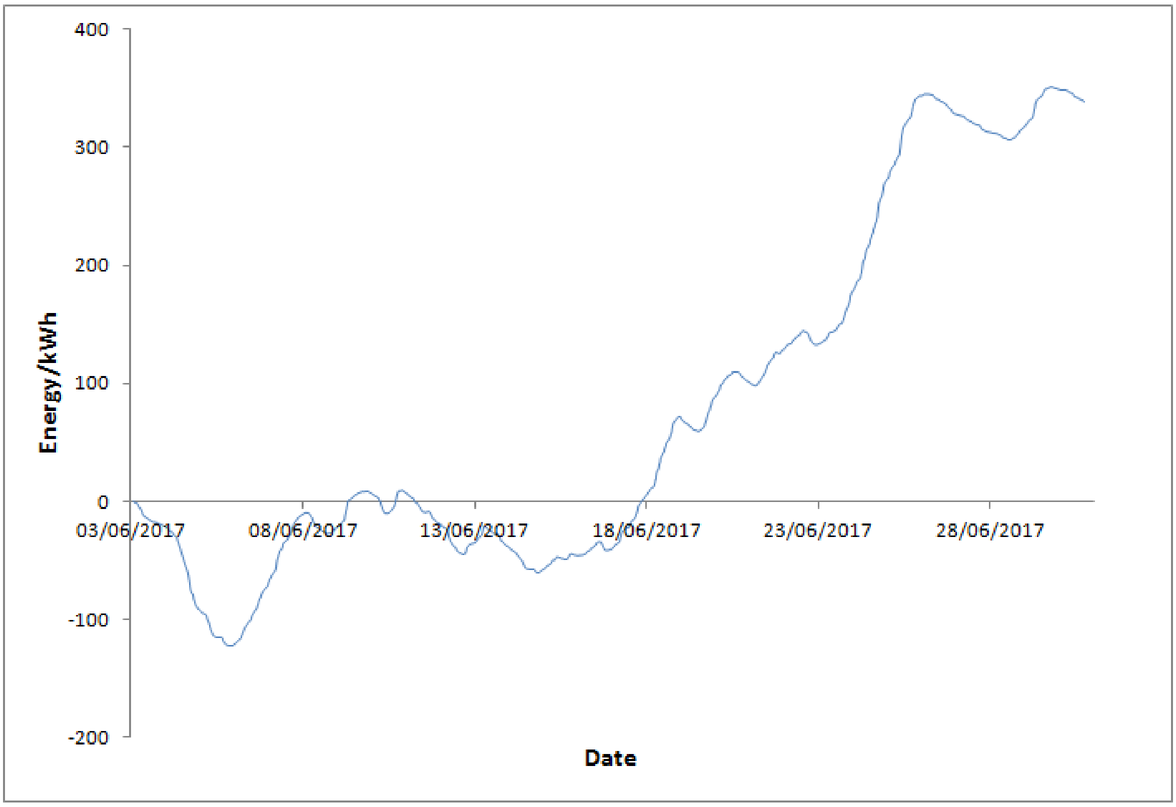

Figure 20: Cumulative energy balance for property group B.

Given this, the impact of implementing battery storage is shown in figure 21 for the week-long period from 05/06/17 to 11/06/17, where the original demand profile can be directly compared to the new one where battery storage has been included. Figure 21 shows a similar effect from battery storage as was seen for property group A. When comparing the new demand profile with the Orkney-wide demand and generation plot in figure 22, it is once again intuitive to see the effect that the model has had on the timing of energy demand for the property group. Around 06/06/17, Orkney-wide generation exceeds demand, providing additional energy for the property group to charge the battery with. This can be seen in figure 21 where at the same point in time the "with storage" plot noticeably increases above the "without storage" plot. This shows that the battery is charging, and equally when Orkney-wide demand exceeds generation just after the start of 08/06/17, the property energy demand with storage can be seen to decrease to 0 at that point until Orkney-wide generation overtakes demand again, therefore reducing the energy consumed by the property that originated from the UK mainland grid (in fact, altogether eliminating it at this particular point). This pattern can be seen to repeat itself throughout the week, and indeed throughout the month as shown in appendix figure A.12.

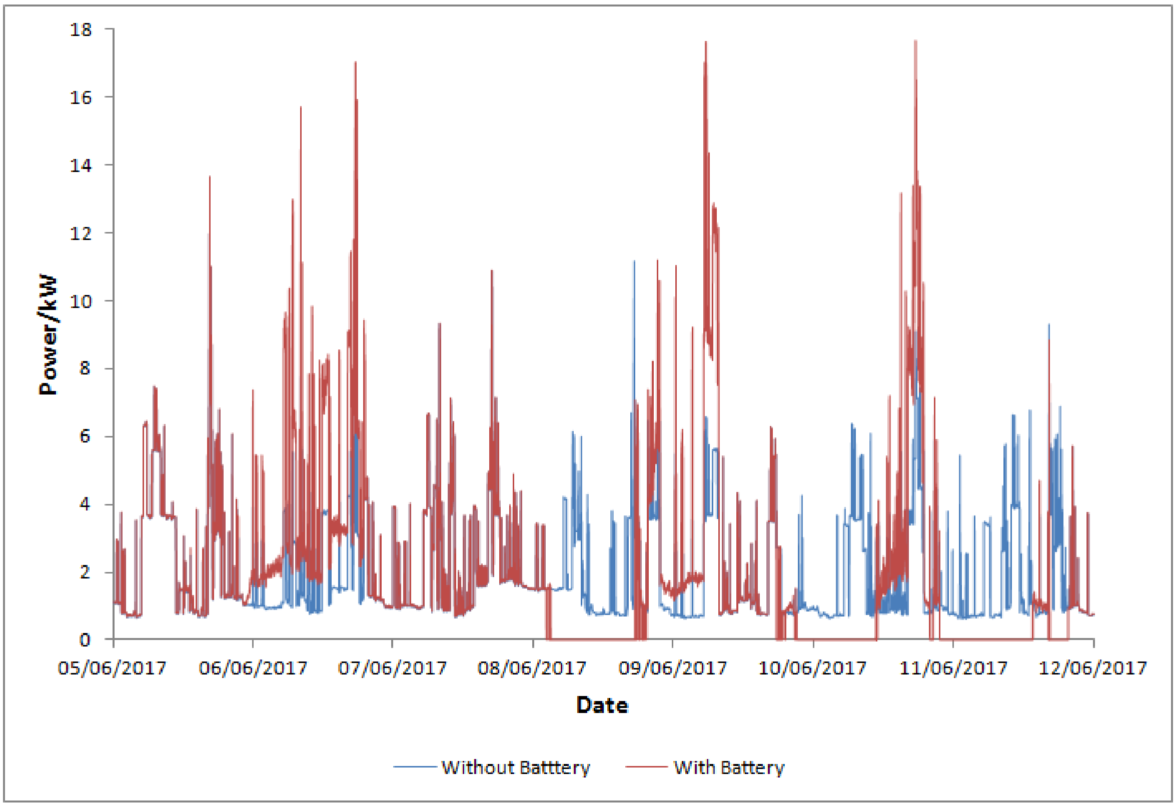

Figure 21: Power demand for property group B from 05/06/17 to 11/06/17 with and without storage.

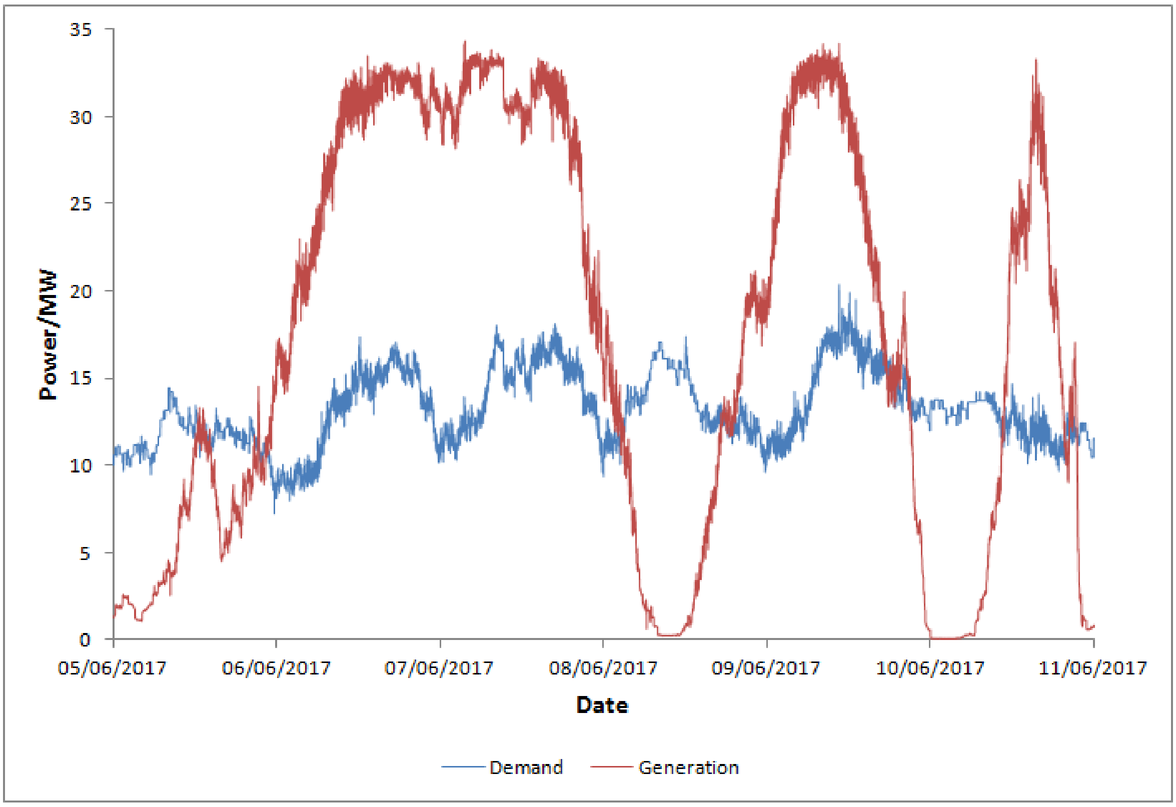

Figure 22: Orkney demand and generation data from 05/06/17 to 11/06/17.

Table 6 shows the recalculated values for imported energy consumption and carbon intensity of energy consumed compared to the original values before storage was implemented, where a decrease of almost 45% can be seen in the carbon intensity value because of the introduction of storage.

	Without Battery	With Battery
Total Energy Used/kWh	1309.48	1317.83
Total UK Energy Imported/kWh	354.40	205.86
UK Import %	27.06	15.62
Carbon Intensity/kg $CO_2e(kWh)^{-1}$	0.1216	0.0702

Table 6: Energy consumption and carbon intensity data with and without storage for group B in June 2017.

Finally, figures 23 and 24 compare the energy consumed by property group B that originated from the UK grid during the month of June. There is a clear reduction in UK grid demand in figure 24 when compared to figure 23, providing a visual depiction of the change in consumption that led to the change in carbon intensity figures in table 6.

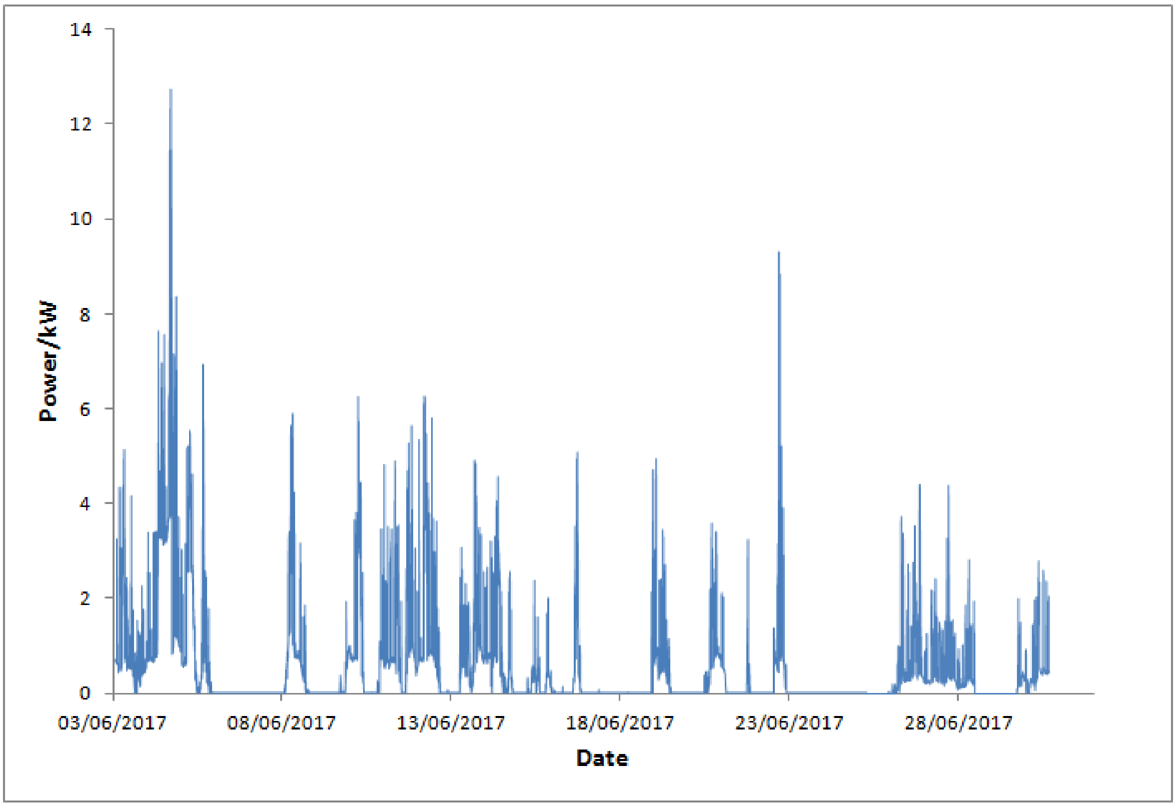

Figure 23: UK grid energy demand of group B without battery storage.

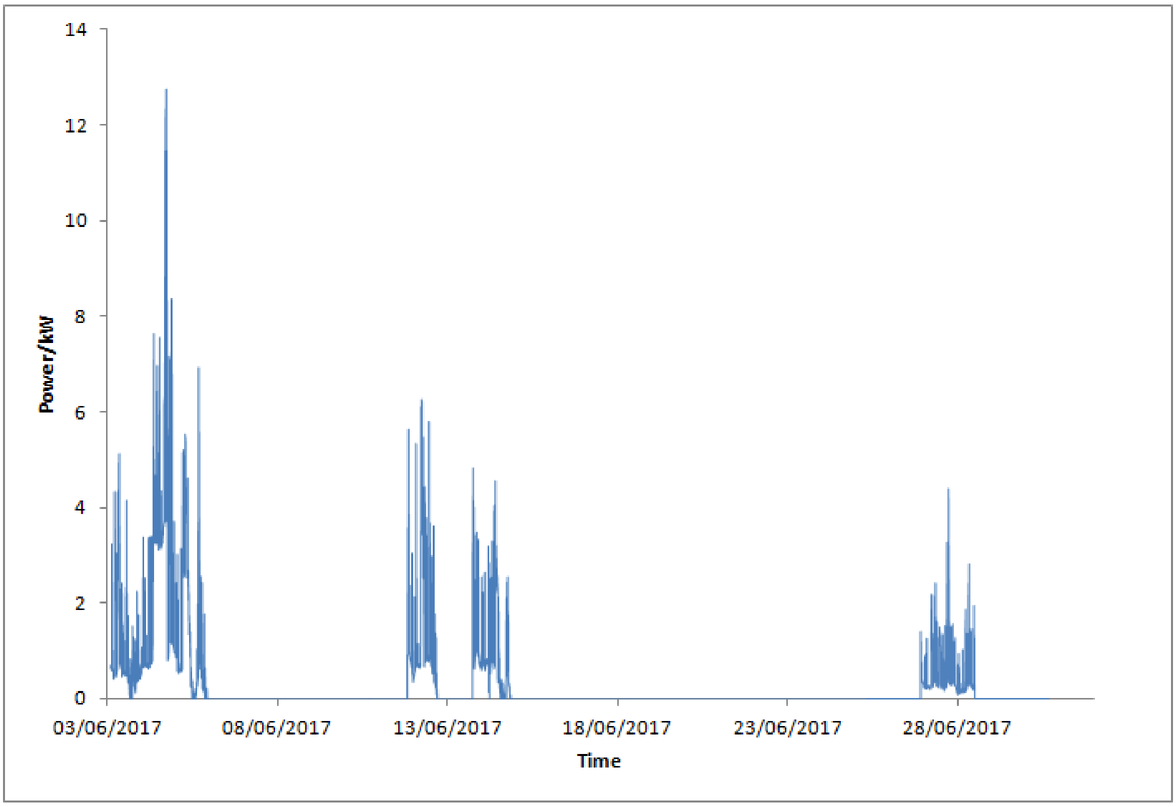

Figure 24: UK grid energy demand of group B with battery storage.

3.3.3 Property Group C

Property group C adds an additional level of complexity to the model due to the presence of behind-the-meter solar power also feeding energy consumption. However, this complexity also means the potential for more interesting results, and the ability for the battery to charge from both solar panels and from the grid at times of excess indigenous energy generation has the potential to make a much more significant impact than it could with one charging source alone. Given that the results for property groups A and B have already demonstrated the difference that battery storage can make to properties without the addition of solar power, the same has not been done for property group C. Instead, when the demand profile of the property group is referred to as being without storage, the implication is without taking full advantage of storage by charging from the grid, but that a battery is still being used in order to maximise solar consumption. This means that the figures to follow will be comparing grid energy consumption between properties with the same hardware installed, i.e. solar panels and a battery, but with one only using the battery for solar power storage and the other also using it to charge from the grid.

Firstly, figure 25 below shows the cumulative energy balance for the property. This shows a familiar profile when compared to the same plots for groups A and B, and simply reiterates the point that, given enough time for battery storage to function and build up an energy reserve, there could in principle be a complete lack of any requirement for imported energy to satisfy energy demand.

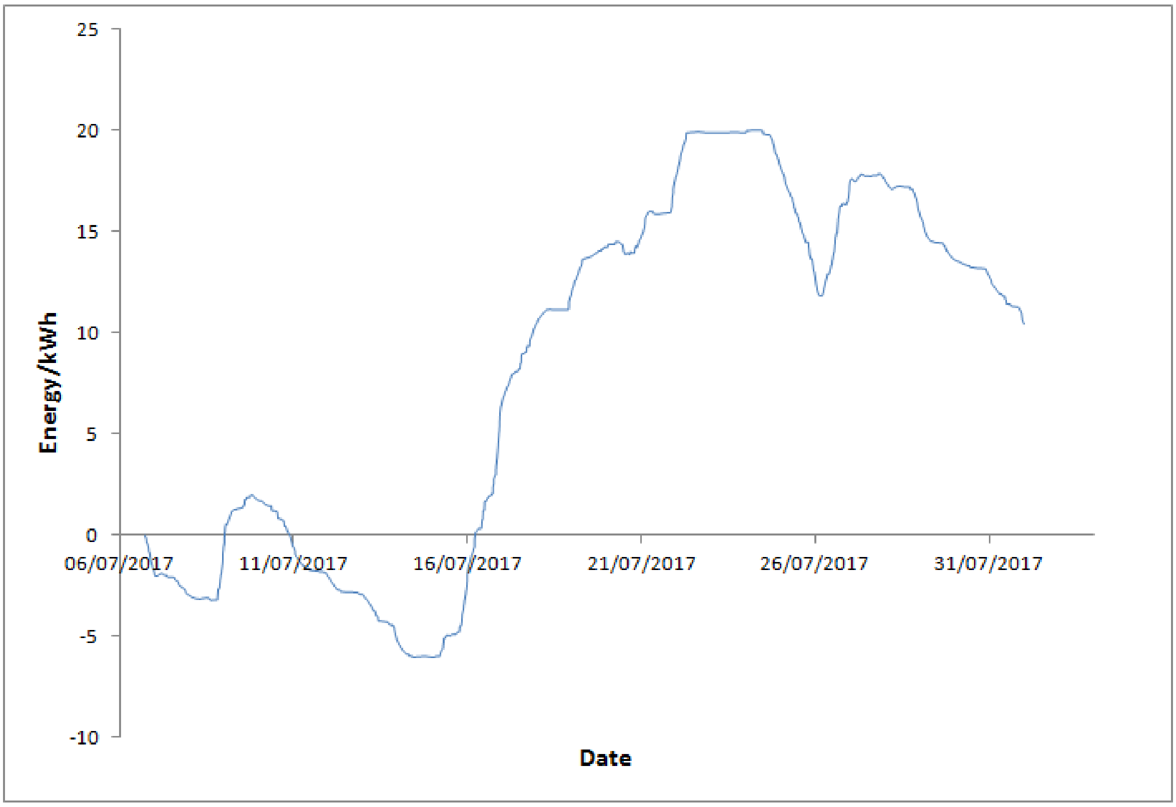

Figure 25: Cumulative energy balance for property group C.

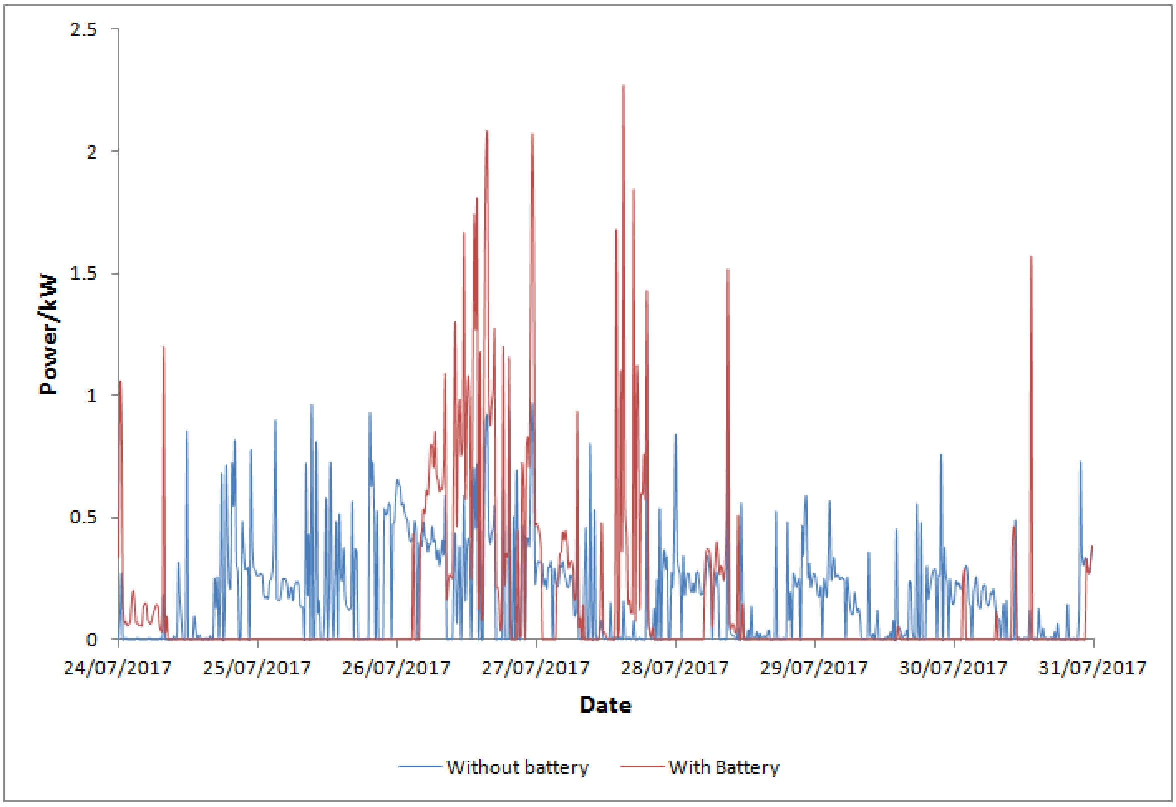

Figure 26: Grid energy demand for group C with and without storage from 24/07/17 to 30/07/17.

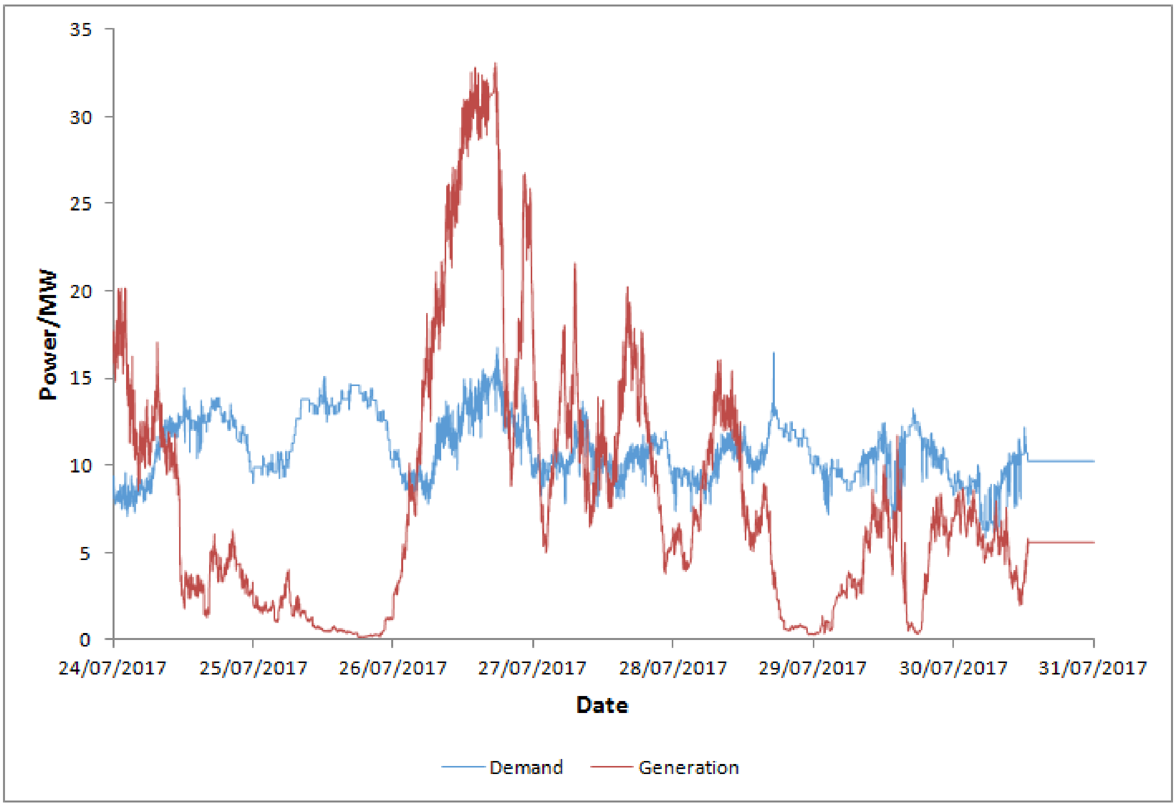

Figure 27: Orkney demand and generation data from 24/07/17 to 30/07/17.

Figure 26 shows the contrast between the original demand profile of the property using solar energy for storage only and the new profile modelled to include both solar and excess grid energy for storage. In much the same way as for groups A and B, it can be seen that, when Orkney-wide generation is greater than demand in figure 27 then the demand level with storage increases above the original level, charging the battery. Equally, when Orkney-wide demand exceeds generation and there is a shortage of renewable energy in the county, the grid demand reduces to 0, relying on both direct solar consumption and previously stored solar and grid energy.

Table 7 shows the contrast between the original Orkney and UK grid consumption and carbon intensity figures for the property and the new values now that full storage has been implemented. Note the difference between the carbon intensity of the total amount of energy consumed by the property, including solar consumption, and the carbon intensity of the energy consumed from the grid. The former is very low in itself, standing at just over 6% of the national UK figure, and the latter is even lower still at less than 4% of the UK average. This demonstrates that introducing battery storage combined with solar power can significantly reduce the carbon intensity of the energy consumed from the Orkney grid, and that the carbon intensity of the total amount of energy consumed by the property—that is, the sum of the energy demanded from the grid and energy generated from solar panels—can be reduced yet further still with this combination.

	Without Battery	**With Battery**
Total Energy Demand/kWh	165.80	165.80
Energy Consumed from Grid/kWh	76.99	99.45
Total UK Energy Imported/kWh	28.78	6.55
UK Import % of Grid Energy	37.38	6.58
Carbon Intensity of Total Energy Consumed/kg $CO_2e(kWh)^{-1}$	0.0780	0.0177
Carbon Intensity of Grid Energy Consumed/kg $CO_2e(kWh)^{-1}$	0.1680	0.0296

Table 7: Energy consumption and carbon intensity data with and without storage for group C in July 2017.

One discrepancy that stands out is that the total amount of energy consumed from the Orkney grid is different between the case with storage and the case without. As originally pointed out for group A, this highlights the limitations of the model and of using discrete data with relatively large time steps for the calculations, as it is clear that, given that the total energy demand for the property for the month is the same, and the total solar generation for the month is also the same, then total grid demand should also remain the same whether storage is used or not. The discrepancy is particularly large in this case because the time step between each data point for property group C was 15 minutes, as opposed to 1 minute for the previous groups. Also, because the "without storage" data is empirical data taken from the property itself as opposed to being produced by a model, it is quite possible that there was already some energy stored in the battery from solar generation at the start of the data series, whereas the modelled data starts with an empty battery.

The second point that stands out is how much of a reduction there is in carbon intensity between the two values. In the case of full battery storage, the carbon intensity of the energy consumed from the Orkney grid is more than 93% less than the UK average, and is less than 20% of the value for the property's consumption even when solar power and limited storage was available. This seems to indicate that there are significant benefits to be gained by using battery storage for grid energy as well as solar generation.

The comparison between figures 28 and 29 shows very clearly how much the requirement for energy from the UK grid can decrease when battery storage is fully utilised, with figure 29 showing that the need for imported energy has been all but eliminated for the period of July. It should of course be remembered that July is typically quite sunny, and that the contribution from solar power to reducing the demand for UK energy in the winter will most probably be substantially less.

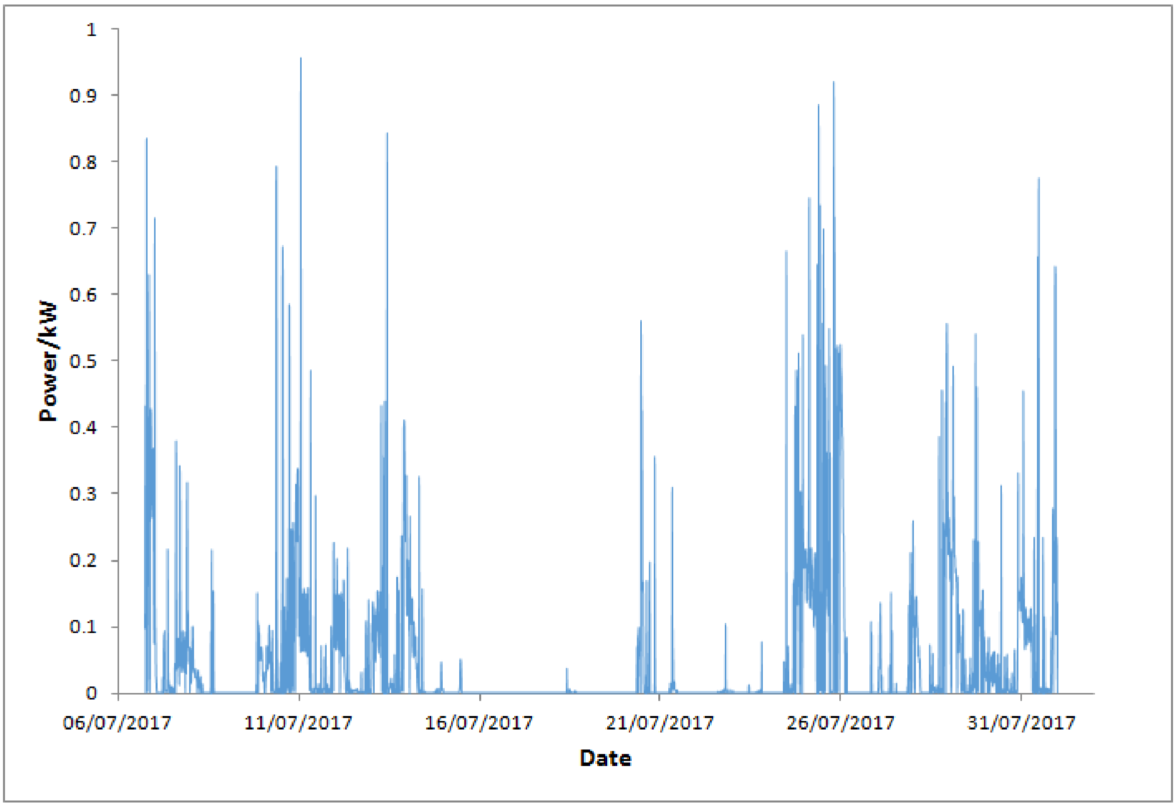

Figure 28: UK grid energy demand of group C without battery storage.

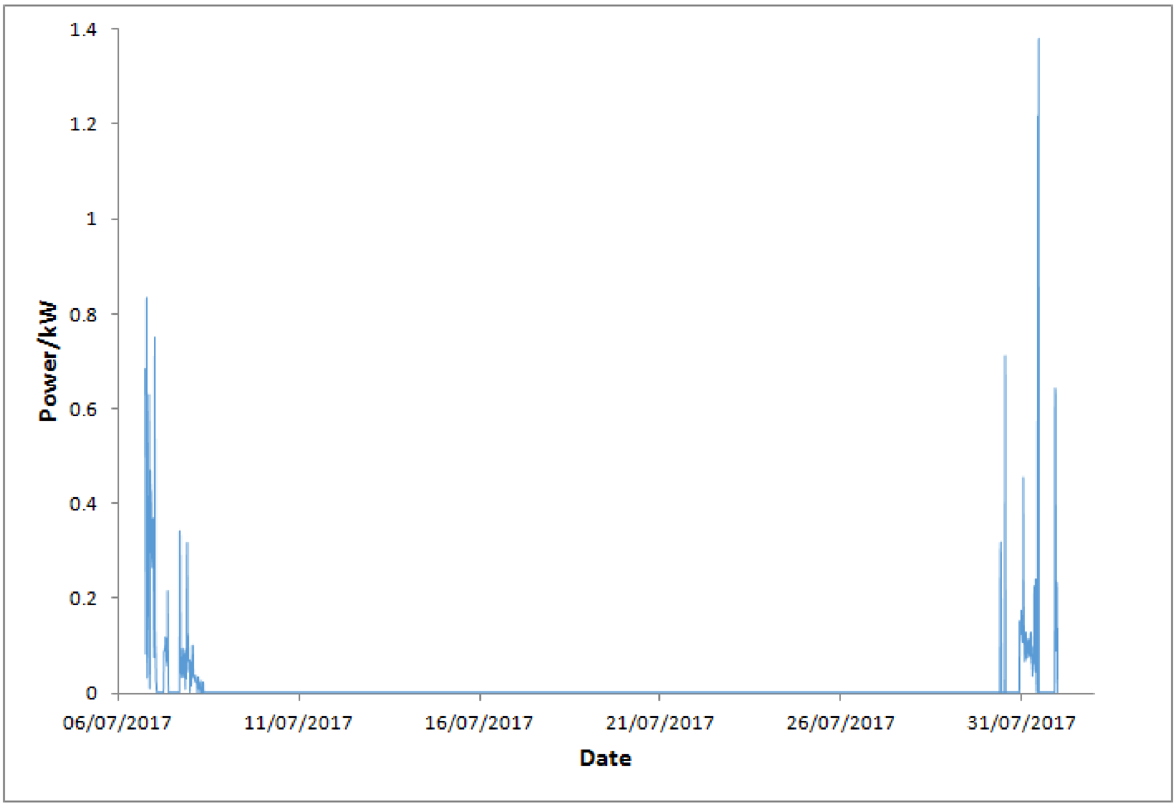

Figure 29: UK grid energy demand of group C with battery storage.

4 Discussion

4.1 Mapping Demand and Generation

The initial results showing energy demand and generation patterns for Orkney help to provide the context in which subsequent findings are to be viewed. The demand profiles shown for property groups A and B are reasonably consistent, and there does not appear to be any significant anomaly in the data which could have caused errors to appear in the subsequent calculations. The demand and generation profiles for group C also show similarities with those of A and B, and having the separate data for solar generation proved useful, showing how demand for energy from the grid can be significantly reduced during the summer months by using solar panels, especially if there is the option to store additional solar generation surplus to immediate requirements.

The Orkney-wide demand and generation data produced some more interesting trends. The first point which stands out is that, in the demand and generation data shown for property group A, there is an approximately 20-hour period, beginning just after the start of 12/10/16, where data for both demand and generation do not change at all, with generation being significantly higher than demand. A similar blip occurs twice more in the month-long generation data for October shown in appendix figure A.2. Based on the rest of the trend shown in the data, this appears to be a fault rather than a true reflection of demand and generation in the county at that time. The data plotted is exactly as the author received it from Aquatera, and so, while it is less than desirable for this apparent blip to be present within the data, there is little to be done about it at this point. Given that it is for a relatively short period of time and does not recur frequently, it is unlikely that this will have significantly altered the subsequent calculations for carbon intensity. All calculations produced from this data will be approximate and uncertain in any case due to the inherent nature of the data, and whether it is ultimately concluded that behind-the-meter battery storage is feasible or not, these short periods of questionable demand and generation data should not be significant enough to affect the result. The demand data presented for the three property groups, as well as Orkney-wide demand and generation data, appear to be generally consistent, reliable and reasonable in form, notwithstanding the above criticisms, and appear to provide a solid basis for the rest of the results to follow. There would of course be a greater scope for taking the research further in the future if demand and solar generation data could be gathered for a longer period of time in order to be able to provide annual mean values, rather than for individual months in isolation.

4.2 Calculating Carbon Intensity

The initial figures showing the calculations for carbon intensity of the energy consumed in Orkney as a whole are fairly promising. During both 2016 and 2017 when data was available, the amount of energy consumed within Orkney that originated from the UK mainland grid was less than 30%. Furthermore, while there is a certain degree of variation in the values for each individual month, as shown in appendix table 8, the standard deviations of the individual monthly values around the annual means were all less than 25% which, given the highly variable nature of wind generation, does not seem particularly high. If all of the assumptions made in the calculations are accepted, then this would be strong evidence to be able to claim that the carbon intensity of the energy consumed within Orkney is less than one third of the

UK average value, even without any form of energy storage or additional renewable energy supply such as solar panels. This could have very significant consequences for sectors such as the construction industry. The lower energy efficiency ratings for properties constructed on Orkney are a result of the assumption that all electricity consumed has a carbon intensity equal to the UK average; the fact that all heating requirements typically come from electricity on Orkney instead of mains gas (something which Orkney does not have) means that, given the assumed carbon intensity, these properties will have a relatively high carbon footprint*. If, as these results suggest, the carbon intensity of energy consumed on Orkney is significantly less than presently assumed, there would be strong justification for requesting a change in the relevant building regulations to take this into account.

When looking at the carbon intensity figures for property groups A and B specifically, the picture is essentially the same, with the values for the properties matching the Orkney-wide values for their respective months within a 2% margin. This should not be surprising, as the energy that they consume comes entirely from the Orkney grid, and the small discrepancy between them will simply be a result of their demand profiles not entirely matching Orkney's as a whole. However, the values for group C are significantly more interesting. If solar generation is ignored and the property is treated as if it were receiving all of its energy requirements from the grid, the carbon intensity value is very close to Orkney as a whole for July 2017, but when solar is included, the carbon intensity of the energy consumed becomes half of what it was previously. This is a highly significant reduction, demonstrating the difference that can be made with solar panels combined with battery storage for excess solar generation. As can be seen in the subsequent section, this effect is magnified even further when the battery is allowed to charge from the grid as well as the solar panels.

4.3 Introducing Battery Storage

The effects of introducing battery storage into the different property groups were significant in all three cases, although the impact that it achieved on energy carbon intensity varied significantly between the different groups. For groups A and B, storage did cause a notable reduction in the consumption of energy originating from the UK grid, showing decreases of around 20% and 40% respectively. However, when solar power and storage were included simultaneously for group C, the change in carbon intensity was much larger. The carbon intensity of the energy consumed from the Orkney grid was more than 93% less than the UK average value, and the carbon intensity for the total amount of energy consumed, including both grid and solar consumption, was 96% less than the UK average. This is a highly significant finding, the impact of which can be seen particularly clearly in the stark contrast between figures 28 and 29, showing the difference in consumption of UK grid energy between scenarios with and without battery storage. There is a similar comparison to be seen for groups A and B, but it is nowhere near as pronounced.

There are a couple of points to be taken away from this. The first is that the largest single factor that can reduce the carbon intensity of energy consumed by a property during the summer is the presence of solar panels. Even before the battery was allowed to charge from the grid, the ability to generate and store solar energy for consumption by property group C reduced its carbon footprint by 50%, a much greater reduction than achieved by any

*If the UK grid average carbon intensity is assumed, then using a gas boiler for heating instead of electricity gives a lower overall carbon footprint.

other single factor not incorporating solar power. The second point is that, while the ability to store solar power can have a very large impact on grid energy consumption, the ability for the battery to strategically charge from the grid in addition to storing excess solar energy allows for a significant additional reduction in carbon intensity during the summer months. During the winter, it is unlikely that much energy will be generated by solar power, and the figures presented for groups A and B are most probably fairly similar to what they would be for property group C during the winter months. While the impact of the battery storage is nowhere near as significant as it is when combined with solar generation, the fact that the battery will have a continuing role to play during the winter, i.e. to charge from and help to balance the grid, even when it is not overly useful for solar storage, means that there can be an additional productive use for the hardware beyond what its current functionality extends to.

The usefulness of the Powerwall batteries could of course be increased if a greater storage capacity were available. While 14kWh is respectable, it is clear to see from the various figures that there would be a direct benefit from having access to a larger capacity. While the various figures comparing the grid demand for the properties with and without battery storage show that grid demand can be reduced to 0 on many occasions when Orkney-wide generation is less than demand, this is not true in every case due to the battery becoming empty before the period of energy import into Orkney has ended. The various cumulative energy balance graphs show that if storage were unlimited then this should never have to occur after a certain point in any given month, and while an unlimited amount of storage is neither necessary nor practical, a modest increase over what is currently available could prove to be beneficial. However, a larger battery would mean greater size and inconvenience as well as greater expense, so while it may make sense from a purely technical point of view, it may be the case that 14kWh is close to the optimum value in terms of economic efficiency.

While these results are encouraging, it is important to recognise their limitations and how much weight they can carry. The following points must be taken into consideration:

1. The model assumes continuous, instantaneous knowledge of whether there is a renewable energy surplus in Orkney or not. While this information is readily available for retrospective studies, there may be logistical challenges in obtaining this information in real time—something which would be necessary in order to have as great an effect on carbon intensity as the model would suggest to be possible.

2. The model does not take into account any inefficiencies in the charging or discharging of the batteries, as already stated in the methodology. While modern battery technology means that the energy wasted would typically be low, it will still be non-zero, and is something that will have to be accounted for if a more precise calculation of energy usage and carbon intensity is to be attempted.

3. The calculations for carbon intensity do not take into account the cradle-to-grave emissions of the wind turbines, the batteries used to store the energy, or the solar panels fitted to the property in the case of group C. The components needed for many battery technologies as well as solar panels often require significant amounts of energy and resources in order to acquire them, and it would be necessary to take this into account if a true like-for-like comparison were to be made between renewable energy which requires storage, and fossil fuel energy which does not. While the combination of these

factors should not be enough to entirely outweigh the reductions in carbon intensity demonstrated, it will no doubt create a significant increase in the figures compared to what has been calculated in this report. As has already been stated, the calculations made here are not 100% accurate and should not be taken at face value because of these additional factors. They are an important initial step in determining what order of magnitude the effect of behind-the-meter battery storage could have, but these simplifications made in the calculation process mean that they should be taken with a large pinch of salt.

4. The model assumes a battery discharge rate that is equal to the property's energy demand until the battery is empty, i.e. it assumes the maximum useful discharge rate. This seems to be a reasonable approach to take for the purpose of simplicity, but in principle a greater reduction in carbon intensity could be achieved if the energy discharge was saved for the point at which the greatest proportion of UK energy is being imported into the county, instead of simply at the first time when any is being imported at all. However, this alternative method would require not only the immediate knowledge of generation and demand as stated in point 1, but also information of what future demand and generation will be in advance, so that the controller would know whether it should allow the battery to discharge or not. At this stage of development it may appear to be overly ambitious to reliably achieve this level of control and foresight.

5. The model takes no account of the location of the properties within Orkney. While this is not likely to be a significant factor when considering only five properties for battery installations, if the project were taken to its logical conclusion and every property across the county were to be fitted with batteries then grid constraint between the different zones on Orkney may become a problem. Even if there is excess renewable generation available in the county for consumption, there is no guarantee that the Orkney grid would have a large enough capacity to distribute the energy from the generators to the locations of demand.

6. The cost associated with the implementation of such a system has been completely ignored. The fact that Solo Energy Ltd are pursuing the implementation of behind-the-meter battery storage with the aim of making a profit would imply that there is a business case for it. However, the full financial implications of the combination of battery and solar panel purchase, installation and maintenance along with the complexities of different tariff rates and the practicability of maximising the potential revenue streams made available by the technology have not been addressed. This project has made an assessment of the feasibility of demand-side storage from a mathematical, physical and technological perspective, but a full assessment of the numerous financial implications of implementing such a system would be required before a definitive conclusion on its feasibility could be reached.

5 Conclusion

Overall, this piece of research has produced a number of notable findings, while acknowledging the limitations of what it has set out to achieve. The energy demand and generation data for the county of Orkney was utilised in order to perform basic calculations of the carbon intensity of the energy consumed within the county compared to that of the UK as a whole, and a significant reduction in the carbon intensity value for Orkney when compared to the UK grid was found. Similar findings were made when the demand data for five individual properties across the county was analysed, and followed by the discovery of a further dramatic reduction in carbon intensity when the data was analysed from a property fitted with behind-the-meter solar panels and battery storage.

Following on from this, by using a basic model in Excel to predict how the energy demand profiles could be changed for the properties by using battery storage to strategically charge from the grid, it was found that, whether solar panels were installed in the properties or not, reductions in carbon intensity of at least 20% could be made, with that figure potentially increasing up to 75% if both solar panels and batteries were utilised. It must be remembered that these are relatively simple calculations, and do not take account of a number of factors including cradle-to-grave emissions of the hardware required to facilitate such a project of energy storage, nor was any attempt made to calculate the financial attractiveness of investing in such a project. These would both be avenues for further research to explore, and if similar results were found once more thorough calculations had been completed, there could be the opportunity to provide direct benefits to domestic consumers, the Orkney DNO and owners of renewable energy generators, as well as additional indirect benefits to sectors such as construction within the county.

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A Appendix

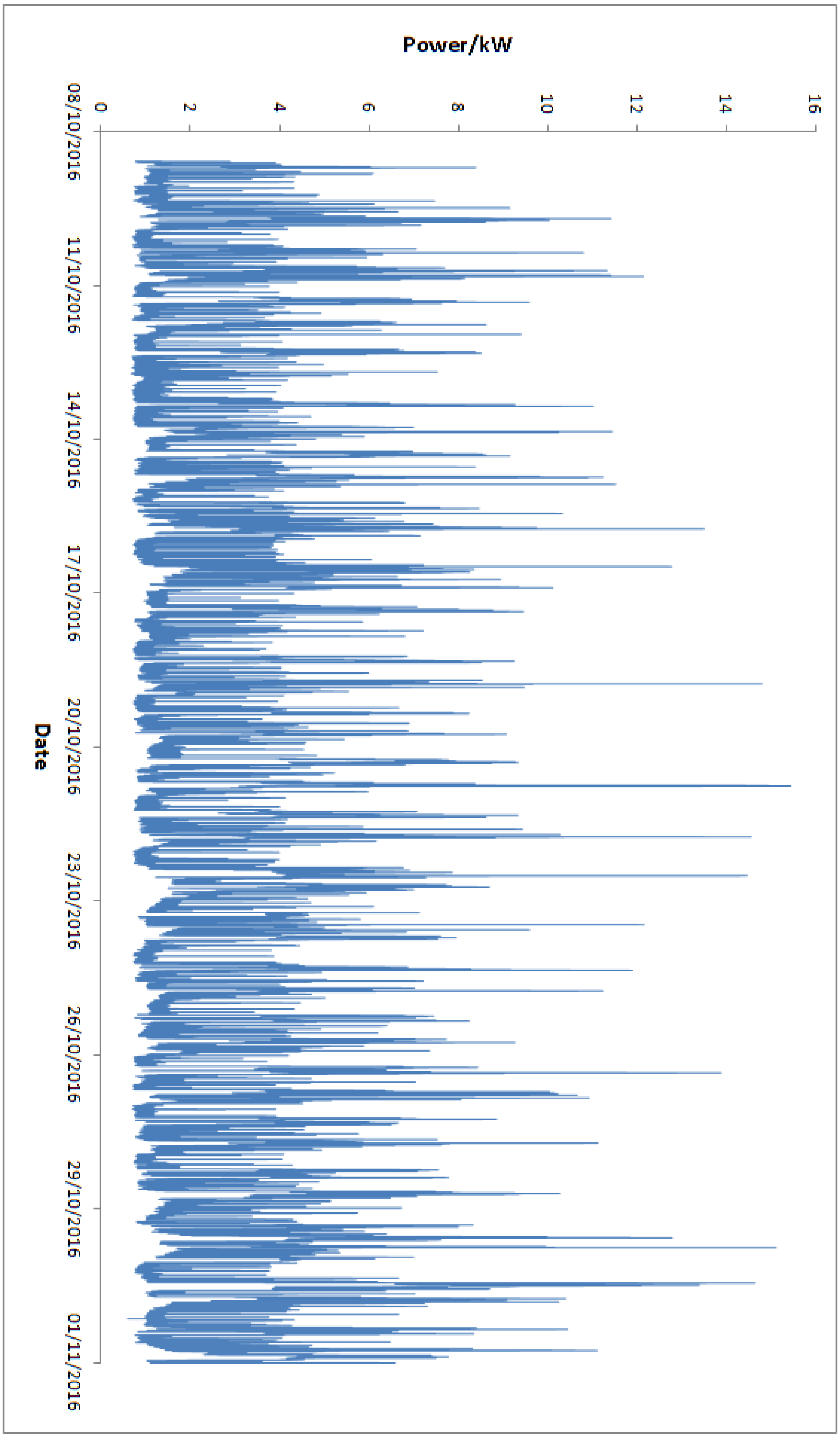

Figure A.1: Full range of consumption data for property group A in October 2016.

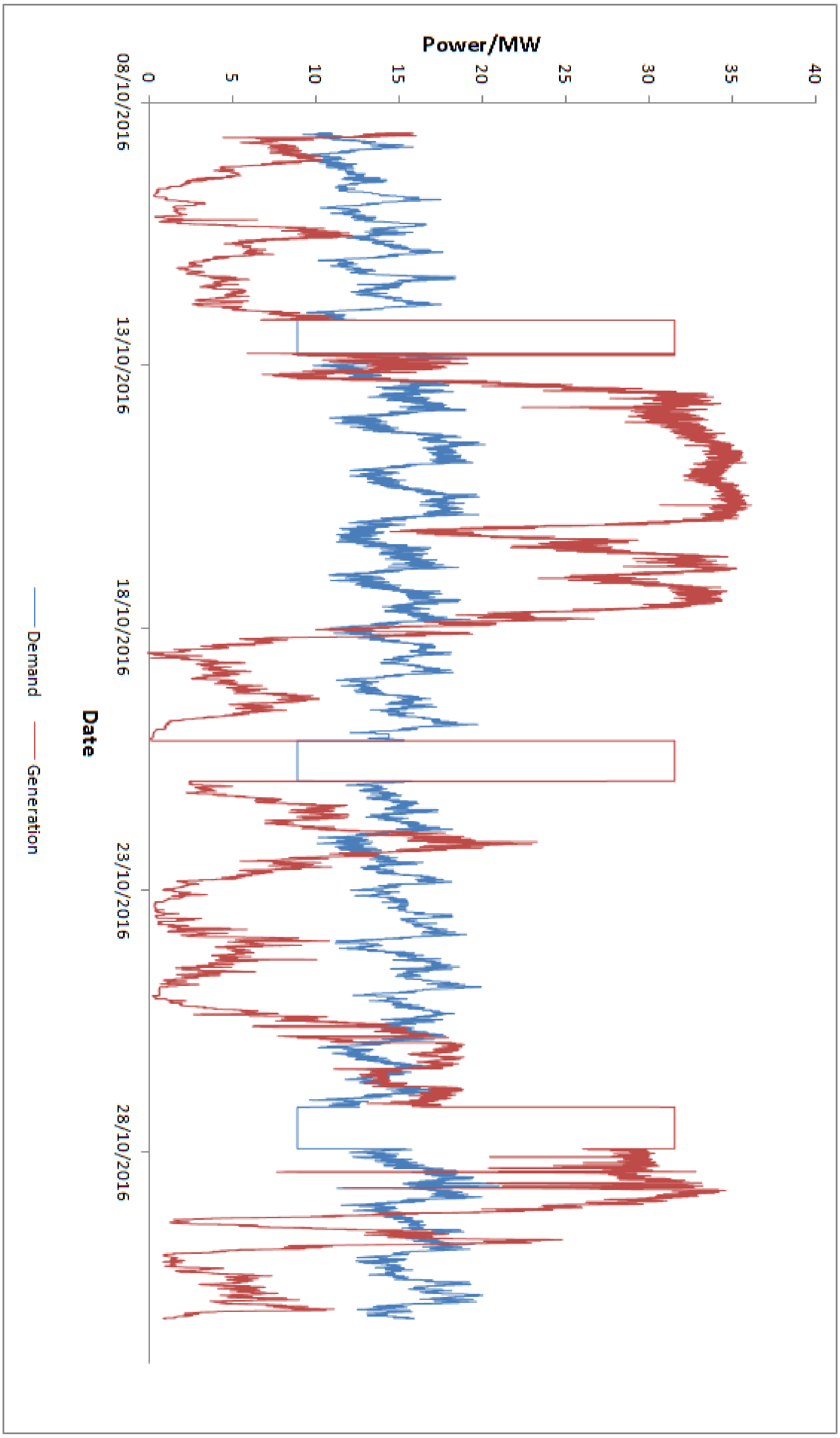

Figure A.2: Full range of energy generation and demand in Orkney for October 2016.

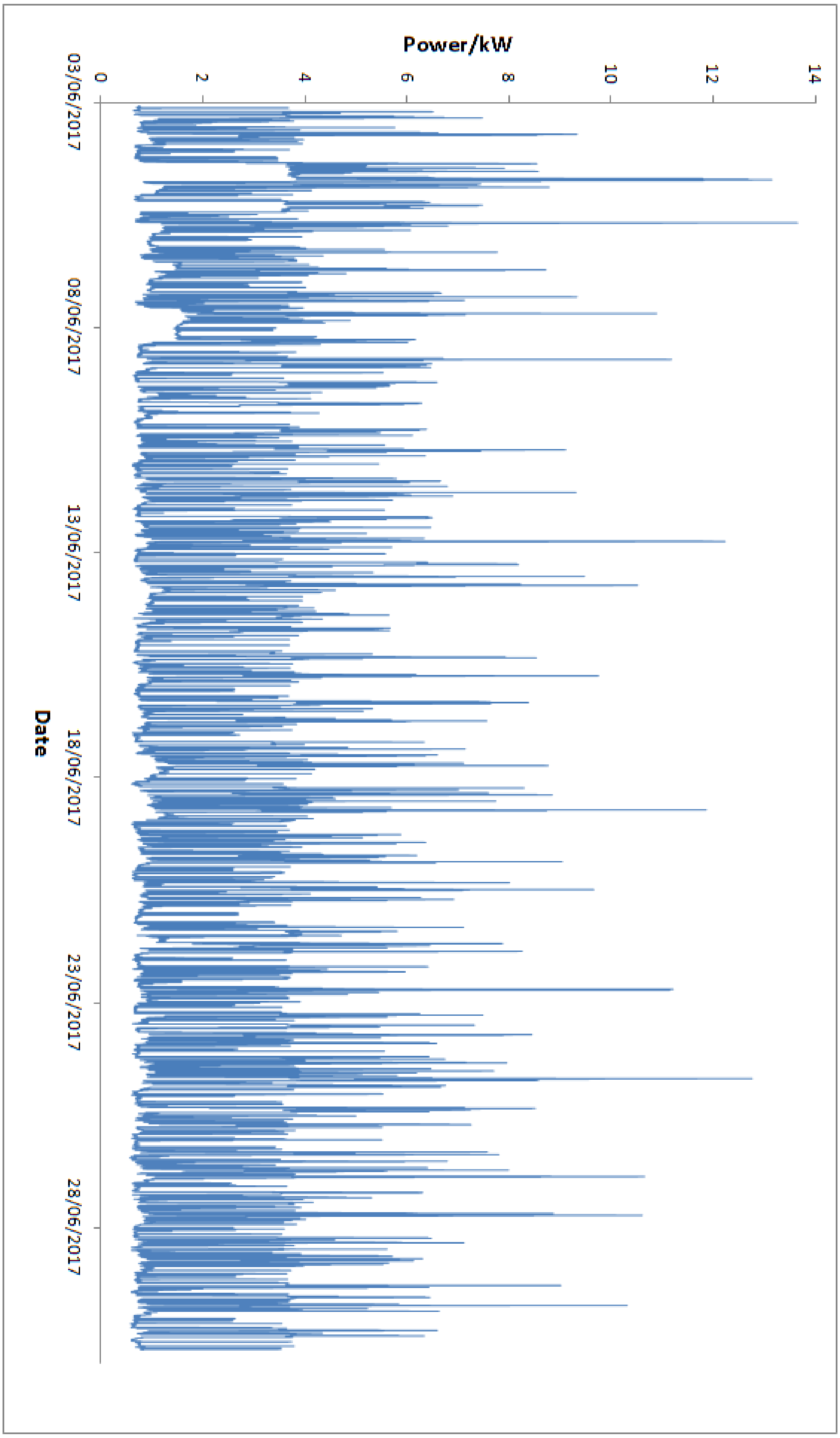

Figure A.3: Full range of consumption data for property group B in June 2017.

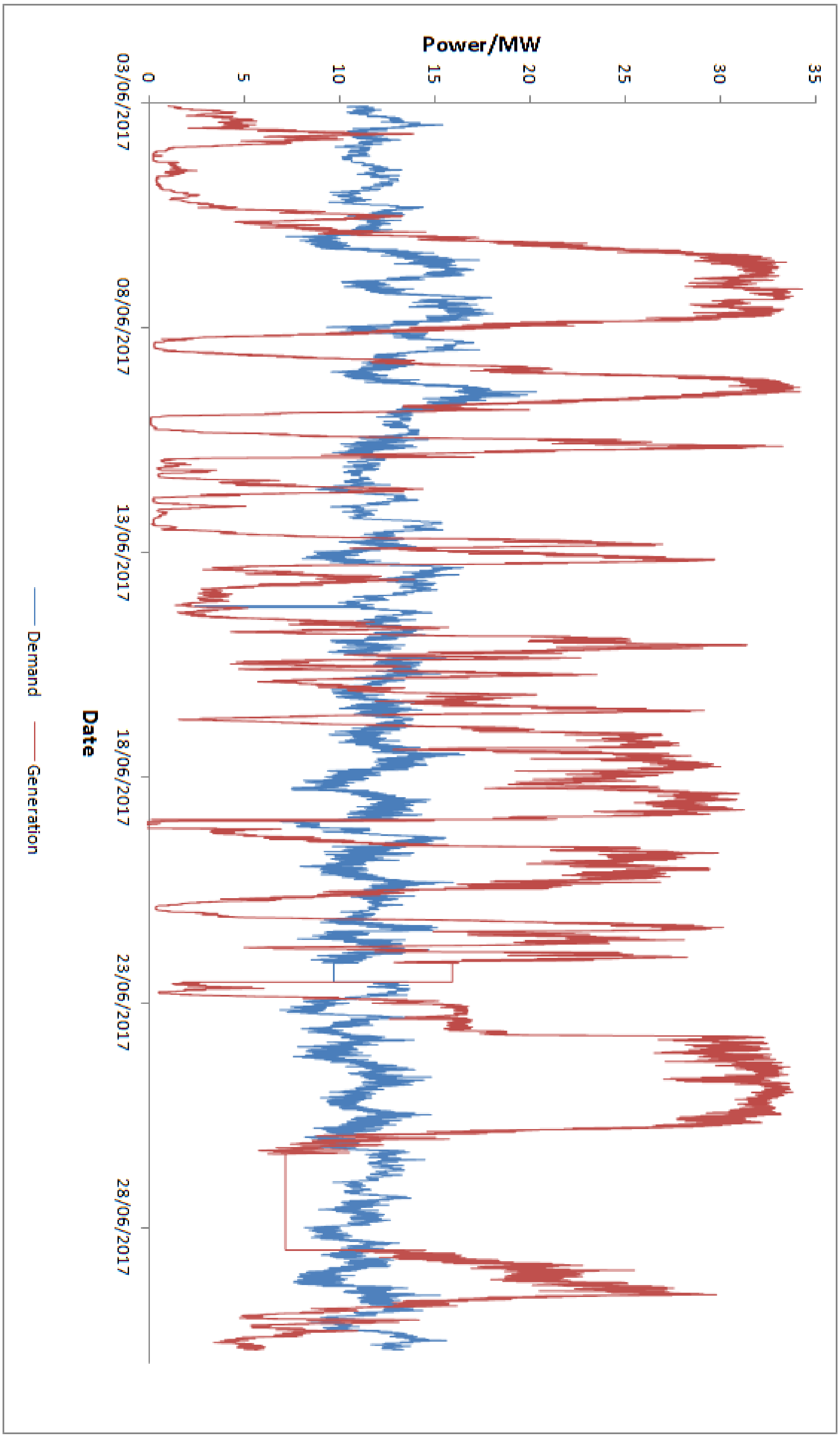

Figure A.4: Full range of energy generation and demand in Orkney for June 2017.

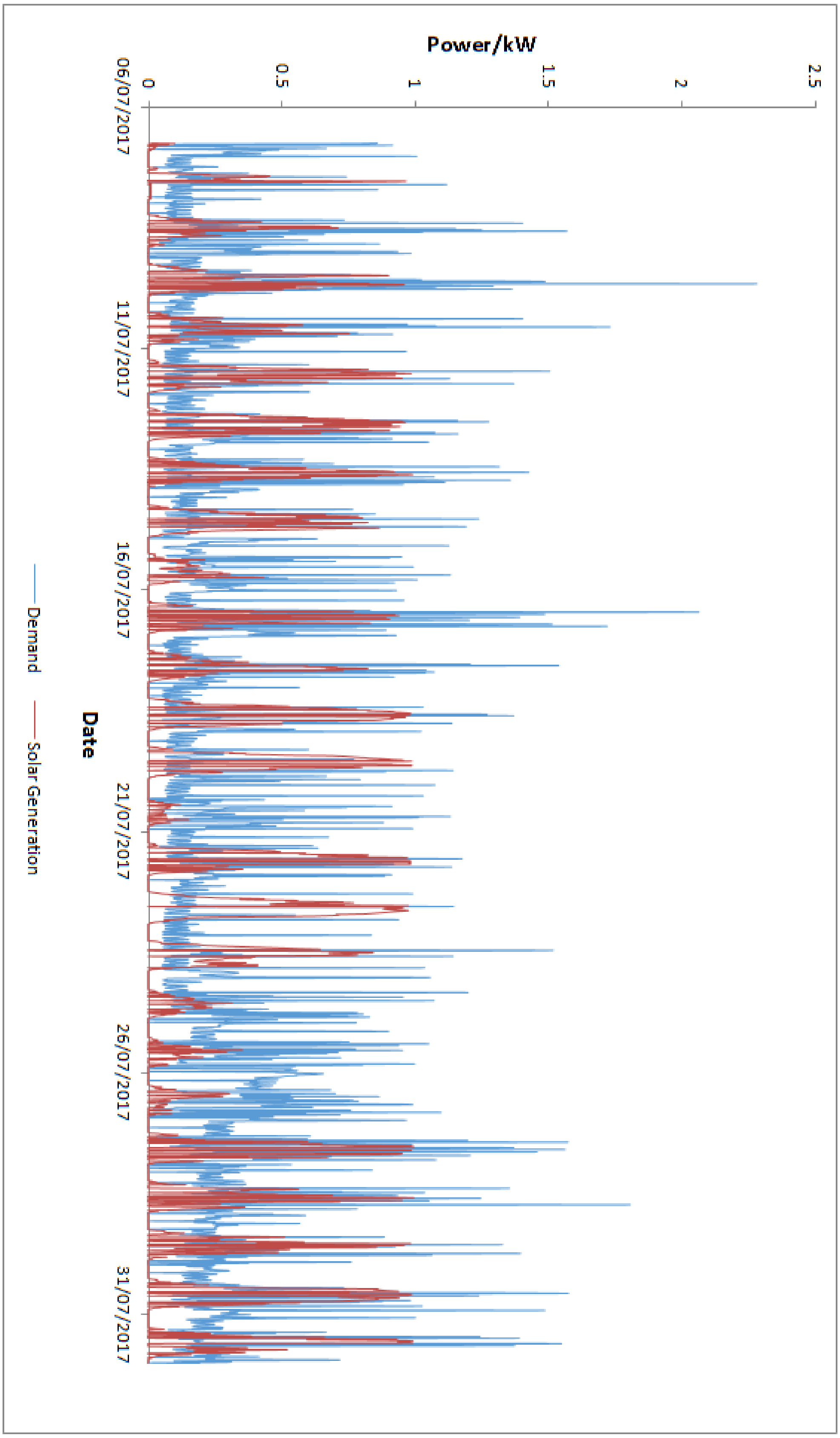

Figure A.5: Full range of consumption and solar generation data for property group C in July 2017.

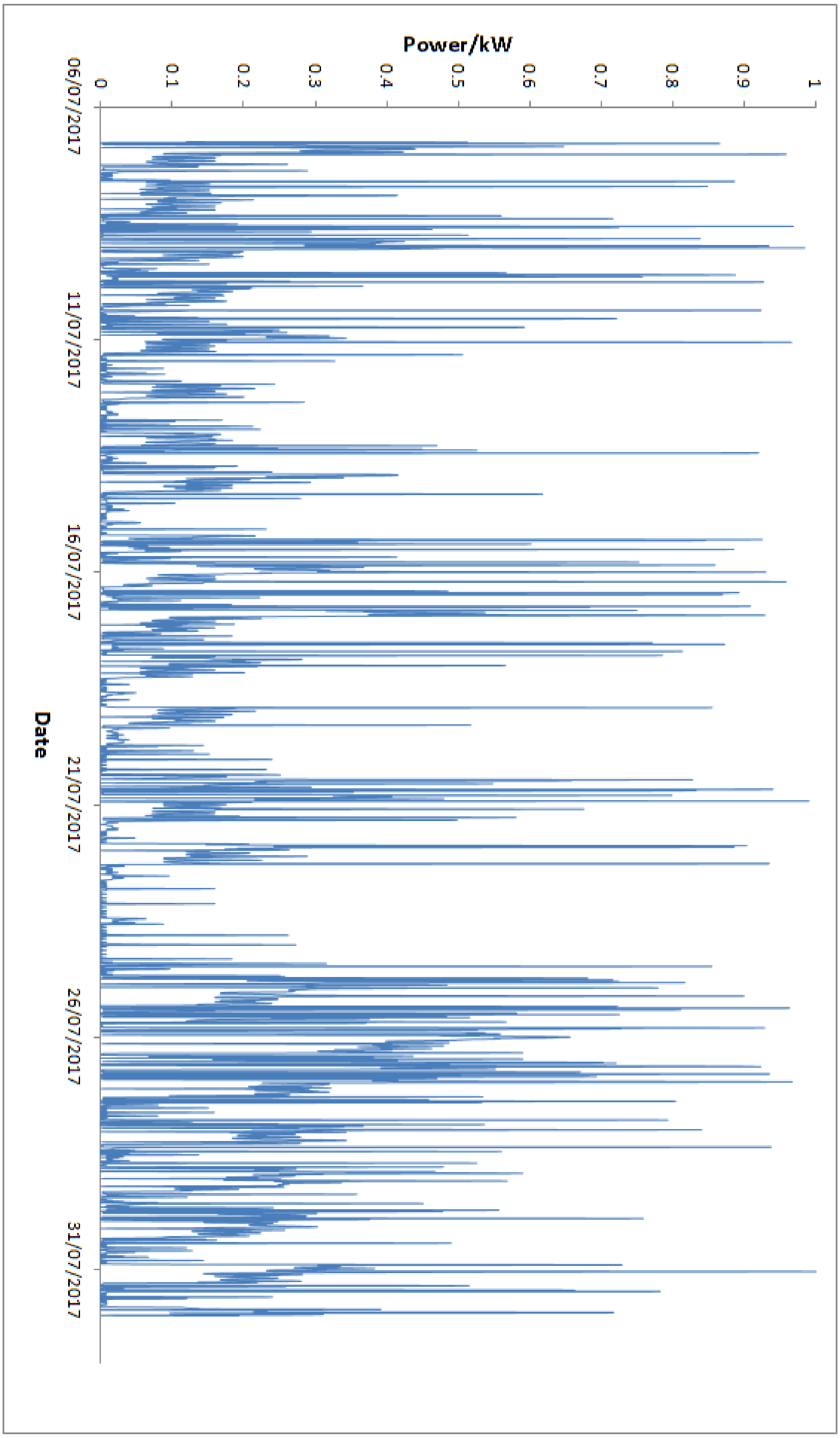

Figure A.6: Full range of grid demand for property group C in July 2017.

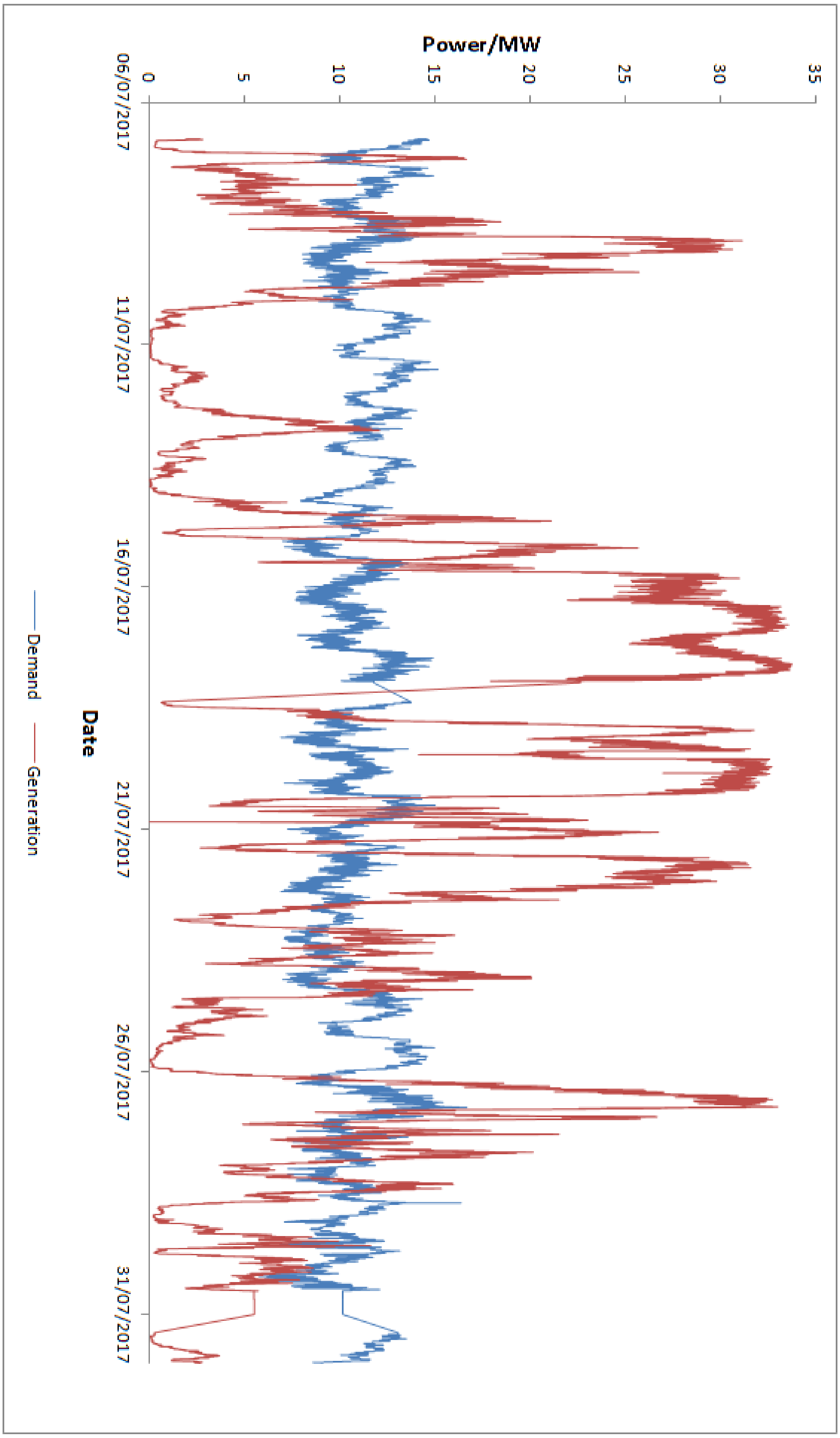

Figure A.7: Full range of energy generation and demand in Orkney for July 2017.

	Total Energy Demand/MWh	UK Import %	Carbon Intensity/kg CO_2e/kWh
Jan-16	9910.1	30.7	0.138
Feb-16	13688.5	18.0	0.081
Mar-16	10889.6	37.0	0.166
Apr-16	10720.1	25.3	0.114
May-16	9518.3	28.5	0.128
Jun-16	7996.2	33.4	0.150
Jul-16	7482.8	26.0	0.117
Aug-16	7385.2	28.2	0.127
Sep-16	7755.8	26.2	0.118
Oct-16	10380.3	32.2	0.145
Nov-16	14024.3	33.4	0.150
Dec-16	13901.5	26.2	0.118
Jan-17	14586.4	25.0	0.112
Feb-17	13146.8	32.6	0.146
Mar-17	13690.9	25.9	0.116
Apr-17	12145.3	17.5	0.079
May-17	10144.5	32.8	0.147
Jun-17	8651.7	29.9	0.134
Jul-17	8245.8	38.5	0.173

Table 8: Monthly Orkney-wide energy consumption and carbon intensity data.

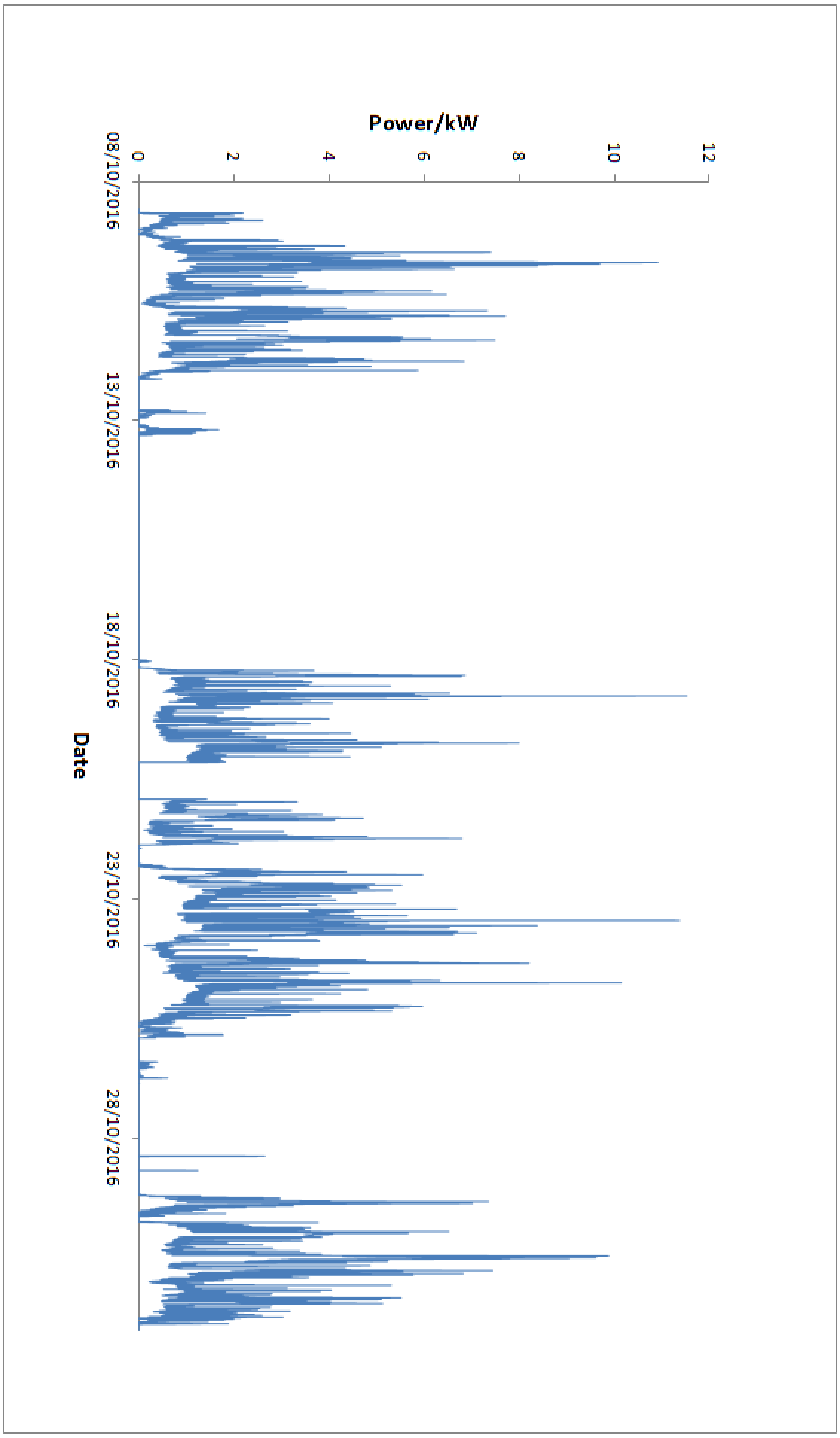

Figure A.8: Energy consumption for property group A from the UK grid in October 2016.

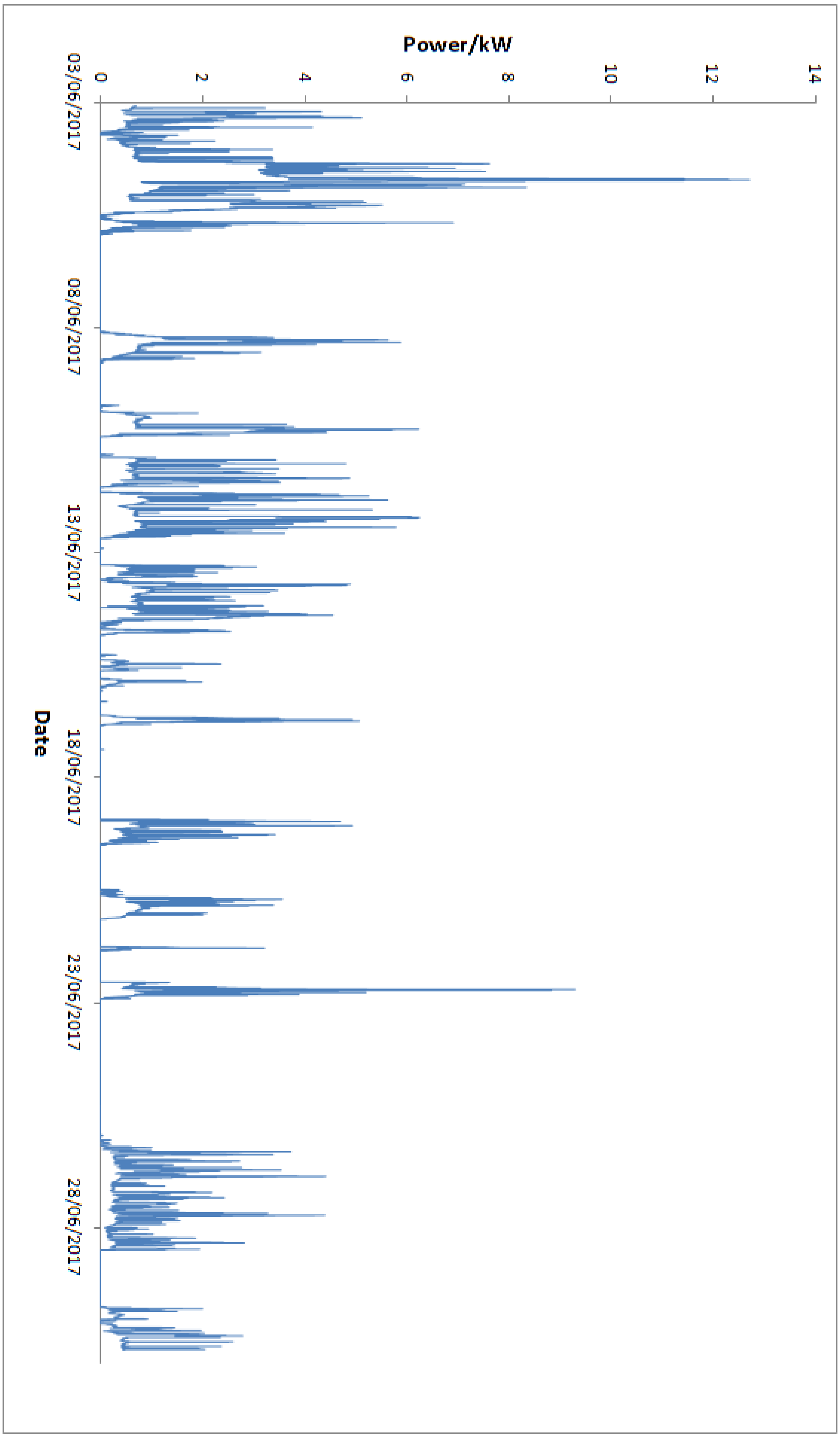

Figure A.9: Energy consumption for property group B from the UK grid in June 2017.

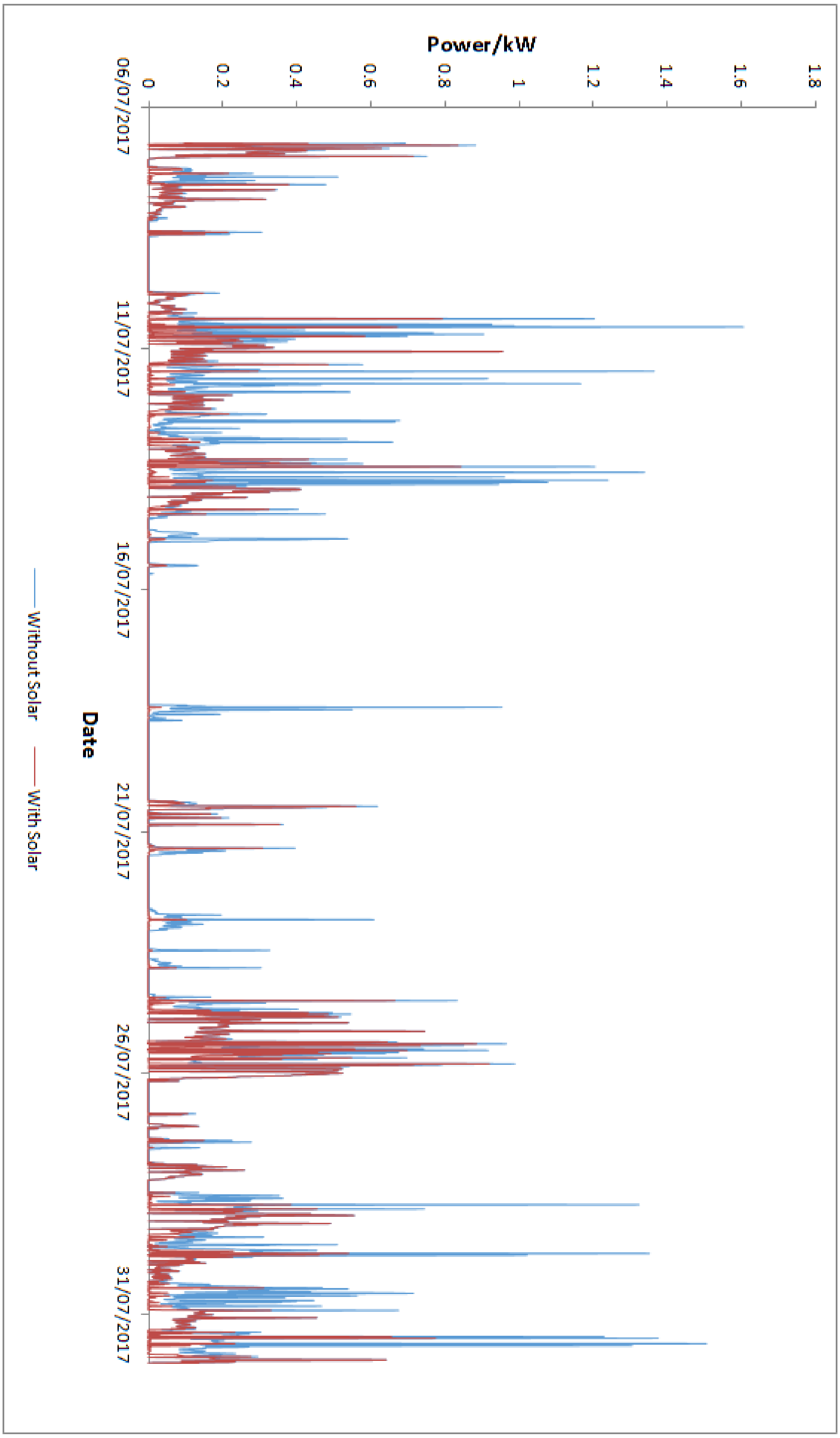

Figure A.10: Energy consumption for property group C from the UK grid in July 2017.

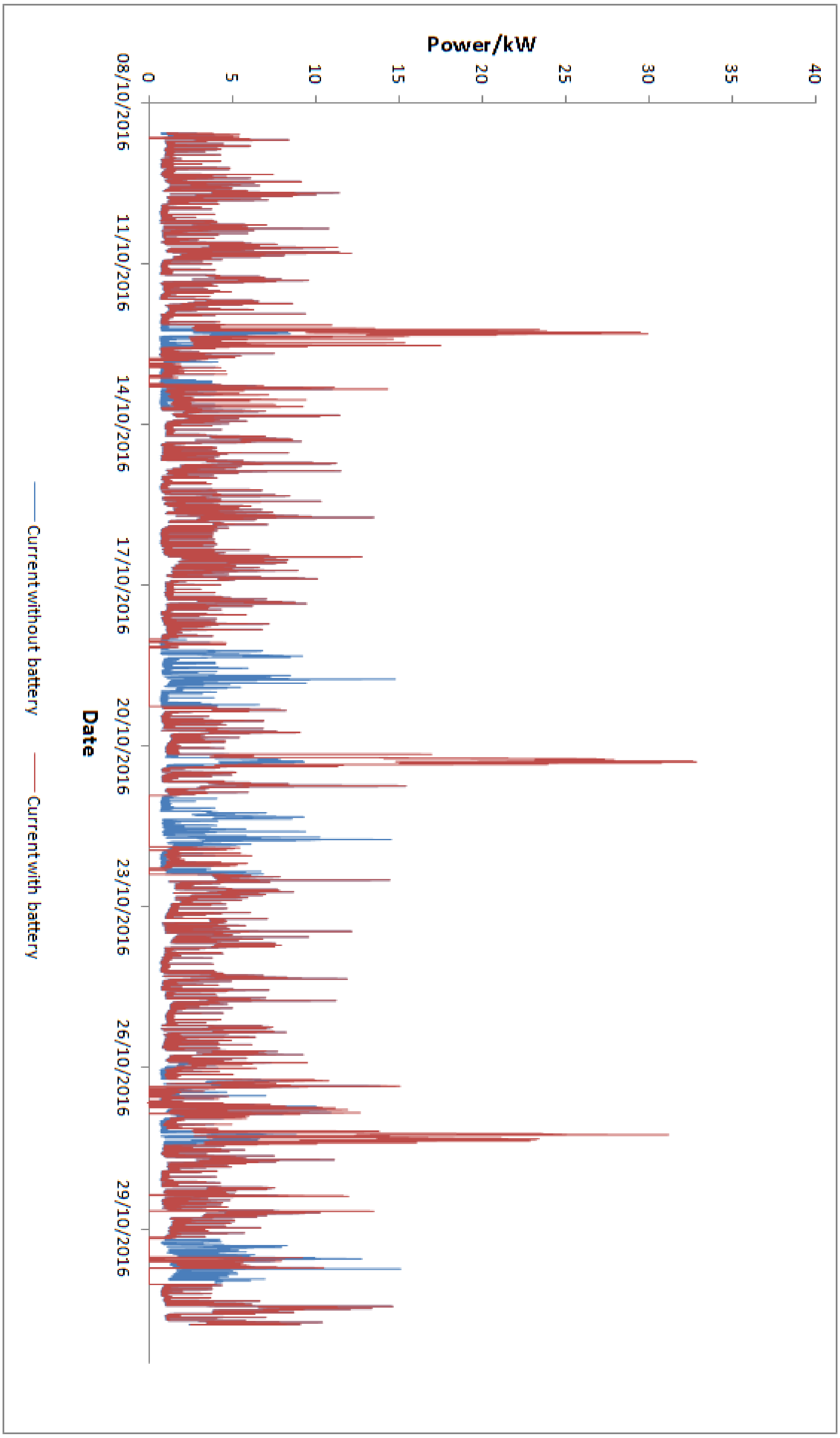

Figure A.11: Power demands of group A during October 2016 with and without battery storage.

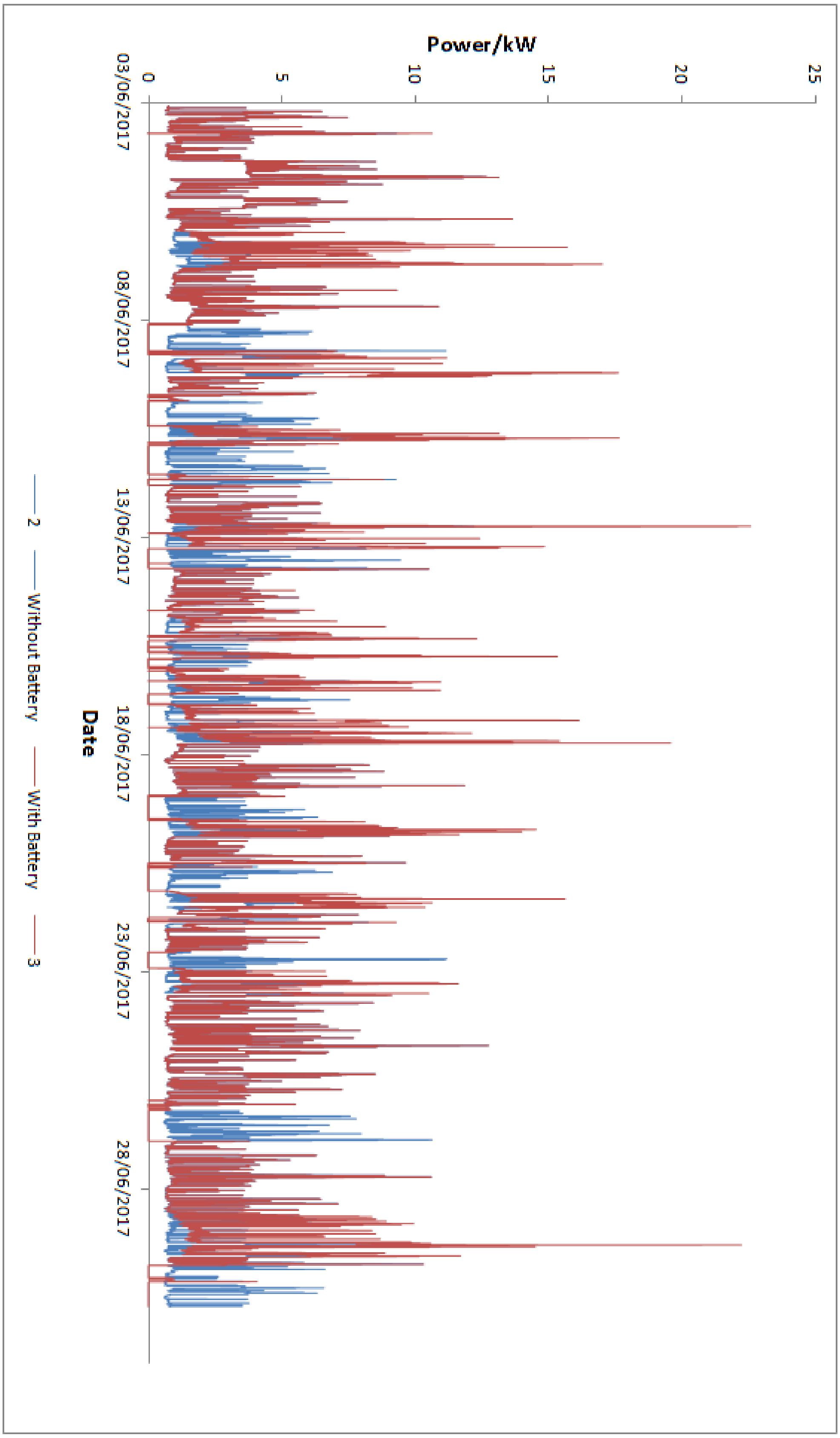

Figure A.12: Power demands of group B during June 2017 with and without battery storage.