DEPARTMENT OF MECHANICAL & AEROSPACE ENGINEERING

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Energy Load Management of Domestic Appliances to Aid the Stabilisation of a Renewable Electric Grid

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ABSTRACT

As the UK moves towards achieving its ambitious renewable targets, the steady increase of renewable technology in the national electric grid risks increased frequency instability. Possible solutions include adoption of creative demand response programs utilising better energy load management. Through increased appliance upgrades and the connective capabilities of the internet, energy load management presents itself as an effective way of bringing stability back to the renewable electric grid in a cost-effective manner.

Alternative strategies such as back-up generation and large-scale energy storage methods require large capital investment and infrastructure construction. Furthermore, wind turbine curtailments (and its associated cost) during periods of oversupply is a ‘bottle-neck’ problem which will only become more expensive as wind energy’s capacity expands. Energy load management offers a cost-effective method of balancing fluctuating supply and demand. Financial incentives and policy changes will be required to encourage wide-scale domestic participation. However, if broadly adopted, energy load management offers a simple, cost effective solution to supporting a fully renewable grid.

The UK’s current demand management potential is lacking in comparison to other countries, but with momentum building behind the renewable energy targets, now presents the perfect opportunity to tackle such challenges head-on. This thesis aims to explore an effective strategy of energy load management focusing primarily on the UK domestic home. Through the shifting of only a small number of appliances, it is demonstrated here that the domestic home can appreciably reduce its daily demand peaks, alleviating evening demand through utilisation of the current economy 7 tariff. Furthermore, such a strategy offers a solution to help address the outstanding challenges facing implementation of a renewable dominant grid.

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ACRONYMS

W - Watts

KW - Kilowatt

MW -Megawatt

GW -Gigawatt

TW- Terawatt

Wh – Watts hours

KWh – Kilowatt hours

MWh -Megawatt hours

GWh -Gigawatt hours

TWh- Terawatt hours

IoE – Internet of Energy

PV -Photovaltic

AC – Air Conditioner

CPS – City Public services

ELM – Energy Load Management

1 INTRODUCTION

1.1 Problem definition

In modern developed countries energy is in the midst of being redefined. Environmental concerns have resulted in new technologies and methods of energy production constantly emerging with the aim of bringing balance to the energy trilemma. Emerging energy generation methods aim to provide the electrical grid in the three attributes: energy security, energy equity, and environmental sustainability. The traditional linear energy transmission means have evolved into a smart energy network with multiple contributors and contribution methods. In the past, fossil fuels have been the dominant energy source for the nations electrical supply resulting in the national grids infrastructure being built around the utilisation of this fuel type. However, as environmental and sustainability issues which ensued from its use, there is now demand for a cleaner more sustainable energy source. Using renewable generators as a source of energy has built up momentum with aims to replace the nation's dependence on fossil fuels. However, the change in infrastructure and the effect on the electric grid renewables has is the source of many challenges which require solutions before a renewable grid can become a reality.

The energy grid is now managed and monitored through the internet as the world of energy entered a new era known as the Internet of Energy (IoE).[1] The internet allows a bidirectional communication between the electrical energy grid and energy consuming applications. The internet also allows the simultaneous monitoring of multiple fields such as power distribution, weather forecasting, electrical demand, etc. The capacity of the internet's role is constantly growing in all aspects of human society with new developing technologies designed to increase the pace and ease of our day-to-day lifestyles.[2]

Consumers embrace an increasing amount of electrical technology into their lives resulting in an ever-increasing energy demand is placed on the national electrical grid. To meet this rising demand, energy companies compete to produce more energy generators increasing the maximum output capacity to meet the peak electrical demands of the country. With a growing energy capacity more development is required from the electrical infrastructure i.e. more interconnecting cables are required to transport the larger volume of electricity.[3]

In the modern domestic home, for most of the hours during a day, energy demand is generally low for reasons such as occupants being asleep or at work. However, for the hours that the occupants are in their homes and are active, the energy demand is generally high.

The demand for energy influences and shapes the energy generation requirements of the national grid and it is anticipated in this thesis that demand will be required to evolve in compliance with renewable energy generation limitations. Additionally, domestic demand will continue to evolve through the addition of future technologies, both energy consuming and energy demand aiding, and with lifestyle alterations. The previously explained domestic demand reduction correlated to occupants leaving for work will likely see a reduction in its effect on demand as the COVID-19 pandemic continues to require many people to work from home. Despite the disruption of the pandemic, the consequences of people staying at home offers an opportunity to allow the general homeowner to become more energy conscious and offers them more flexibility in chore related appliance usage.

Despite the disruption of the pandemic, the peak domestic demand will remain evening time prime time that a domestic home will experience a high energy demand is when the occupants come home from work. For example, when the home occupants return from work, they may turn on electrical appliances such as their television, washing machine, electric heater, shower, kettle, etc, all appliances which build up a large energy demand. In the UK, most households will finish work at 5pm which means that there will be a national energy demand peak starting at around 6pm and continues until 10 pm.[4]

As previously mentioned, growing technologies result in the production of more electrical appliances being brought into the home.[5] The consequence of this is an increasing national energy peak load necessitating large capital investments to increase the capacity of energy generation.[6] Importantly, these energy grid infrastructure expansions are only required to satisfy the demand generated during a small period of the day.

The UK's energy network is perfectly capable of satisfying the current energy demand and its energy industry has the established tools and methods to meet a steady growing demand.[7] However, complications will arise as the UK continues to strive to meet its renewable energy targets with the aims of decarbonization. As the percentage of renewable energy contributing to the national energy grid increases, the less controllable energy supply comes, including a higher degree of fluctuation between maximum energy output capacity and low energy output.[8]

Furthermore, the increased adoption of renewable energy generators will require careful consideration of its influence on energy load management. In many countries the aim to completely decarbonise their national energy grid by replacing coal, oil or gas fueled energy generators with renewable energy generators. Currently in the UK renewable generators contribute a portion of national energy supply with natural gas providing the largest proportion of the nation's baseline energy demand. The major difference between renewable energy systems and gas-powered systems is the system's dispatchability. Natural gas systems are completely dispatchable allowing large energy production to begin on short notice. Most used renewable energy systems such as wind turbines or solar are non-dispatchable and rely on stochastic factors (e.g. wind speed) making them a less controllable energy source.[9]

Because of this aspect of renewable energy generators, a renewable heavy grid will experience increased difficulties and strain when matching energy supply to national demand without major changes to the current system. Continuing to outrun the demand through increased output capacity is the main method in use today, however it is a costly method and may prove unsustainable. An alternative solution to this problem would be tackling demand management itself.

The first intuitive method of reducing demand peaks is by increasing the energy efficiency of appliances, however greater energy efficiency does not always result in a reduced energy demand due to unforeseen unintended consequences. For example, the evolution of the television for example, the early models of the television were large blocky appliances with large electrical requirements for a small screen. The television evolved into thin screens with better energy efficiency technology with much less energy being wasted as heat. As a result of this improved technology, consumers began buying bigger televisions with larger screens. The result was that despite televisions greatly improving their energy efficiency, their electrical demand remains similar to the original models. This is in addition to other television factors such as marketing and additional services which results in the television remaining an energy intensive appliance.[10]

Another method of reducing peak load demand is Energy Load Management. This concept introduced the idea of spreading or shifting the peak load to hours of low national demand to reduce the maximum national peak load. This can be achieved through many methods such as Demand Side Management (DSM) which involves managing energy demand through larger customer awareness/ incentive methods.[11] An Additional method (and the primary focus of this thesis) is reducing the peak load through greater appliance control by energy companies. Both these methods would be aided by increasing smarter technology integration and development similar to the smart meter.

Current domestic smart meters are mostly used to accurately monitor energy usage in the home allowing the energy company to correctly bill the customer for their true energy usage and to allow the customer to evaluate times and sources of high energy usage. [12] The core difficulty facing energy load management is shifting energy demand with minimum disruption to the consumers electrical needs. The term ‘shifting’ in reference to energy loads is used to describe a strategy of changing the period of an appliance’s peak energy usage. It is believed that through further development of smart meters in cooperation with smart appliances and further internet-driven automation, energy load management can be carried out seamlessly to the consumer while importantly reducing peak loads.

1.2 Aim

Currently the UK, in comparison to other developed countries, has inferior demand response capabilities.[13] In order to address this, a better understanding of domestic demand is required. The overall objective of this thesis is to provide a detailed analysis of energy load management potential in the current and future UK home. The specific aims of this work are:

1) Identify specific domestic appliance usage from household demand profiles based on their energy signatures

2) Optimise domestic energy load management for current economy 7 tariff

3) Optimise domestic energy load management for future renewable dominant grid

1.3 Overview of methodology

Smart appliance development analysis will be carried out by investigating current technologies and policies and offering insight into adaptations to aid the home's ability to undergo energy load management. Most strategy of energy load management created will aim to be realistic interventions to the current way of life which will aspire to aid both the national grid and the consumer.

Energy load management analysis in this thesis will begin by categorising the electrical appliances by their ability to shift their energy usage accordingly and so minimise disruption to the consumer. This will indicate how much energy can be removed from the peak load and either spread evenly across the day or accumulated to create a new load peak at an alternative hour during lower demand. Finally, a renewable energy heavy grid will be modelled featuring a stochastic high-low demand supply and will be incorporated to analyse the original system's flexibility to continually shift its demand loads to appropriate hours of high energy supply. Following this, modifications will be applied to the system to improve its ability to adapt to a renewable grid.

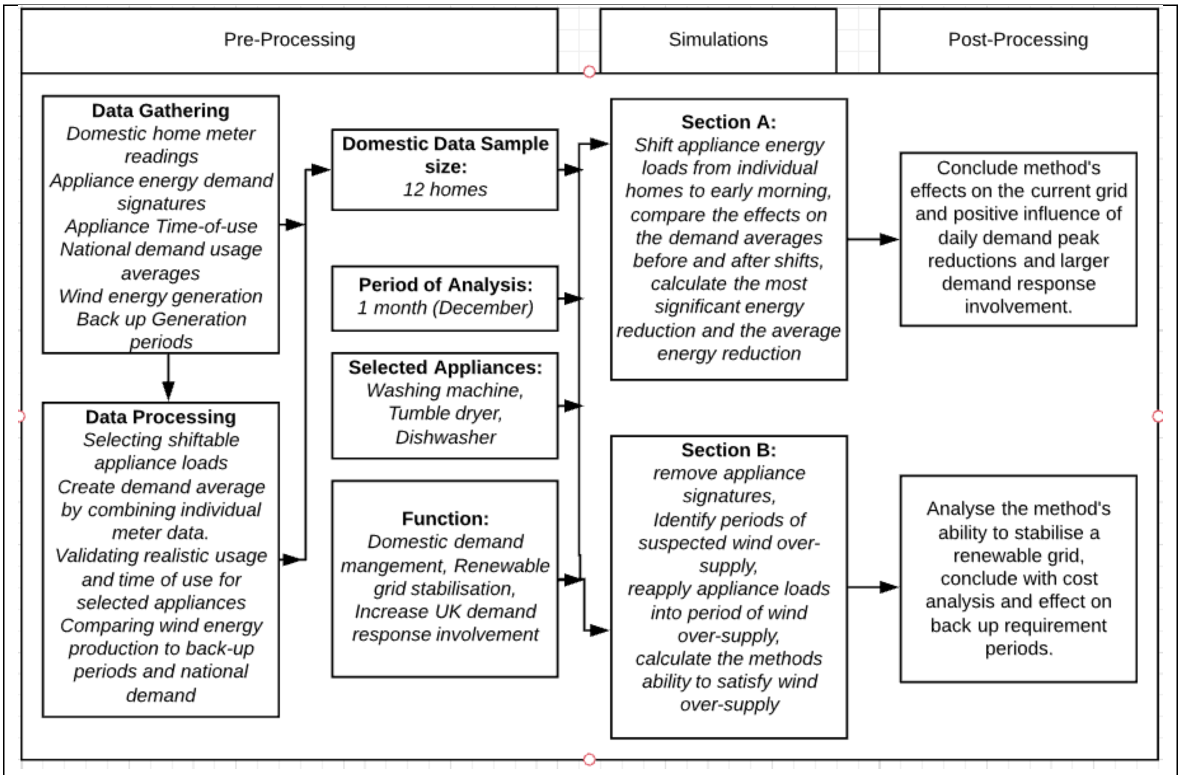


Figure 1 . Overview of the methodology.

1.4 Structure of the dissertation

This dissertation is divided into 6 sections, as follows:

1.0: Introduction – The Introduction chapter of this thesis provides the background to the chosen topic and explains the problems to be investigated. The aims of the thesis are established, and the adopted methodologies are described.

2.0: Literature Review - The literature review chapter of this thesis will give a detailed analysis of the modern energy grid, describing the electrical narrative starting with its generation and ending with its usage in a domestic home. The literature review will explore the future of the electrical grid concerning changes to its supply and demand which are in the current development scope. This chapter will also expand on how smart appliance upgrades can play a more assertive role in managing the current domestic home's energy demand and more notably the future of the domestic home's needs.

3.0: Methodology – The methodology chapter of this thesis will give a detailed strategy of an effective energy load management techniques. In this section data will be gathered and formatted to allow for energy load shifting simulations. These simulations will aim to show the effects of individual appliance shifts and the accumulated effect on the monthly domestic demand average. The methodology will be split into two sections. The first aim will focus on shifting energy loads from throughout the day into early morning, i.e. low energy demand period. The objective of this section is to analyses the effects of energy load management for the current grid in compliance with current grid requirements and demand response tariffs. Additionally, the methodology aims to simulate energy load management strategies for the requirements of a renewable energy grid focusing mostly on decreasing shifting demand into periods of renewable oversupply.

4.0: Results – The results chapter of this thesis will give a detailed analysis of the results produced by the strategies applied in the previous chapter presenting data that emphasise the benefits and limitations of domestic energy demand management.

5.0: Discussion – Here the data presented will be reviewed and the implications of the results will be discussed highlighting the methods practicality in the real world.

6.0 Final Remarks - The final remarks chapter of this thesis will provide a detailed conclusion of the research carried out in this thesis. The aims set out at the beginning for the thesis will be discussed and remarks will be made on this thesis' ability to satisfy them. Additionally, data validation, thesis limitations, and areas of future research will be explained.

2 LITERATURE REVIEW

2.1 The National Electric Grid

2.1.1 Electrical Grid Frequency

Frequency stability is the key factor to providing electrical network stability. An increase or decrease in frequency is an indicator of imbalance between electrical generation and demand. If energy demand exceeds supply then the frequency decreases, if energy supply exceeds demand then the frequency increases.[14] The UK's national electrical grid operates at a frequency of 50 hertz and has a 5% deviation tolerance.[15] A frequency increase or decrease past the tolerance threshold will result in electrical "blackouts" leaving large areas without electricity. Therefore, it is of great importance that the supply to demand balance is closely monitored and controlled.[16]

In the event of an unexpected generator malfunction there will be a loss of electrical input to the grid leading to a drop in frequency. The primary response to a frequency drop occurs instantly following any extent of frequency change. The primary response's role is to halt or delay the increase or decrease of frequency, the second response acts to restore the energy supply to demand balance.[14]

The UK's electric grid maintains frequency stabilisation through various frequency shifting responses. The UK's national grid operators work to maintain a target frequency within a 1% difference of 50 hertz, to stay within this frequency boundary they have automatic responses and generation at their disposal.[17] However, the core solution to frequency shifts is through balancing supply and demand which in turn requires cooperation from energy providers.

Energy providers can supply a static or dynamic demand response. Static response is concerned with containing system frequency within the set boundaries in the event of a fault whereas dynamic is concerned with the management of system frequency under normal operation prior to a fault. Energy providers can financially gain by participating in the National Grid's Firm Frequency Response (FFR) service. The energy providers are required to pledge a minimum of 10 MW for frequency response services curtailable within 30 seconds of a frequency shift.[17] However, there is great potential for energy consumers to help balance the energy grid through alterations in their energy demand.

2.1.2 Forecasting

For the National Grid to effectively balance supply and demand while reducing the premium costs of using the standby energy generators, national electrical grid companies requires judgement forecasting.[14] Forecasting considers the possible electrical demands of the coming days ahead. Forecasting considers upcoming events, weather, human lifestyle patterns, and many other occurrences which will result on an increase or decrease from the baseline demand curve.

The National Grid has an archive of models which evaluate the coming days and models the effect on demand caused by the events of that day. For example, when predicting the weather's effect on energy demand the national grid will apply models based on three weather related attributes: temperature, illuminance, and wind. Temperature has the largest weather related effects on the day's energy demand, illuminance (daylight hours) is useful for choosing the energy profiles base curve according to nightfall hour and wind speed is related to temperature through winds cooling effects.[18]

The average domestic home consumer's demand profile features highs and lows which can be forecast through common and predictable lifestyle patterns. This pattern can be seen in figure 2 showing the typical UK daily domestic home's demand profile including specific appliance usage.

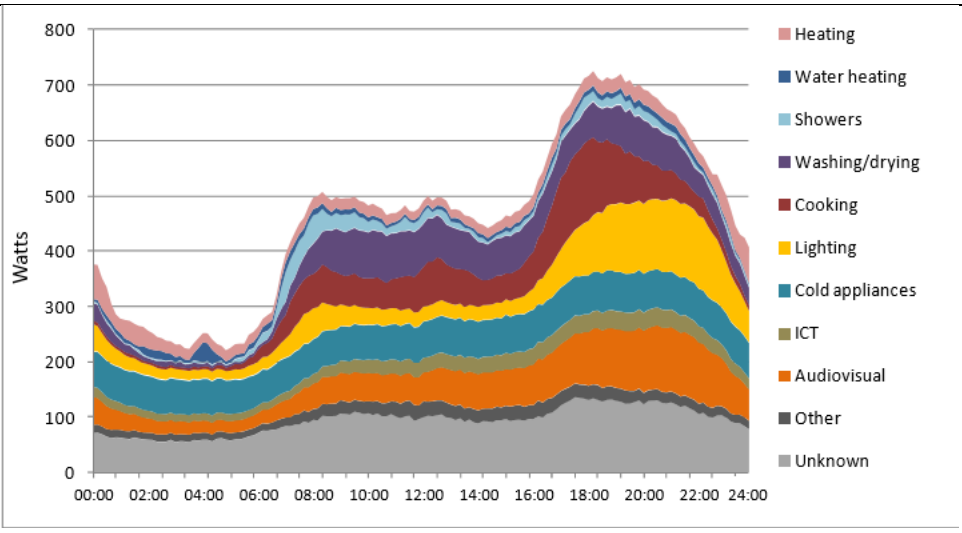


Figure 2. *Annual mean daily demand for a typical UK household including specific appliance usage.* [19]

In general, the domestic home's demand profile has reduced usage during the night when most of the population is asleep. There is an initial spike in energy demand in the morning corelated with breakfast times. In the afternoon, the domestic energy usage is at a reasonable energy consumption demand. However, this will be affected depending on whether it is a working day, or the weekend and the number of people who leave the household for employment. Demand rises into the evening peak related to cooking, leisure, and house chore related energy usage. Finally, the energy demand decreases later into the night as most of the population sleeps.[20]

2.1.3 Current Electrical Grid Balance

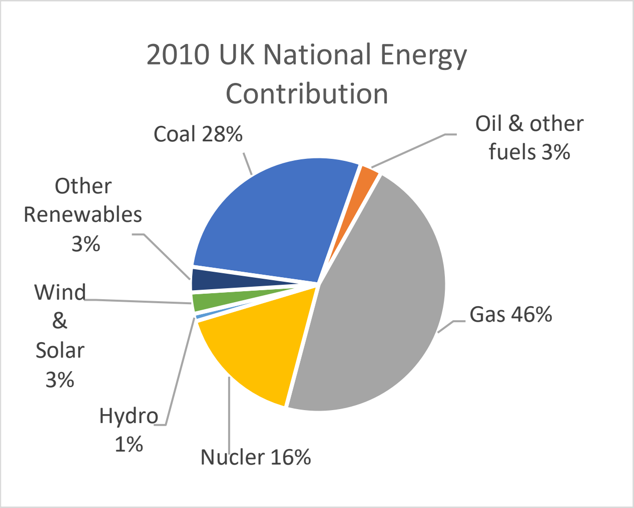
In the UK government's 2019 energy brief, the government provided data for the national energy usage and the contribution sources from 2018. [21] The relevant data on the 2018's annual energy supply is showing in figure 3c and table 1.

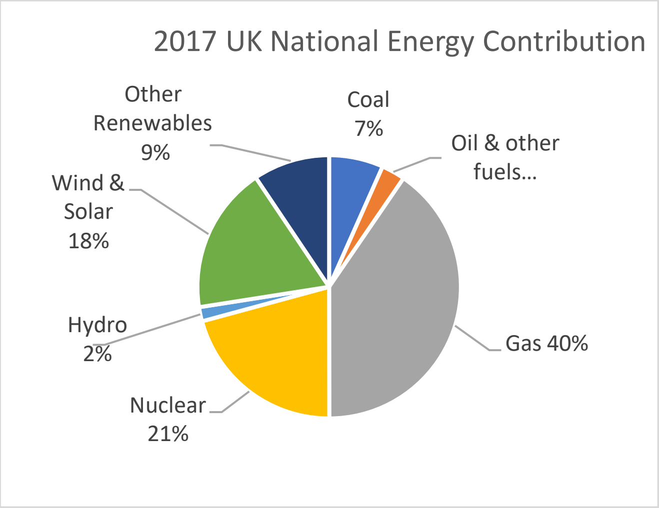
Table 1 . Electricity generated by fuel type [21]

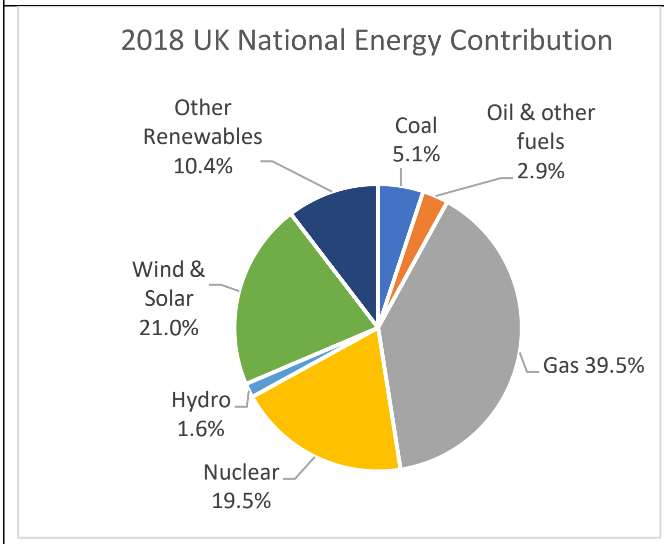
Energy Source	Annual TWh	Percentage Contribution
Coal	16.9	5.1
Oil & other fuels*	9.5	2.9
Gas	131.5	39.5
Nuclear	65.1	19.5
Hydro	5.5	1.6
Wind & solar	69.8	21.0
Other renewables	31.8	10.4
Total	332.9	100

*Includes generation from pumped storage

Table 1 shows that the current UK electrical grid is largely run on fossil fuel energy systems. The largest contributor to the electrical grid is natural gas systems providing 39.5% of UK's electricity demand. The contribution to the electrical grid from renewable sources combined is stated to be 33%.







- *Figure 3a* (top left) shows the 2010 UK national grid's electrical source composition.[21]
- *Figure 3b* (top right) shows the 2017 UK national grid's electrical source composition.[21]
- *Figure 3c* (bottom left) shows the 2018 UK national grid's electrical source composition.[21]

Fossil fuels have been the backbone of the UK's national energy supply since the industrial revolution's utilisation of coal.[22] Established fossil fuels are energy dense materials which provide cost effective energy systems. They are a finite resource meaning they are not classed as a renewable energy source and when burned they produce carbon dioxide meaning they do not help meet the UK's net zero targets. Over the years, coal fuelled energy generation has been phased out in the UK and has mostly been replaced with renewable sources as seen in figures 3. The total combined renewable energy offers an installed capacity of 44.3 GW, increased from 9.3 GW since 2010, while Combined Cycle Gas Turbines offer 31.7 GW and conventional steam systems offer 18.0 GW.[21] However, completely replacing the remaining fossil fuel energy generation in the national grid is not as simple as increasing the renewable energy output capacity. To maintain electrical grid frequency energy generators must provide balance to the system's inertia.[23] Electrical network inertia is improved through an energy generators ability to slow the system's initial rate of change of frequency which is mostly linked to the generators ability to be turned up/on or down/off. Synchronous generators in classical power stations can contribute to this inertia, because of the coupling between their rotational speed and the electrical network's electrical frequency.[23]

Current renewable energy generation technology such as photovoltaic panels and wind turbines require converters to allow the electricity to be transported by the grid. For this reason there is a poor coupling ability between wind turbines and the grid frequency and no coupling abilities from solar farms/ panels.[24] To increase renewable energy generation's percentage contribution to the national grid, developments must be made to counteract the lack of inertia. Energy demand management will likely have an important role to play in the UK's future of a renewable electricity grid.

By replacing coal source generation in the electrical grid with renewable energy generation is a huge step forward in the UK's commitment to a sustainable and carbon neutral energy grid. However, the greater challenge will be replacing the other major fossil fuel contributor which is natural gas. Natural gas is the most used energy sources providing energy for a wide range of services as shown in table 2.

Table 2. 2018 Natural Gas Demand[21]

Energy Source	Annual TWh
Electricity Generators	273.4
Energy Industries	86.3
Industry	110.5
Domestic	309.2
Services	94.7
Total	874.0

As shown in table 2, ntural gas's largest areas of usage, electricity, and domestic heating, are all areas which need to be addressed in order to make the domestic home carbon neutral. The UK Government and Scottish Government have set out ambitious targets to replace gas in domestic heating by 2035.

Phasing out fossil fuels as energy sources to the national electricity grid is the key aim of the net zero targets. However, they play a crucial role in the national energy supply and attempting to replace them is proving to be a formidable challenge. Fossil fuels provide affordable energy to consumers allowing the majority to access their electrical appliances, which the modern lifestyle has become dependent on. A major challenge encountered when replacing fossil fuel powered systems is maintaining the affordability of domestic energy and preventing an increase in fuel poverty. This is particularly relevant when replacing natural gas boilers for home water and space heating.[25]

It is unclear what heating source will replace natural gas. Assuming the policy is retained, the most likely replacement for the majority of heating systems is through electrified heating due to its familiarity and low installation costs over newer heating system concepts.[25] This change will result in greater strain on the national electric grid, leading to a greater requirement of energy load management during peak hours.

Like other fossil fuels, natural gas is used to fuel energy generators by through burning to heat steam or gas cycles. Modern gas fueled power stations convert gas to electricity through Combined Cycle Gas Turbines (CCGT). CCGT systems provide thermal energy efficiencies as high as 60% whereas conventional steam powered stations have efficiencies of 36%.[26] These high efficiency systems provide a cost effective and dispatchable energy source which currently is essential in balancing the national electrical grid.

Nuclear

Nuclear power systems are an effective method of large-scale electricity production through heating steam or gas cycles using nuclear fuel. Nuclear power plants produce large volumes of carbon neutral energy which makes it an energy source which complies with the future net zero target. Nuclear power plants are powered by radioactive isotopes that undergo a fission reaction releasing huge amounts of energy with a self-sustaining output generation flow.[27]

Despite this being an energy rich source of fuel, nuclear power is a very costly method of energy production. Once constructed, a nuclear power plant has relatively low running costs. However, the construction of a power plant is incredibly expensive. The construction cost for nuclear is so large that, for nuclear power to have an acceptable profit margin, it must be running at full capacity all year around, excluding maintenance periods.[28] Combining this with the fact that nuclear power systems have a long start-up/ shutdown time, this method of large-scale energy generation is primarily used to provide a baseline energy supply for the electrical grid.[27]

Nuclear power has a largely negative public image due to previous nuclear disasters being ranked as some of the worst and most harmful man-made disasters in history.[27] Nuclear energy's poor public image and poor supply shifting flexibility means that its role in the future of the national grid will be undoubtedly limited to its current role of supplying the baseline demand.

2.1.4 Renewable energy contribution and expansion

This section will explore the current contribution to the energy grid by renewables and aims to briefly explain the relevant fundamentals which aid or prevent their further expansion over the coming years. The ambitious renewable energy and net zero greenhouse targets set by both the UK government's push for massive renewable energy expansion.

Each year there is an increase in the energy contribution to the national grid supplied by renewable energy generators. The overall capacity increased by 10 percent from 40.3 GW at the end of 2017 to 44.3 GW at the end of 2018.[21] On top of this, future development plans aim to greatly expand on this current capacity with offshore wind farms receiving large capital investments. [29]

Table 3. Electricity generation from renewable sources 2010, 2017, & 2018. [21]

Energy Source	TWh 2010	TWh 2017	TWh 2018
Onshore Wind	7.2	28.7	30.2
Offshore Wind	3.1	20.9	26.7
Solar PV	0.0	11.5	12.9
Hydro	3.6	5.9	5.5
Landfill Gas	5.2	4.3	3.9
Other Bioenergy	7.0	27.5	30.8
Total	26.2	98.8	110

Table 3 shows the growth of each renewable energy source's contribution to the UK's electricity grid between 2010 and 2018 revealing trends of where the UK's interests and focused development lies. Tidal energy has been combined with Hydro energy's data however, tidal has only contributed 0.09 TWh in 2018.[21]

As shown in table 3 most renewable sources have increased their contribution to the electric grid except for landfill gas. Landfill gas considered a renewable fuel because it recycles waste by utilising it's derived gas as a fuel source. Additionally, environmentally harmful emissions generated from landfills are reduced when the gas is burned, however burning the gas still produces carbon dioxide.[30]

Between 2017 and 2018, hydro energy features a small reduction in electrical contribution to the grid.

Offshore wind energy has featured the largest increase between 2017 and 2018 of the renewable energies due to the UK's growing renewable technologies and capital investments in this particular technology.[29]

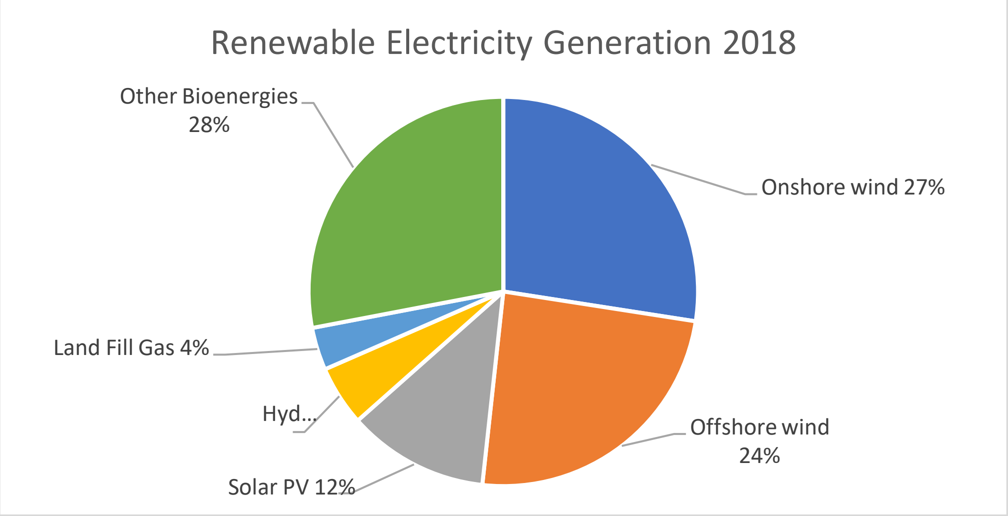


Figure 4.: Electricity generation from renewable sources, 2018.[21]

Figure 4 shows the 2018 percentage contribution of the renewable sources highlighted in table 4.

Energy Generation

The next part of this section will provide a brief description of each of the previously mentioned energy sources and highlight the challenges which need to be overcome by each source to allow its further expanded contribution to the electrical grid in order to replace natural gas.

Wind Energy

As shown in table 4 and figure 4, wind energy provides the largest amount of carbon neutral energy for the electrical grid of the renewable energy sources.

An onshore wind turbine is a non-dispatchable energy generator. It relies on wind speeds to be fast enough to provide a force strong enough to spin the rotary turbine blades at a speed capable of producing useful energy. For most turbines, the wind speed required for the turbine to start producing electricity is usually 4 m/s. [31] This wind speed is known as the cut-in wind speed. With speeds below the cut-in wind speed, wind turbines are disconnected from the grid and left idle.

When wind speed increase and reach ~12.5 m/s the standard onshore turbine will be generating electricity at its full capacity.[31] This wind speed is referred to as the rated wind speed. If wind further increases the wind turbine will continue to produce electricity at capacity until wind speeds reach ~25 m/s (critical wind speeds vary between turbine models).[31] At this point the wind speed is too great and the turbines are turned off. This is referred to as the cut-out wind speed.[31]

A wind turbine's generation power output curve can be seen by figure 5.

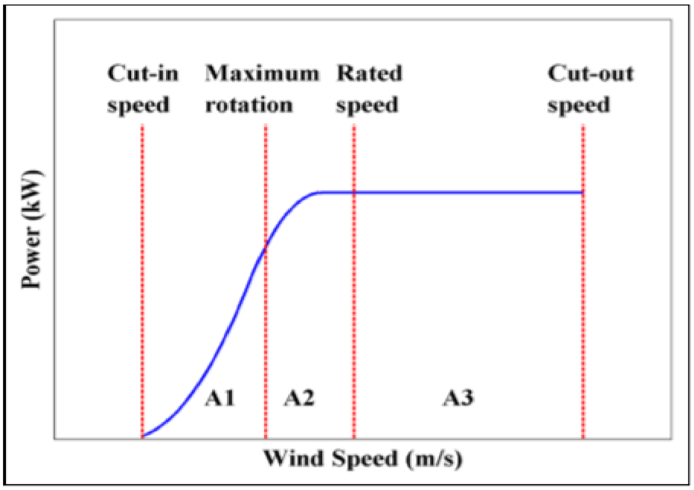


Figure 5: showing the power production trend against wind speed.[32]

Wind turbine farms built can be measured by their peak capacity however, the average electrical generation output will be far smaller. This is because the turbines are not receiving the wind speeds to run at its full capacity all the time. The ratio of the average generation output vs the peak output is referred to as the capacity factor. The typical capacity factor for a modern turbine is ~30%.[33]

The utilisation of wind as an energy source leads to a degree of incompatibility with the current electricity grid, these are issues which need to be resolved before wind energy can be expanded enough to phase out natural gas. In situations when wind turbines are disconnected due to experiencing cut-in or cut-out wind speeds, when the wind speed returns to operating range, the turbines are suddenly reconnected. The abrupt connection of a large or multiple wind turbines can result in a brownout (occurring when voltage drop incurred when instantaneous load exceeds generated power) often followed by a power peak when active power from the generator is fed to the network.[34]

The stochastic nature of wind results in incompatibility between supply to demand matching. During periods of low supply from wind turbines the national grid will require dispatchable sources to provide additional energy to balance the grid. This is an unfavorable system as a likely dispatchable system used to provide the difference will be fossil fuels generators. Furthermore, energy provided by frequency response ancillary services is more costly than contracted and planned energy supply meaning the stochastic fluctuations from wind energy are economically adverse.[35]

Undersupply is not the only challenge of wind energy to grid incompatibility. As wind energy capacity increases, the periods and severity of wind over supply increases. This results in periods when wind energy output exceeds the national demand for electricity. This is currently solved by disconnecting the appropriate number of wind turbines effectively discarding environmentally friendly energy production and resulting in governmental compensation pay-outs. Most of these compensations pay outs are greater than the value of electricity lost. This is because energy production shutdown requires compensation payments for loss of sellable electricity and loss of renewable obligation certificates (ROC). [36]

Because pay-outs must compensate for loss of ROCs, most pay-outs are over double the price of sellable electricity lost. This is a very costly solution which the head of the Renewable Foundation John Constable describes as "bottleneck" problem in Scottish wind energy. Furthermore, this problem will only increase in occurrence and severity through increased wind farm development. [36]

The fundamentals of offshore wind generation are the same as onshore wind. The largest difference relevant to energy capacity is that offshore wind turbines are typically much larger than the onshore turbines meaning each offshore turbine has a larger energy capacity. Offshore wind energy is receiving more attention with more offshore wind farms approved for development making it the likely direction for future wind generation expansion.[29]

Solar energy

Photovoltaic (PV) panels have experienced a growth in energy capacity and contribution to the electrical grid shown by table 4. The cause of PV's increasing usage is the April 2010 governmental feed-in tariff incentivising owners to allow energy generation on their property through small renewable sources, most commonly through PV panels.[37]

PV panels are very versatile where they can be placed on large open areas to inhabit a solar farm or they can be placed on building roofs allowing energy generation to occur within city or town spaces. Additionally, PV panels are often used for microgeneration to power individual buildings to reduce the building's energy requirement from the national grid.[38] Like Wind turbines, PV panels rely on a stochastic factor because the electricity produced is directly correlated to sun light intensity on the PV's surface panel.[33]

Solar PV panels do not require direct sunlight to generate electricity and can work on diffuse sunlight (e.g. sunlight filtering through cloudcover). However, The greater the volume of cloud coverage the more diffuse the sunlight is that the PV panel receives and the lower the intensity of the sunlight, the lower electrical generation output from the panel. [33]

Because PVs require sunlight, this means they do not produce energy during the night which is an issue for demand management as demand peaks can occur after sunset. After the sun sets many homes increase electrical demand through the use of more lighting appliances and electrified heating systems as the external temperature drops. This is an issue particularly during seasonal change into winter as daylight hours get shorter.[33]

PV panels are well suited for supplying energy for industrial buildings or other places of work as the peak sunlight hours match with the UK's standard working hours. However, PVs face problems when producing energy compatible for domestic home demands shown in figure 6.

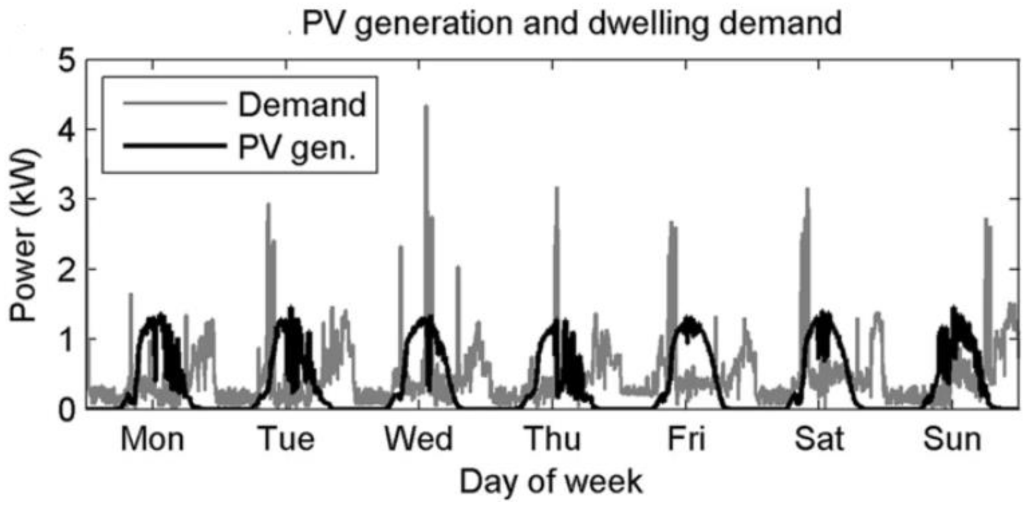


Figure 6: Showing the PV electrical generation and dwelling demand, results taken over the course of a week in June 2006 for a 2.03 kW_{peak} PV system in the UK. [39]

Figure 6. shows the overlapping periods of PV energy generation and the energy demand of a domestic home. As the figure shows PV generation often starts after the breakfast electricity demand spike and PV generation ends before the evening demand peaks. However, during the midday demand hours (which vary from home to home depending on number of occupants in employment) the PV generation is able to meet the electrical demand. The positive effects of the PV generation on energy demand during the day can be seen in figure 6. Additionally, during many of the hours of PV generation the energy produced is greater than the demand highlighting the potential for energy optimisation through energy load management.

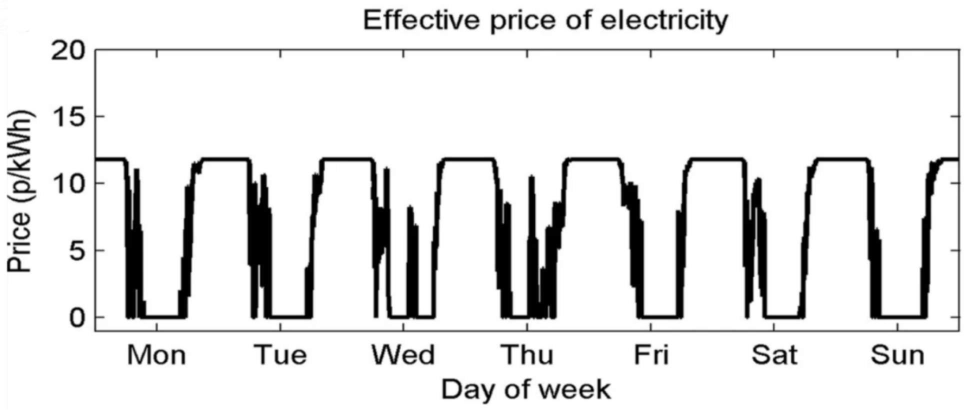


Figure 7. showing the Effective price of electricity with incorporated PV generation in dwelling demand. Data for 1 week in June 2006 for a 2.03 kW_{peak} PV system in the UK. [39]

Figure 7 shows that during the periods of PV generation, shown in figure 6, the consumer benefits from low to no electricity costs, thus requiring no electricity from the national grid. PV is an effective way to reduce daytime demand loads and excess energy generated can be used by the national grid. Solar PV panels can play a useful role in a building's demand management.

Pumped Hydro

Pumped hydro dams are one of the few large-scale carbon neutral dispatchable renewable energy sources. Pumped hydro dams hold large amounts of water in a natural reservoir then release the water through turbines generating electricity. A major advantage hydro dams have over all other large-scale energy sources is that it can begin generating energy at a moment's notice providing the reservoir holds the appropriate water supply.[40] Other systems require starting up times, for example gas cycles have short start up times, but still require 2-8 hours to heat up the system and reach full capacity energy generation.[26] Nuclear requires a far longer start up time of about 2-3 days to reach maximum energy output.[27]

There are significant limits to hydro dams which hinder the energy source's abilities for large-scale expansion. Building a hydro dam is a very costly and difficult process because the surrounding area needs to meet strict geographical requirements to allow the water to accumulate in the reservoir safely. Hydro dams also require rivers with substantial height drops. These geographical restrictions result in difficult construction conditions and material transport to suitable hydro dam locations. These geographical locations requirements are the leading limitation to the expansion of hydro dam electricity's contribution to the national grid as there are a very limited number of suitable locations.[33]

Hydro dams are also limited in their dispatchability by reservoir refill times, linked to volume of rainfall, and volume of water held in the reservoir. These limits prevent the system's ability to generate energy continuously. [33]

Because of these limiting factors, hydro energy's role in the national grid is primarily a buffer to quickly balance supply and demand at short notice. In times of unforeseen demand spikes, hydro dams can quickly supply large amounts of energy at short notice. In times of oversupply, the dam's turbine system can be reversed allowing energy to be used by pumping water into the reservoir. The water pumped into the reservoir can then be released through the turbines creating usable energy at a later time effectively creating energy storage.[41]

The buffering effect pumped hydro has on the national generation supply can be seen in figure 8.

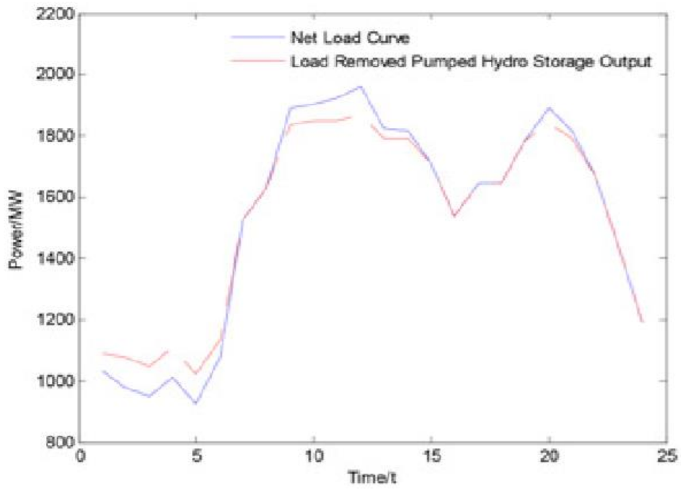


Figure 8: showing energy generation in megawatts against time before and after pumped hydro peak-shaving effect.[42]

Figure 8 shows an occasion where too much energy has been produced due to wind and solar over supply during the early hours of the morning.[42] Normally energy generators would be required to shutdown which would result in wasted energy and loss of cost profit. On the occasion presented in figure 8, pumped hydro in use to reduce the energy generation peaks between 01:00 and 06:00. The excess energy generation is absorbed by using the excess energy to pump additional water into the hydro dam's reservoir, thus, storing energy for later use. Water from the hydro reservoir is released to aid evening during the evening demand peaks (09:00-15:00 and 19:00 – 21:00) generating power effectively providing a peak load shift through pumped hydro storage.

This technique of energy load management is not only an effective method of balancing the grid but also provides cost benefits. The usage of the pumped hydro seen in figure 8 results in reduced wind and solar energy curtailment costs in the morning and reduces cost by decreasing the requirement of thermal generation units in the evening. The use of pumped hydro storage in this situation results in a positive cost benefit of £20,120 (converted from Yen to pound sterling August 2020).[42]

2.1.5 Energy Grid Summary and Future Stabilisation Technology

To summarise this section of the literature review covering the national electrical grid, the UK is in the process of successfully phasing out fossil fuels from its national energy generation with renewable sources. Analysing the energy contribution and research it is evident that wind and solar are the two major renewable generation sources which are superseding fossil fuels and will likely provide the bulk of future supply, However, the limitations of increasing wind energy and PV's electrical grid penetration will result in increased, if not complete, grid destabilisation. Hydro dams are effective tools to quickly balance the grid. However, their geological restrictions limit their supply/demand buffering capabilities. Therefore, additional large-scale buffering techniques will be required as renewable energy penetration is increased. If no large-scale buffering technologies or techniques are created, then fossil fuel back-up reserves will be required to balance the grid, hindering the goals of a completely renewable energy powered grid.

There are two major energy strategies which can be expanded to aid this situation: further energy storage either directly in large batteries or indirectly in energy processes such as hydrogen production. However, these processes will require large capital investments to create the infrastructure required. A more cost-effective method and the method which will be analysed in this thesis, is tackling demand itself through energy load management.

The incorporation of large-scale storage units will compensate for the deficiency in renewable generation during peak demand periods, while absorbing the excess energy when renewable generator farms experience high generation conditions producing greater electrical output than is required by the national demand. However, incorporating storage systems at such a large scale is limited by technical and economic feasibility. Building the storage is hindered by technological maturity, cycle efficiency leading to energy loss, operation and maintenance costs.[43]

The UK has shown interest in achieving demand response through electrical grid upgrades such as the 'Smarter Network Storage' project capable of applying the demand response it megawatt scales in the distribution system and is believed to play an active role in the future of residential and commercial demand response.[44]

2.2 Energy Load Management

2.2.1 Motivation for Further Energy load management

Energy load management is a useful tool used used to balance a country's energy demand. Currently, demand management is focused on reducing energy peak time consumption spikes. As countries increase renewable energy penetration into their electrical supply grid, more comprehensive demand response measures will be required to cater for both demand and supply spikes.

Opportunity to develop more comprehensive energy load management within the domestic home has great potential with modern smart technologies and the capabilities of linking appliances through the internet.[1] This benefits the domestic home as it allows for greater automation abilities of energy load management. Additionally, this allows the home occupant or energy services to remotely schedule the appliances externally.

Energy providers using renewable generation are likely to benefit from more effective utilisation of energy supply highs, reducing the requirements for energy generation curtailment seen currently in wind which will provide a more cost effective method of energy generation.[36] Consumers will benefit from decreased energy bills and rewarded credit through participation. Ideally, future energy load management in the domestic home will be largely automated allowing consumers to seamlessly manage their energy loads while maintaining comfort and receiving the advantage of reduced energy pricing through effective real-time pricing schemes (this will be discussed in more detail in subsequent sections).

Energy load management permits social welfare maximisation. This is when the retail price of energy is equal to the utility cost of generating and distributing energy.[45] Through larger renewable penetration resulting in higher energy quantities produced at stochastic generation times and with larger energy load management development and incorporation into the domestic home, a participating consumer will experience lower energy bills. When energy demand loads are shifted to times of abundant energy generation energy providers converge to more competitive and flat rate pricing at which point social welfare is maximised.[45]

2.2.2 Understanding Domestic Demand

In order to identify key domestic appliances that could be distinguished by their distinctive energy signature, average daily household energy consumption was plotted. Figure 8 shows the average UK household's whole year daily energy consumption trends provided by the early findings report from the UK government data service. The data was analysed as part of Household Energy Survey measured electricity consumption at an appliance level in 250 owner-occupied households across England from 2010 to 2011, the most detailed monitoring of electricity use ever carried out in the UK at that time. This analysis uses raw data, unadjusted for seasonal effects. This means the sample sizes for short periods of the year are rather small, since the analysis includes only the dwellings monitored over the period selected.

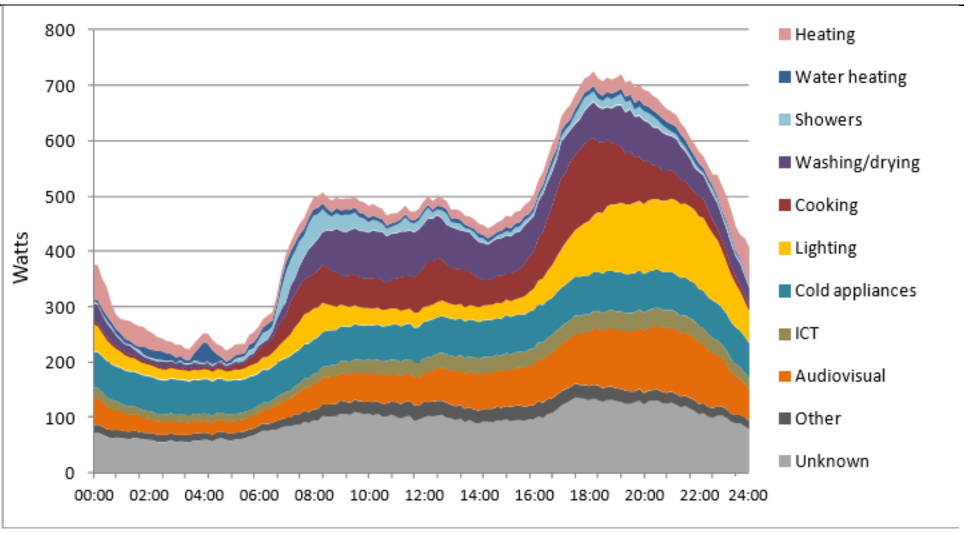


Figure 9. Daily energy usage of all households' average daily profile over a whole year, provided in the report: Further Analysis of the Household Electricity Survey Early Findings: Demand side management.[19]

Figure 9 also gives insights to the average daily domestic energy consumption pattern. Energy usage will fall to a baseline of ~300 watts as a result of the household being asleep. During these hours most of the consumption comes from appliances that are required to remain running over night such as fridge and freezer. Additionally, there is a small spike at 4 AM which is a result from hot water pre-heating. There is an initial spike in energy occurring ~7 AM as the population wakes up and starts their day with showers, cooking breakfast, and turning on electrical appliances. This peak shows a slight decrease after 10 AM featuring a small peak at 12 PM related to lunch time and energy usage then decreases again throughout the afternoon. The late morning and afternoon decrease trends are likely related to occupants leaving their homes (daily routines/ employment) or carrying out activities which are less electrically demanding (an activity which only requires a few appliances/ requires no electrical appliances). At 5 PM begins the domestic home's dominant peak lasting until 9 PM at which point it begins a decrease back to baseline. The post 5PM peak is due to high cooking related energy demand, more occupants in their home after returning from daily routines such as employment, larger requirement for lighting and heating as the sun begins to set, and general higher electronics and appliance usage as occupants relax and/or complete chores.

Figure 9 shows the mean energy usage over the full year. To highlight the difference that can been by an individual day figure 10 shows the demand experienced by a substation on a specific day of the year.

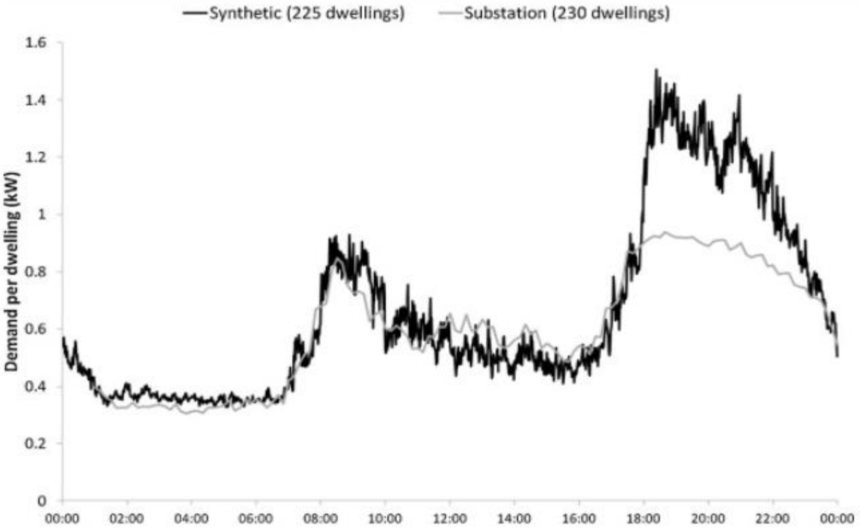


Figure 10. Comparison of diversity in demand profiles for 90 synthetic homes and 230-dwelling substation data for January 17th 2014.[46]

Figure 10 shows a synthetically modelled average domestic home demand vs the average domestic home's demand experienced by a substation powering 230 domestic homes. Figure 10's domestic demand trend features the same peaks and pattern as figure 8. Notable analysis of figure 10 shows that the 5 PM peak is ~600 watts higher in the synthetic demand than the substation's average demand. This likely a result of the types of homes and community that the substation supplies having different influence percentages than the national average demand. When comparing Figure 10 with figure 9, the demand peaks require around double the wattage in figure 10. Figure 10 shows the evening peak experienced by the substation to have a relatively equal demand peaks whereas the synthetic demand and figure 9's demand trend shows the evening peak to be far higher.

Additionally, the afternoon energy demand post 12 peak has a larger decrease gradient in figure 10. This is likely due to figure 10 showing data of one day of the year (a Thursday) whereas figure 9 shows the full year average, meaning figure 10's weekday results will be more greatly influenced by occupants in employment nevertheless, a good overall correlation between the two is observed.

The difference in daily demand between a weekday and a weekend day is shown in figure 5.

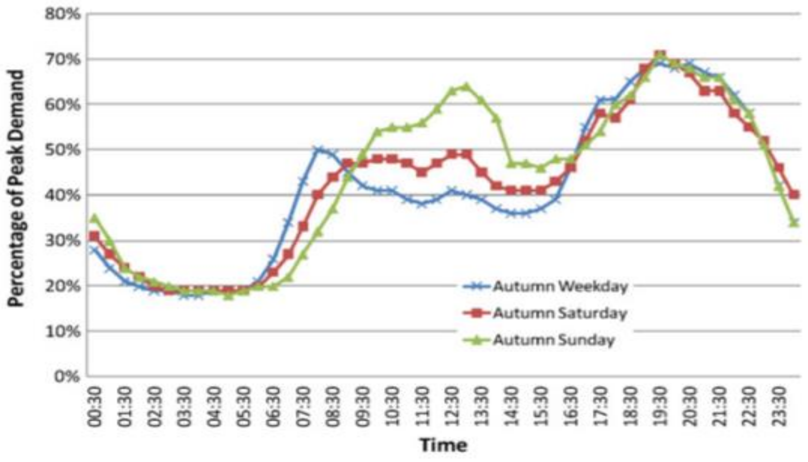


Figure 11: Domestic load profile showing a standard weekday, Saturday, and Sunday in Autumn.[47]

Figure 11 shows that the evening peak for each day of the week is similar however, the major differences can be seen between 06:30 and 17:30. Weekday demand is the lowest of the three demands during the afternoon whereas Saturday and Sunday have larger demands. These differences can be correlated to the effect of employment on the average daily demand.[47]

Most of energy demand is highly uncontrollable due to energy's entwined relationship in modern business and lifestyle. demand changes both over the course of the day and seasonally over the course of a year. In the UK summer nights experience the lowest annual demand with its average demand around 30% of the winter demand peak.[48]

Some appliances are by their nature less time-sensitive than others. For example, households clearly need some form of electric lighting when it is dark outside, and occupants are active. Conversely, households have more discretion about when they choose to run their washing machines or tumble-driers. Given the right incentives, domestic consumers may be persuaded to use selected appliances overnight, or at other ideal periods of low electricity demand.[19]

When considering a domestic home's appliances for their potential in energy load management there are 3 categories shown in table 4.

Table 4. Appliances Categorised by Switchability.

Switchable	Partially Switchable	Non-switchable
Washing Machine	Oven	Lights
Tumble dryer	Space heaters	TV
Dishwasher	Cold appliances	Audio Equipment
Water heater	-	Computers
-	-	Hobs
-	-	Microwave

The term 'switchable' is used to describe the appliances characteristics. A 'switchable' appliance has low time constraints according to its usage. For example, the washing machine has a high level of flexibility as it is an appliance which once turned on runs on a fixed cycle and lifestyle requirements do not rank the appliance as urgent for its usage. Therefore, a switchable appliance can be easily enrolled onto a demand management scheme.

A 'partially switchable' appliance is an appliance which can be shifted within a limited period. For example, an oven is required during mealtimes and incentives are likely to be ineffective at changing consumer behavior by the consumer for the appliance's usage at their preferred time. Alternatively, a partially switchable appliance may be limited by the energy demand to complete its function. Cold appliances such at refrigerator run continuous cycles during the day, cycles can be manipulated but are limited through the appliance's requirements to complete its function therefore, is 'partially switchable'.[49] A partially switchable appliance has potential in a demand management scheme but will experience limitations and resistance in its participation.

A 'non-switchable' appliance is a time sensitive appliance which can only be incorporated into a demand management scheme through unrealistic lifestyle changes and/or is required during a specific period of time (e.g. lights are only required after sunset hours or when occupants are entering dimly light areas).[19]

2.2.3 Automated demand management

Energy load management can be greatly improved through automation. Minor upgrades would be required for most appliances to increase their controllability through the internet increasing the appliances demand management capabilities.[1] Home appliances have experienced upgrades through policies before concerning their efficiencies. European commission 2000 policy prevented the distribution of low energy efficiency appliances with an aim of achieving an energy consumption reduction of 20%.[50] Policy resulted in appliance producers building higher efficiency appliances to maintain trading agreements. This knock-on effect shows the effect policy change can shape the standard of appliances available. The same technique can be used to create a larger distribution of internet connected, energy load management friendly appliances in all homes.

Domestic housing as a whole faces greater difficult in monitoring and applying energy load management manually as it consists of millions of buildings with different energy loads many of which will respond differently to incentives to reduce their energy load. A more optimal method of residential demand management would be through the automation of smart appliances. Automation would provide the consumer with an easier lifestyle transition and provide more reliability to domestic home energy load management.

The automated system layer adds a layer of assurance and efficiency to the energy load management which is not achieved though consumer incentives alone. Motive based systems rely on the consumer to be constantly knowledgeable of their energy consumption/ reductions and must cater for consumers who forget or are unable or choose not to reduce their energy load when requested. An automated system removes the need for the consumers awareness allowing them to continue their day while the City Public Services CPS manages their energy loads for them.

Automated program enrollment will still require encouragement through incentives.

2.2.4 Challenges to demand management

It is important when energy load management is introduced that the full impact is carefully considered. Load shifting techniques disrupt the natural diversity of appliance demand which can lead to some undesirable effects. For example, a partially switchable appliance such as the refrigerator is turned off for a period of time they will heat above their target temperature. When reconnected to power, they will then consume they will consumer larger amounts of energy to cool to the correct temperature. If a large number of appliances are turned off during peak hours when they are reconnected to power they may all result in a sudden spike of electrical demand.[48]

The socio-economical barriers which may occur when moving towards automated demand management, require the domestic home to have smarter appliances which can be externally controlled through the internet or other forms of external manipulation such as radio waves. This means that households will require a large amount of disposable income to replace outdated appliances in order to fit the criteria for program enrolment and may be the cause impeding national demand management results and capabilities through automation centered tariffs. Additionally, there is a potential for many social consequences where only households with a higher degree of wealth can meet the requirements to enroll in automated demand management programs meaning only these households can take advantage of money saving incentives. This consequence would result in a larger divide between affluence and deprivation within a country likely damaging the public image of the energy industry and the opportunity of a renewable heavy, carbon neutral electrical grid.

This would not be the first-time renewable energy incentives have been the cause of a social income divide in the UK. The 2010 British Feed-in Tariff payed £500 million per annum to home or landowners who installed small scale renewables on their property. By 2013, approximately 366,465 domestic homes registered small renewable installations through the tariff but according to socioeconomic data the majority of these installations were by wealthy households with very low poor household participation.[37] Additionally, the government had to delegate the responsibility of funding the tariff to energy companies who funded the scheme through increased consumer bills. Not only did the outcome of this tariff result in the wealthy households benefitting, but poor households were further disadvantaged by enduring increased energy bills.[37]

This divided socioeconomical outcome can also been seen in similar international programs such as the Australia Solar Homes and Communities Program (ASHCP) which also observed a pattern of uptake which disfavors deprived households in the initial rush-to-register. However, over time the divide became more equitable achieved through cost-spreading polices which charged wealthier communities more to fund the scheme.[37]

In contrast, California's California Solar Initiative adopted countered the socioeconomical divide by using 10% of the program's funds to support low income household's involvement. Both Australia's and California's equality measures resulted in a more equal participation between affluent and deprived households while no such policies or safeguards have been adopted by the UK.[37] Because of this the tariff enrollment was mostly by affluent households.

2.2.5 Demand Management the UK

Largely, in the UK, demand tariffs simply aim to reduce energy during evening peaks. The tactics applied are mostly incentive based to promote end users to be more energy aware and to reduce energy through the turning off of on non-essential appliances (i.e. Television when on standby mode).

International companies such as Kiwi Power Company, a company driven to supply renewable objectives) demand response programs to many retail industries in the UK. [13] The UK's Power Network Company offers demand response programs for energy provider partners to enrol in. Aiding the governmental program 'Low Carbon London' energy provider companies such as EDF and EnerNOC participated in the UK Power Network Company's 'Flexitricity'. This trial program aimed to introduce energy load management (mostly peak-time reductions) to industrial and commercial participants.

These examples show that the UK is expanding on its demand response capacity. However, its prime focus remains on the demand response of commercial buildings. Commercial buildings are a source of high energy usage and businesses are highly responsive to incentive. However, commercial buildings have limited energy usage outside the business' opening hours. This makes them limited in early morning demand response management which will be a requirement in a future renewable grid.

In the UK, the domestic sector accounts for 29% of the national electricity demand making it an important sector to apply demand management to. The UK's Economy 7 is a scheme for domestic consumers that incentives consumers to use appliances during a 7-hour period at night through reduced energy pricing. Another scheme is called Economy 10 in which features 10 hours of low energy pricing is split between day and time (usually 2 hours in the morning, 3 hours in the afternoon, and 5 hours overnight.)[47] These tariffs sole purpose is to encourage appliance usage away from the daily demand peaks however, energy services do not communicate further with the participants as seen in demand response programs in other countries. For this reason, enrolled occupant participation is entirely at an occupant's discretion and how much they want to benefit themselves through reduced priced energy periods.

2.2.6 International demand management

Globally, many efforts of developing demand response schemes have taken place. According to the Transparency Market Research, North America is the global leader for demand response capacity followed by collective European countries and Asia-Pacific countries. other countries which have shown impressive development in their demand response capabilities include Canada, Australia, New Zealand, and Singapore. Additionally, developing countries such as South America and Africa are displaying intuitive methods of demand management despite still requiring critical development in their energy systems .[13]

North America

Energy load management programs differ in North America from state to state and cater for different climates, cultures, events, industries, and lifestyles.

California

In hot climates, the primary objective it to combat midday demand peak largely produced by air conditioning (AC) systems. Unlike the UK, summer seasons in hotter climates are the periods in need of demand management. Additionally, AC is an electrical appliance whereas UK heating systems are largely oil and gas which contribute to larger electricity demand peaks thus, a larger demand response capacity as seen in California.

The North American energy provider Pacific Gas&Electric Company (PG&E) has developed a demand response "SmartAC" air conditioning systems program to its commercial and residential customers, primarily applied in California which has a warm climate and is USA's most populated state. The program aims to control energy demand loads by controlling ACs by cycling aggregated AC load during occasional summer peaks largely caused by the simultaneous operation of hundreds of thousands of ACs.

The SmartAC program disperses AC cooling cycles preventing large simultaneous usage therefore shifting/spreading the peak load. The SmartAC program applies energy load management while also ensuring that the temperature in the working area will not exceed the nominal temperature setting by more than four degrees for commercial customers. The SmartAC program is driven by customer incentives, cooperating with the customer by catering to different lifestyles. If the AC cycling event happens at an inconvenient time the customer can refuse to respond without facing any repercussions. The consumer can adapt the program to their requirements to the best of their abilities or to receive full incentives, they can allow the SmartAC to be remotely controlled allowing full automation of the program and are rewarded more for their full cooperation.

PG & E is not the only energy company in California that offers incentive driven demand management programs. Other energy provides such as Southern California Edison (SCE) has a program targeting energy loads produced by the agricultural sector or San Diego Gas & Electric (SDGE) have programs aimed to manage energy loads by incentivising businesses to enroll in capacity bidding or pledged energy reductions based on monthly bill credits. Each company offers a demand response program focused of various individual energy demand sources however they all work together to combat energy load demand spikes.[13]

Texas

In the state of Texas in Northern America, the second most populated state, the electricity flow is managed by the Electric Reliability Council of Texas (ERCOT) covering over 90% of Texas' domestic homes and commercial buildings. The program is highly cooperative with the participating consumers by allowing the consumer to provide offers to the energy ERCOT energy markets. The ERCOT energy market allows users to pledge energy consumption reductions easily by allowing them to analyse and respond to wholesale market prices.

City Public Services (CPS) in the state of Texas provide an interesting energy load demand management curtailment program, designed to suit both the industrial and the commercial consumers. Like many of the other hotter climate states/cities, the focus of the program is for energy users to reduce the energy demand during peak summer periods where energy grid demand is at its highest due to AC energy loads. The CPS program aims to tackle weekday demand spikes generated between 3pm and 6pm. For consumers willing to participate, they are required to demonstrate at least a 50 kW of curtailable electric load before they can qualify for the program. The CPS install Smart thermostat and control equipment for the residential end-user free of charge. Rather than relying on consumers to cooperate with incentive rules and requirements, this program allows the CPS to have complete control over the home's energy demand complying with a 2-hour advance notification to the consumer.

The program manages the domestic home's electrical demand through the high energy appliance: the AC. The CPS monitor the temperature of the home through the smart thermostat and cycle off the home's AC units for short periods at appropriated times during the peak day demand spike. The AC's are controlled through radio signals between the AC and Smart Thermostats. Through this program the CPS can control energy loads in the domestic home without relying on enticing the consumer with incentives to self-manage their energy loads. The end-user benefits through a guaranteed heating/cooling related energy bill reduction of 10% at the same time providing the grid with guaranteed domestic housing demand management. [13]

Florida

Florida Power & Lights (FPL) company has a Commercial Demand Reduction Program which aims to gain direct control of smart appliances allowing them to remotely reduce a domestic home's energy load after pre-notifying the consumers. For each kW of curtailed energy during a shutdown event, the consumer is compensated with credit along with a fixed rate monthly credit for being enrolled in the program even if shut-down events do not occur.[13]

New York

The New York (a cooler climate from the previously mentioned) Independent System Operator (NYISO) "Day-Ahead Demand Response Program" (DADRP). This system forecasts the next day's energy demand peaks allowing them to apply incentives more accurately and appropriate to the degree of the demand peak that requires mitigation. The DADRP system benefits end-users who can pre-plan and bid their energy load reductions in the day-ahead market and allows the NYISO to select the most economically viable bids which satisfy the day-ahead forecast.[13]

These are just a few examples of the demand management strategies applied in North America demonstrating its successful demand management reputation. These systems showcase the diversity in the methods that may be required to satisfy a renewable heavy grid.

Europe

Belgium

Belgium has enrolled many of its industrial energy consumers to pledge an accumulation of hundreds of megawatts to its demand response program to aid the national grid in times of generation vs demand inequality.[13]

Other European Countries

Most other European countries have also developed their demand response capacity allowing Europe to have the second highest demand response capacity after North America.[13]

Oceania

Australia

Australia has made obligations to expand its demand response capabilities through various planned schemes after realizing its importance in stabilizing the electric grid as the world enters a renewable era. The proposed systems provide consumers with an array of choice on how they wish to participate in demand management. Examples are the 'cool saver' scheme which focuses on AC systems much like that seen in California, or the 'peak saver' in which the consumer pledges to reduce their demand during pre-notified periods. Additionally, there is a 'pool saver' option in which the consumer allows the energy service to install automated power supply circuit to an eligible consumers pool pump. [13]

New Zealand

New Zealand has developed a significant demand response capacity. New Zealand's Transpower company has developed demand response programs which includes the country's commercial buildings and agricultural sector.[13]

Asia

In general, countries in Asia have not developed demand response into their energy markets. However, demand management projects are beginning to appear, especially in the Asia-Pacific region. Only a small number of individual countries have successfully developed demand response programs into their energy distribution. [13]

Japan

Until recently Japan has been slow to develop its demand response capacity and has suffered from intense energy requirements during high emergency conditions, especially after the Fukushima nuclear incident. Japan aims to introduce an automated demand response management system planned to send a power-saving request to energy consumers during periods of system stress. The program also considers allowing energy services to gain control the consumers electrical consuming sources if necessary.

Japan is an example of a highly technologically developed country (like the UK) which has ignored building a demand management capacity and consequently experiences high stress on its electrical supply system.[13]

Singapore

Has the highest developed demand management capacity in Asia. All customers that can offer a 0.1 MW of reduction for half an hour can participate. The participants benefit by gaining a share of one third of the savings obtained by the reduction in electricity prices as incentive payments, up to 4,500$/MWh of wholesale electrical prices. The enrolled consumers are encouraged to provide temporarily the required reduction by switching off non-critical equipment or can use personally owned back-up generators/ electrical storage utilities participate directly or through retailers or demand response aggregators. [13]

2.2.7 International Demand management summary

Most developed countries have successfully integrated demand management as a means of bringing stability to the electric grid. Countries what have not applied this strategy have experienced less stability on the grid requiring periods of high stress on the energy generation sector. Japan, which has encountered these problems, is now actively pursuing demand response as the solution.

Energy networks in hotter climates experience greater electrical demand stress due to electrical AC usage than networks in colder climates that installed the use of fossil fuels for heating. Space heating/cooling is a very energy intensive task therefore, energy networks in hotter climates have had to tackle demand management head-on more aggressively than colder climates. Additionally, these countries have a larger variety of programs which focus on domestic housing energy management. Colder climates which do not use the electricity grid for temperature regulation do not have as many demand response programs focused on domestic house. Therefore, colder climate electrical networks demand response programs primary focus on large industrial consumers who can pledge larger amounts of energy to the program.

Internationally demand management is used as a tool to bring stability to the electrical grid during times of stress resulting from high demand. As countries progress towards a renewably powered electric grid the challenges to maintain stability are increased. Additionally, fossil fuel heating systems will require replacements. For this reason, countries like the UK will likely be required to expand their demand response programs in other sectors such as domestic demand and take a more aggressive approach as seen in other countries.

2.3 Conclusions

Many countries around the world have actively sought to improve their electrical demand response capacity. Many different methods have been adopted each showing measurable improvements for grid stabilisation and minimalizing back-up generation cost. Most demand management strategies solely aim to reduce routine daily peaks. As the renewable gird increases the complexity of grid stabilisation, these periods may not be the sole focus and demand management will be driven by weather conditions of a given day. However, the strategies and programs applied will only require minor adjustment to adapt particularly in countries with high demand management capacities such as New Zealand.

The UK currently has a limited variety of demand management programs likely because for the current demand trends, such measures are not required for grid stabilisation. However, grid stability is a major challenge moving forward into a renewable grid and demand management is an energy strategy yet to achieve full effort and potential. As the nation pushes forward to meet its renewable energy generation targets, demand response management is an intuitive method of addressing the challenges which arise from the renewable transition. Expanding demand management programs requires a small infrastructure change and inspiration can be drawn from the other countries' attempts.

Difficulties arise when attempting to entice nationwide participation in demand management. It is assumed that the energy consumer is motive-driven and requires incentive to undergo an energy related lifestyle change. However, because energy demand management has favourable outcomes for national energy services and providers, incentive-based tariffs and policies will be beneficial for both parties. Nonetheless, the breaking of consumer energy habits or upgrading home appliances for automation will require a degree of adjustments.

The aim of the result section of this thesis is to lay out a strategy of introducing energy load management into the domestic home and how this strategy can benefit the current and future grid. The strategy will involve appliances with the ability to be shifted with minimum disruption to the consumers lifestyle. The outcome will hopefully provide a base for further energy load management to occur and result in a more energy conscious consumers.

3 METHODOLOGY

3.1 Input data

3.1.1 Domestic appliance usage

In order to identify domestic appliance usage and analyse energy load shifting strategies, average demand data was gathered from 22 dwellings fitted with energy meters (covering electricity usage from the entire home) over two years (2008-2009). This data was acquired from a data set titled One-Minute Resolution Domestic Electricity Use Data, 2008-2009 supplied by the UK Data Service. These meters recorded appliance use to the nearest minute, yielding a view of domestic demand with a high temporal resolution. From this study, the data from 12 out of the 22 homes were analysed as the remaining 10 were discounted due to incompleteness of the data sets (missing data) or due to the home being unoccupied during the period of analysis (judged by the lack of electricity usage throughout the day).

The meter reading data supplied daily energy demands of these 12 homes for everyday of the year however, due to time constraints the month of December selected as the focus month. December was selected due to its seasonal conditions resulting in higher average UK domestic energy peak usage due to larger lighting and heating requirements making it a month which requires greater urgency for energy load management. Additionally, due to the same constraints Tuesday and Sunday were selected as the focus days for data analysing and modeling. Tuesday was selected in hopes of representing a standard weekday. Sunday was selected due to it typically being the day of most appliance usage and with the hopes of Sunday representing a typical weekend day.

The meter readings of the 12 surveyed homes were analysed for each Tuesday of December 2009 (1st, 8th, 15th, 22nd, and the 30th) and each Sunday of December 2009 (6th, 13th, 20th, and the 27th).

3.1.2 Specific Appliance usage

In order to explore energy load management, this thesis will focus on shifting the energy demand created from 3 specific appliances: washing machines, washer-dryers, and dishwashers. These 3 appliances typically result in about 10% of a household's electrical consumption.[19] They were selected due to their switchability i.e. the ease with which a consumer might shift the appliances' demand period through appliance timers or decision-making. As such, changes to the usage of the selected appliances were expected to cause the least disruption to consumer lifestyle and so confer aid their successful adoption.

Data on domestic washing machine, wash dryer and dish washer usage were gathered from the Household Electricity and Activity survey conducted by UK Data Service.[51] This survey collected surveyed households about their weekly washing routines and gave a daily breakdown. Data were recorded from February 2016 to January 2019. In total, this resource includes 264 electricity records (28 hours each) with 16,378 recorded activities from 529 people. From this dataset, there were recorded 133 uses of washing machines, 22 recordings of tumble dryers and 67 recordings of dishwashers. Differences in household ownership likely accounted for the varying numbers of recordings (table 4). The Household Electricity and Activity survey also collected information on appliance ownership and importantly this closely matched the national averages (table 5).

Table 5. Summary statistics of appliance ownership and age.[40]

Appliance	National Household Ownership (%)	Survey household ownership (%)
Washing machine	96	100
Tumble dryer	57	50
Dish washer	40	62

3.2 Energy load management: optimal utilisation of economy 7 tariff

3.2.1 Methodology overview

The major challenge when attempting to apply energy load management to meter reading data is correctly identifying each appliances energy signature. These energy signatures often vary in energy consumption through the period of constant level energy consumption vs alternating volumes of energy consumption. The three washing appliances selected all have distinguishable energy load signatures. Individual household data used is not intended to represent typical or average demand of national domestic housing. Rather, this data will be used to demonstrate a novel methodology that could be carried out on any similar dataset. A time-of-use data set giving insight to the usage periods and patterns of appliances in the domestic home. This dataset was acquired from the UK Data Service where the dataset was titled 'METER: UK Household Electricity and Activity Survey, 2016-2019'. This data was analysed to give the daily periods of accumulated high usage throughout the homes and the usage variation spread between the days of the week.

3.2.2 Washing machine energy load shifting

Washing machines have two distinct sections; a main cycle and an end section. The main cycle is between 10 and 30 minutes in duration, with a constant power draw of 2,000 W. The end period is generally much longer, with an alternating power draw of either 200 or 0 W.[53] Based on the appliance usage data and previously published sources the following conclusions were adopted for the purpose of mathematical modelling:

- Appliance usage data shows every home has a washing machine.
- Appliance usage data shows 10% of washes occur on a Tuesday.
- The average wash cycle is 30 minutes.[54]
- When in use, a washing machine's electricity demand is a consistent 2000 watts.[54]
- In the UK, the average household used a washing machine 165 times (3 times a week).[52]
- 55% of washing machines are turned on during the evening demand peak.
- Number of surveyed homes (12) x averge useage (3) x ownership probability (1) x Tuesday usage probability (0.1) x evening usage probability (0.55) = ~2 (1.8) average uses. therefore it is predicted that 2 energy load can be shifted from the Tuesday evening demand to the morning from the 12 surveyed houses.

Based on the above, washing machines are used on average 3 times a week of which it is expected that 2 (1.8) usages will occur during evening periods. For the data gathered over the month of December it is expected that 8 washing machine loads from the evening demand can be potentially shifted.

The method of shifting washing machine energy loads will involve analysing the minute-by-minute domestic household electricity demand of individual households. The one-minute time resolution of these profiles enabled peak demand to be delineated and even allowed the use of high demand appliances to be predicted by their 'energy signature'. These household demand profiles were then analysed for a 2,000 W spike, on the assumption that this corresponds to washing machine usage. The 2,000 W corresponding to such spikes were then moved into the time period covered by the economy 7 tariff. Once the washing machine energy signatures of 4 individual households had been manipulated, the effects on the combined average were compared to analyse the energy reductions during peak times.

3.2.3 Dish washer energy load shifting

Using an identical methodology to the energy load shifting of washing machines, the energy load of dish washers will also be shifted. The dishwasher can be identified by its energy signature. A dish washer's run program is more complicated than a washing machine as there are four distinct sections: two main washes and two idle periods. The first main wash takes 25 minutes while the second takes 30 minutes.

- The dishwasher, when it is in use and running a cycle, used a constant 1,600 watts.
- Data from Table 4 shows that 62% of the surveyed homes own a dishwasher.
- Figure 13's data shows that 68% of dishwashers are turned on during the evening peak time (17:00 - 22:00).
- From time of use dishwasher is used the Dishwashers probability of usage on a Tuesday is 15%.
- The UK averge number of dishwasher usage is twice a week.[52]
- Number of surveyed homes (12) x averge useage (2) x ownership probability (0.62) x Tuesday usage probability (0.15) x evening usage probability (0.68) = 1.52 uses. Therefore it is predicted that 2 energy load can be shifted from the evening demand to the morning from the 12 surveyed houses.

Based on the above, dishwashers are used 2 (2.23) times a week of which it is expected that 2 (1.52) usages will occur during evening periods. For the data gathered over the month of December it is expected that 8 (2 x 4 Tuesdays) dishwasher loads can be shifted.

n this appliance signature, there are four distinct sections: two main washes and two idle periods. The first main wash takes ~25 minutes while the second takes ~30 minutes, during both of which a constant power of 1600 W is drawn. The first idle period lasts 20 minutes during which an almost constant power of 50 W is drawn.[53] Individual household demand profiles were then analysed for the presence of this distinctive energy signature. These spikes were then moved to were then moved into the time period covered by the economy 7 tariff. Once the dish washing energy signatures of an individual households had been manipulated, the effects on the combined average were compared.

3.2.4 Tumble dryer energy load shifting

Finally, the energy load of tumble dryers will also be shifted, using the same strategy as outlined above. When in use the power draw by the appliance alternates between 2000 and 200 W over a duration of between 60 and 140 minutes.[53] Based on the appliance usage data and information from published sources the following assumptions were adopted for the purpose of mathematical modelling:

- The data provided in table 4 shows that 50% of the surveyed homes own a tumble dryer.
- In winter, 86% of homes with tumble dryers dry their clothes once or more a week. The average number of weakly usages is 3.[52]
- As tumble dryers are linked to the washing machine usage through their functions, it is assumed they experience the same usage patterns. Therefore, experience 10% of usage on a Tuesday.
- The evening usage probability is 52%.
- Number of surveyed homes (12) x averge usage (3) x ownership probability (0.5) x Tuesday usage probability (0.1) x evening usage probability (0.52) = 0.9 uses.

Based on the above, it is predicted that 1 energy load per week can be shifted from the Tuesday evening demand. For the data gathered over the month of December it is expected that 7 (7.2) tumble dryer loads can be shifted from all the Tuesday's in December's meter reading. A tumble dryers energy signature can be identified by its the main cycle and the end of the cycle. During the main cycle, the power draw alternates between 2000 and 200 W over a duration of between 100 and 140 minutes. Individual household demand profiles were then analysed for the presence of this distinctive energy signature. These spikes were then moved into the time period covered by the economy 7 tariff. Once the tumble dryer energy signatures of an individual households had been manipulated, the effects on the combined average were compared.

3.2.5 Extrapolated weekly washing machine usage

It is assumed that the Tuesday demand average is representative of all the week days (Monday - Friday). As weekends represent a significant change in lifestyle, the above analyses method was repeated for Sunday individually. Alterations were made to the predicted amount of weekend washing machine usage based on the following findings:

- The probability of using a washing machine on a Sunday was found to be 21% higher compared to Tuesdays.

- Number of surveyed homes (12) x average usage (3) x ownership probability (1) x Sunday usage probability (0.21) x evening usage probability (0.55) = 3.8. Therefore, it is predicted that 4 energy loads can be shifted from the Sunday peak demand to the morning from the 12 surveyed houses. Over the month of December it is predicted that ~15 (15.2) washing machine loads can be shifted on Sundays.

3.2.6 Extrapolated weekly dish washer usage

Again, it was assumed that the Tuesday demand was representative of all week days (Monday - Friday) and sunday was reanalysed. Alterations were made to the predicted amount of weekend dish washer machine usage based on the following findings:

- The probability of using a disher washer on a Sunday was found to be only marginally higher (16%) higher compared to a Tuesday's calculated usage (15 %) and so the predicted energy load shift remainded unchanged (2).

3.2.7 Extrapolated weekly tumble dryer usage

As above, it was assumed that the Tuesday demand was representative of all week days (Monday - Friday) and weekends were reanalysed. Alterations were made to the predicted amount of weekend dish washer machine usage based on the following findings:

- The probability of using a tumble dryer on a Sunday was found to be 21% higher compared to Tuesdays, consistent with the increased washing machine usage.
- Number of surveyed homes (12) x average usage (3) x ownership probability (0.5) x Sunday usage probability (0.21) x evening usage probability (0.55) = 2.07. Therefore, it is predicted that 2 energy loads can be shifted from Sunday peak demand to the to the time period covered by the economy 7 tariff. Over the month of December this equates to ~8 (8.28) shifted tumble dryer loads.

3.3 Energy load management: optimal utilisation of a renewable dominant grid

3.3.1 Method overview

(intro blurb about switching from econoimc 7 tarrif load management to a future one based on renweable dominant grid)

Firstly, all the identified energy signatures corresponding to all three washing appliances were removed from the 12 surveyed homes so as to give a base demand minus these appliances. These baseline demands were assumed to be representative of the national demand average.
Next, the national energy grid electrical supply input data was analysed for high and low wind energy supply periods which will give a simplistic analysis model of stochastic energy supply. Additionally, hydro energy electricity input to the grid was analysed to give a simplistic analysis model of periods when back-up energy is required to the grid. The grid input analysis was again limited to the month of Decemeber.
The renewable grid was compared to the national domestic demand averages and during periods of high and low wind supply over the course of a december week. Appliance loads were then shifted from periods of low wind supplies to periods of low wind supply with the goal of optimising load management.

3.3.2 Estimating baseline weekday demand

Energy signatures corresponding to the three washing appliances energy signatures were removed from the demand profiles of the 12 meter recorded homes. Again the data and energy load management was derived from the Tuesdays falling in the month of December.

- For washing machines, it was predicted that 14 energy loads could be removed from the four Tuesdays in December.
  (Number of surveyed homes (12) x average usage (3) x ownership probability (1) x Tuesday usage probability (0.1) = 3.6 (~4) daily uses x 4 = 14.4 (~14) Tuesday uses in December.

This includes the previous 8 identified evening appliance energy signatures shifted in the previous section in will be included when removing the 14 full day predicted loads.

- For dish washers, it was predicted that 9 energy loads could be removed from the four Tuesdays in December.
  (Number of surveyed homes (12) x averge usage (2) x ownership probability (0.62) x Tuesday usage probability (0.15) = 2.23 (~2) daily uses x 4 = 8.92 (~9) Tuesday uses in December.

This includes the same 8 previously identified evening appliance energy signatures shifted in the above section in will be included when removing the 9 full day predicted loads.

- For tumble dryers, it was predicted that 7 energy loads could be removed from an average household’s demand from the four Tuesdays in December.

(Number of surveyed homes (12) x average usage (3) x ownership probability (0.5) x Tuesday usage probability (0.1) = 1.8 (~2) daily uses x 4 = 7.2 (~7) Tuesday uses in December.

This includes same 4 previously identified evening appliance energy signatures shifted from the above section in will be included when removing the 7 full day predicted loads.

3.3.3 Estimating baseline Sunday demand

The three washing appliance's energy signaures identified over the course of the full average Sunday and will be removed from the meter readings of the 12 homes in compliance to the time of use data.

- For estimated Sunday washing machine usage, it was predicted that 30 energy loads could be removed from the four Sundays in December.
  (Number of surveyed homes (12) x averge useage (3) x ownership probability (1) x Sunday usage probability (0.21)= 7.56 (~8) daily uses x 4 =30.24 (~30) total Sunday uses in December.

This includes the same 15 previously identified evening appliance energy signatures shifted in the previous section in will be included when removing the 30 full day predicted loads.

- For estimated Sunday Dishwasher usage, it was predicted that 9 energy loads could be removed from the four Sundays in December.

  (Number of surveyed homes (12) x average usage (2) x ownership probability (0.62) x Sunday usage probability (0.15) = 2.23 (~2) daily uses x4 = 8.92 (~9) total Sunday uses in December.

This includes the same 8 previously identified evening appliance energy signatures shifted in the above section in will be included when removing the 9 full day predicted loads.

- For estimated Sunday tumble dryer usage, it was predicted that 15 energy loads could be removed from the four Sundays in December.
  (Number of surveyed homes (12) x average usage (3) x ownership probability (0.5) x Sunday usage probability (0.21) = 3.78 (~4) x4 =15.12 (~15) total Sunday uses in December.

This includes the same 4 identified evening appliance energy signatures shifted in the previous section in will be included when removing the 15 full day predicted loads.

3.3.4 predicting wind oversupply

Datasets were aquired on Pumped hydro generation supply and wind generation supply to the national grid were provded by G.B. National Grid Status (Data courtesy of Elexon portal and Sheffield University). When designing the future grid a large number of assumptions must be made. Therefore, the method adopted in this thesis is is to simply analyse the current grid for characterisitics that can give clues to the influences of a future grid. National pumped hydro generation and wind generation was analysed for the insight they can provide. Pumped hydro, as discussed in section 2 of the thesis, is mostly used as a buffer providing insight into periods in which backup energy is required in the current grid. Wind turbines are assumed to be the predominant renewable energy generator of the future and will be analysed for its stochastic characteristics in the current grid.

The data is limited as it does not give any indications to when wind turbines are shut down due to oversupply and when pumped hydro is reversed with the aims of consuming energy. Additionally, wind curtailment periods are commercially sensitive information so no other datasets can be gathered to resolve this limitation. To counter this wind turbine oversupply limitation wind speed data was gathered over the same month (December 2019) and compared to give clues to when oversupply may be occuring.

Because pumped hydro acts as a buffer it gives insight as to when back-up energy is required i.e. when the pump hydro contrubution increases this suggests that reserve energy is required. When the pump hydro contribution decreases this suggests the current supply is comfortablly meeting demand. Combine this with periods of wind high wind then it is possible to predict plausable periods of wind oversupply.

Once periods of over supply were predicted the meter readings data sets under went energy load management by shifting the washing appliances to the period of oversupply. The objective here was to apply all the possible loads into the period of oversupply which was in contrast to the previous section where they were spread evenly.

3.4 Software:

The data manipulation, modelling, and the results provided in this thesis were achieved using Microsoft Excel. This software tool was developed by Microsoft and features calculation, graphing tools, pivot tables, and a macro programming language called Visual Basic for Applications.

3.5 Data Sources:

3.5.1 Renewable energy data

Data concerning UK renewable energy supply, demand, usage, and sources was gathered from the UK Governments data collection organisation in the Department for business, Energy & Industrial Strategy. https://www.gov.uk/government/collections/renewables-statistics.

3.5.2 Meter reading data

Data on meter readings, housing conditions and appliance time of use data for domestic housing was gathered from UKERC ENERGY DATA CENTRE an outward-facing energy data service to the UK energy research community datasets or pointers to data generated from any source (whether Research Council funded or third party), including national and international sources. Found at: https://www.ukdataservice.ac.uk/get-data.

3.5.3 Electrical Appliance Energy Signatures

Data on appliance energy signature examples was gathered from public data source Disaggregated Homes. This data source provides NIALM data provided by researchers who have begun to publicly release their data sets, therefore enabling other researchers to compare their approaches against common benchmarks. Found at: http://blog.oliverparson.co.uk/2011/01/appliance-survey-tumble-dryer-washing.html.

3.6.4 UK wind speed

Data on wind profiles used to identify periods of oversupply were found at:

https://gmao.gsfc.nasa.gov/reanalysis/MERRA/.

This wind profile data was formatted and gathered from: https://www.renewables.ninja/ allowing data sheets of wind speeds occurring at Whitlee wind farm and Dogger bank to be analysed.

3.5.5 National Demand, Wind Supply and Pumped Hydro Supply to the National Grid

Data files providing data on individual energy generation methods and their energy contribution to the UK's electrical grid. The data provide hourly data to allow analysis of generation and demand over a defined period. Datasets were found at: https://gridwatch.co.uk/.

3.6 Ethical considerations

The data used in this thesis was supplied from open sources provided by homeowners who volunteered to provide their meter data. However, if energy load management were to expand to a national level with the aims of more aggressive usage larger volumes of meter data and appliance usage would be required. Furthermore, if energy load management were to become automated then the system would become intrusive into the domestic home. The data that would be required and the action needed to be carried out on domestic appliance usage times for a notable difference to be made would be directly intrusive to the occupant's lifestyle.

3.7 Data privacy

The data used in this thesis was supplied from either open sources provided by homeowners who volunteered to provide their meter data, or peer reviewed research papers.

3.8 Uncertainty analysis in experiments

The largest sources of plausible error within this thesis are correlated to the assumptions made on the future grid and when identifying energy appliance signatures. The assumptions on the future grid are based off widely agreed predictions. However, they do not account for unforeseen changes and technological advancements. This error was reduced by only using current data on wind and hydro as representatives of the future grid but is flawed as it reduces scope for the full picture. Additionally, domestic home appliance generated demand on the grid is assumed to be the same which can lead to inaccuracies through appliance efficiency improvements and future technologies used in the home such as battery storage.

Errors which may occur through the appliance data will most likely occur since the meter reading and the time of use data were from different sources and therefore cannot be directly linked to each other. This may lead to appliance energy signatures being wrongly identified.

4 RESULTS

4.1 Identify specific domestic appliance usage from household demand profiles based on their energy signatures

4.1.2 Individual domestic meter recordings

Following this understanding of the current average demand pattern, one-minute resolution meter reading data was gathered with the aim of identifying appliance usage and the ultimate aim of analysing energy load shifting strategies. This study (UK data service) includes electricity data measured in 22 individual dwellings over two years (2008 and 2009).

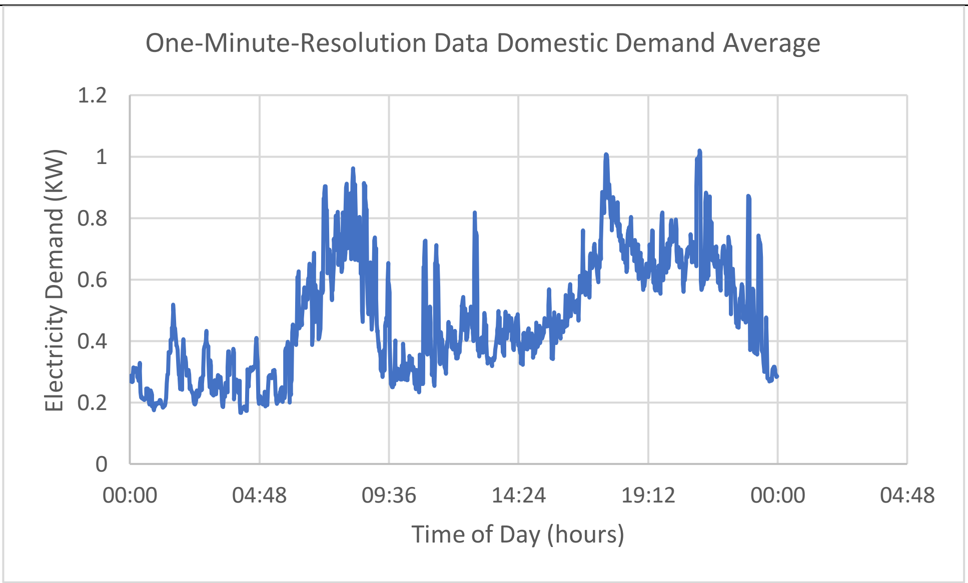


Figure 12. showing one-minute resolution weekday electricity demand average of 12 UK homes in December.

Figure 12 shows one-minute resolution of the average domestic electricity demand accumulated from such dwellings. The resulting graph reveals the demand pattern of a small cluster of homes. The high time resolution allows analysis of appliance activity to the nearest minute at which electrical appliances are being turned on. The daily energy trend of figure 12 is similar in appearance to figures 8 & 9. The lower pool of participating homes resulted in greater influence from each individual household's energy usage patterns on the average results. For this reason, the graph's curves are slightly more variable compared to the UK average.

The morning peak begins at 06:25 and ends at 09:04 reaching 975 watts at its highest demand at 8:17 AM. After the morning peak there are four energy spikes which last one minute between 9:04 and 12:47 all producing a demand between 600 and 750 watts. In between these four spikes the demand stays between 250 and 450 watts. At 15:30 there is a gradual increase before the evening demand spike beginning at 17:42. The evening spike lasts until 22:33 before falling back down to 400 watts. During the evening spike there are two notable peaks which exceed a demand of 1000 watts occurring at 17:38, and 20:00. There are two other evening peaks exceeding 800 watts at 21:21 and 22:07. After the evening peak there are two peaks at 22:57 reaching 860 watts and one at 23:20 reaching 720 watts before the demand falls to a nighttime base line ~200 watts. The average energy usage trend seen in figure 12 follow the demand pattern that was expected and is valid when compared to national demand averages such as figure 12 in the literature review section of this thesis.

4.1.3 Domestic appliance usage

This study chose to focus on 3 domestic appliances: washing machines dish washers and tumble dryers. These appliances were selected as it was predicted that their distinctive energy demands would make their energy signature easy to identify. They are also highly switchable appliances with energy loads that can be shifted with minimum disruption to consumer lifestyle.

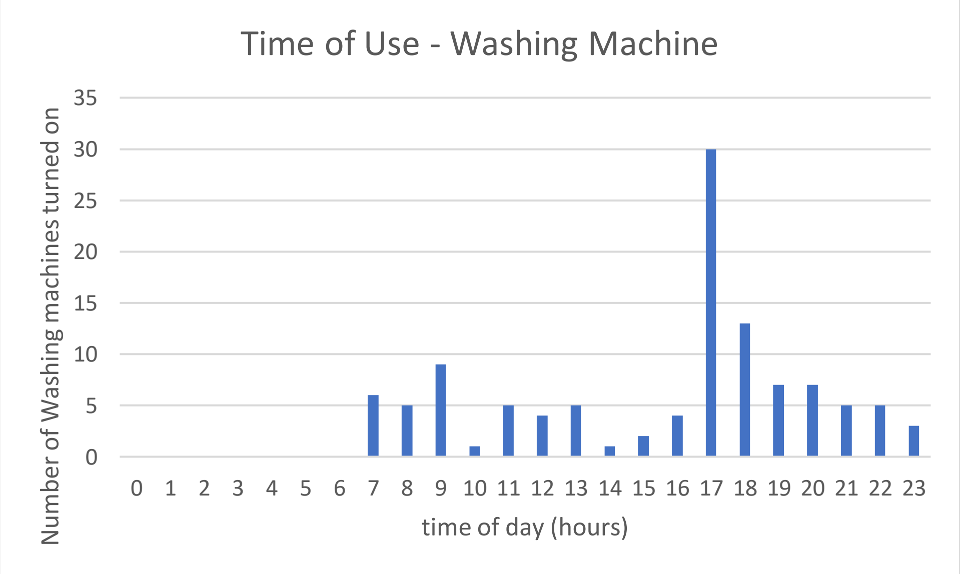


Figure 13. showing time of use data of washing machine appliance usage according to the time of day.

Figure 13 shows that current lifestyle patterns result in the washing machine being turned on between 5pm and 7pm in the evening. evening usage continually decreases after 5pm (peak) and features a small spike at 9am. During the afternoon the usage does increase

above 5 washing machines turned on per hour. The washing machine has the largest volume of recorded data of the 3 appliances from the time of use survey due to more dwellings owning a washing machine over the other appliances (table 4). Furthermore, washing machine usage throughout the week is relatively even (Figure 14).

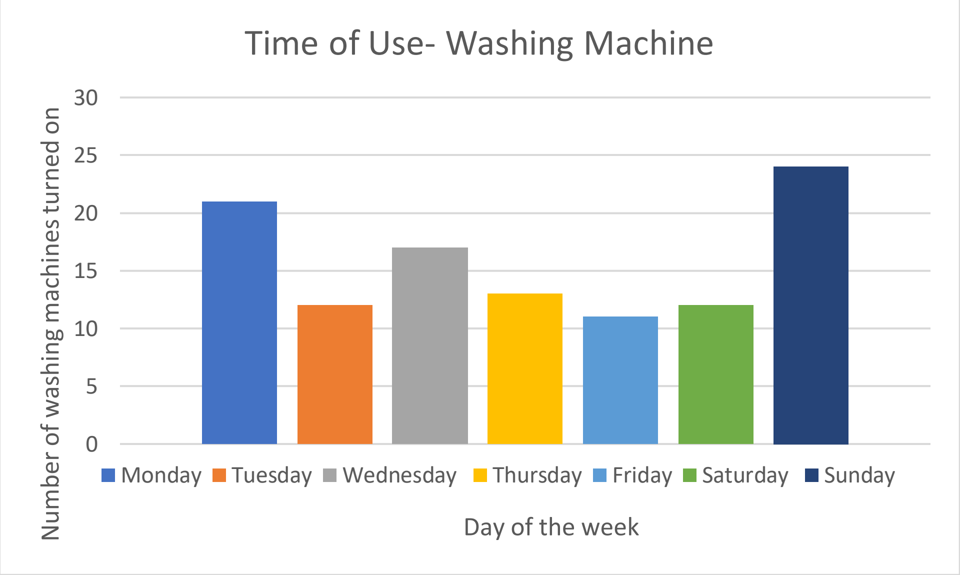


Figure 14. showing time of use data of washing machine appliance usage according to the day of the week.

Sunday is the most used day (17% of washing machines turned on) and Friday is the lowest used day.

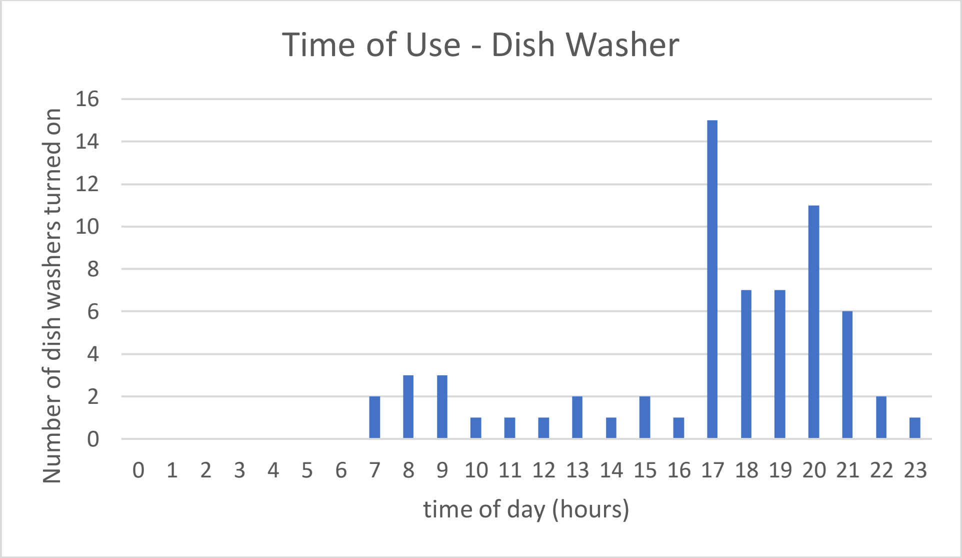


Figure 15. showing time of use data of dishwasher appliance usage according to the day of the week.

The dishwasher is mostly used between the hours of 5pm and 9pm, which is presumably corelates with mealtimes (Figure 15). The data provided 67 recordings of dishwasher usage of which 46 (69%) of dishwashers are used during the evening energy demand spike. As shown in Figure 15, dish washers are most commonly used on a Monday and Wednesday (14 (20.9%) total uses). Friday and Saturday see the lowest usage of the dishwasher with 5 people of the 67 recorded using it during this period.

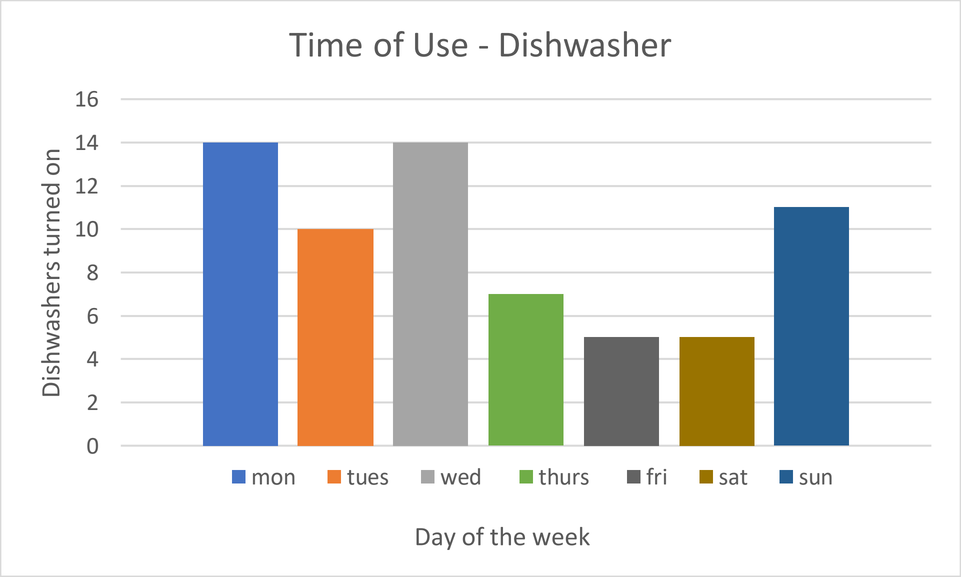


Figure 16: showing time of use data of dish washer appliance usage according to the day of the week.

However, it should be noted that that when applying demand management, the dishwasher can only be shifted to later in the night aiming to complete its task before 7am the next day. i.e. the dish washer is slightly less switchable than the other two appliances.

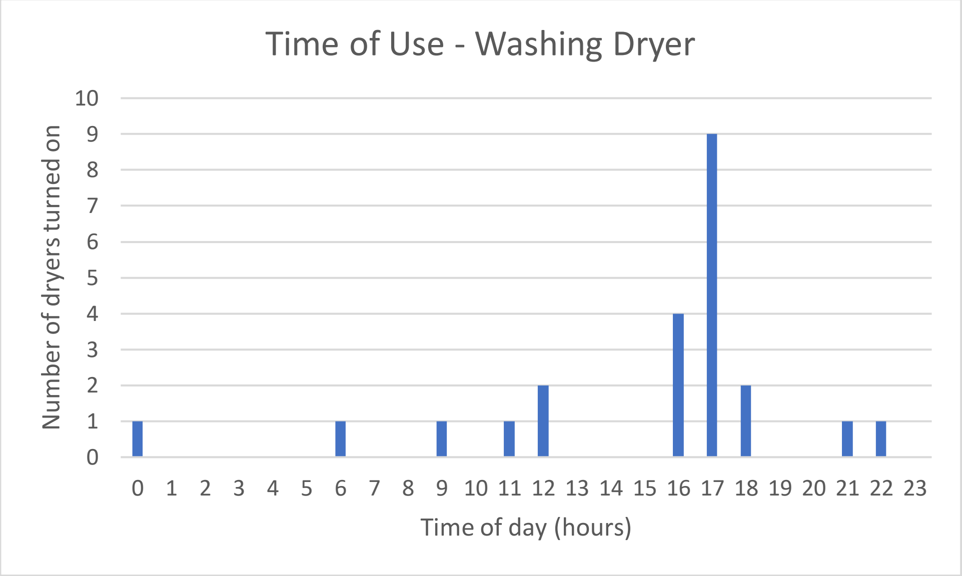


Figure 17. showing time of use data of washing dryer appliance usage according to the day of the week.

Figure 17 shows time of tumble dryer use. There is less recorded data in comparison to the washing machine likely due to less household ownership of the appliance. Like the washing machine, 5pm is the peak usage of the appliance. For washing dryer usage, 12 (54%) out of the 22 recorded usages land within the evening spike (17:00 – 22:00).

For day of week usage data, the tumble dryer and less recorded data (data not included). Therefore, it is assumed the tumble dryer follows the same trend as the washing machine as the are paired through their functions.

4.1.4 Identifying appliance energy signatures from domestic meter recordings

Having analysed appliance usage, this information was combined with the known energy demand of these appliances to identify their distinctive energy signatures from individual domestic daily meter recordings.

For example, Figure 17 shows the meter reading of a home (#20) with another identifiable washing machine energy signature.

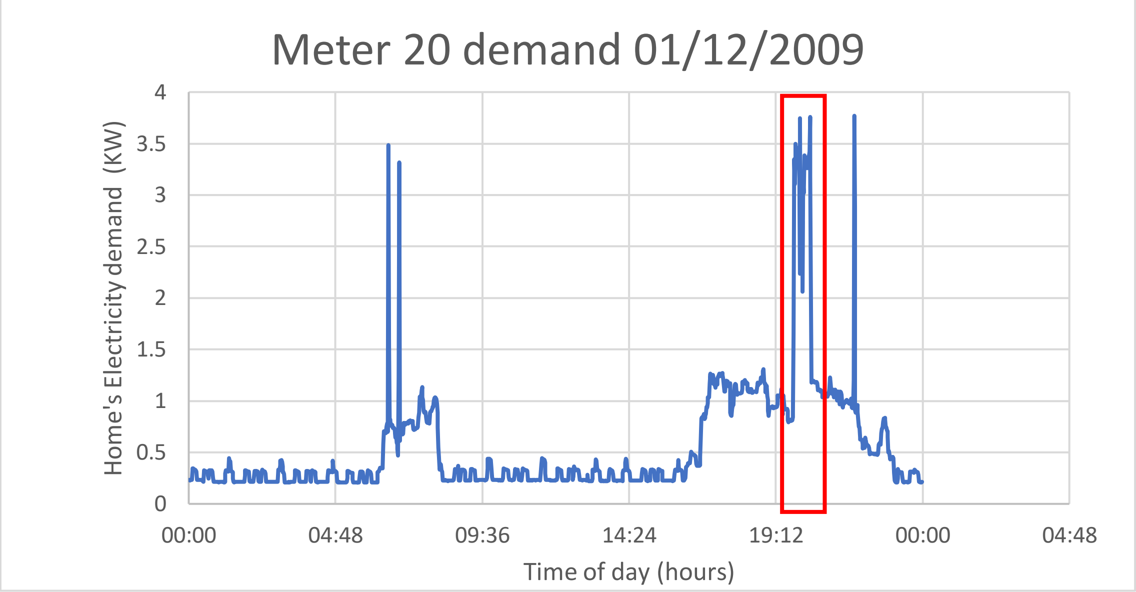


Figure 18: Individual home meter reading for Tuesday 1st of December. Meter 20 from dataset.

The washing machine energy signature can be seen between 19:47 and 20:18 (highlighted by the red box) increasing the usage by 2000 watts the whole period.

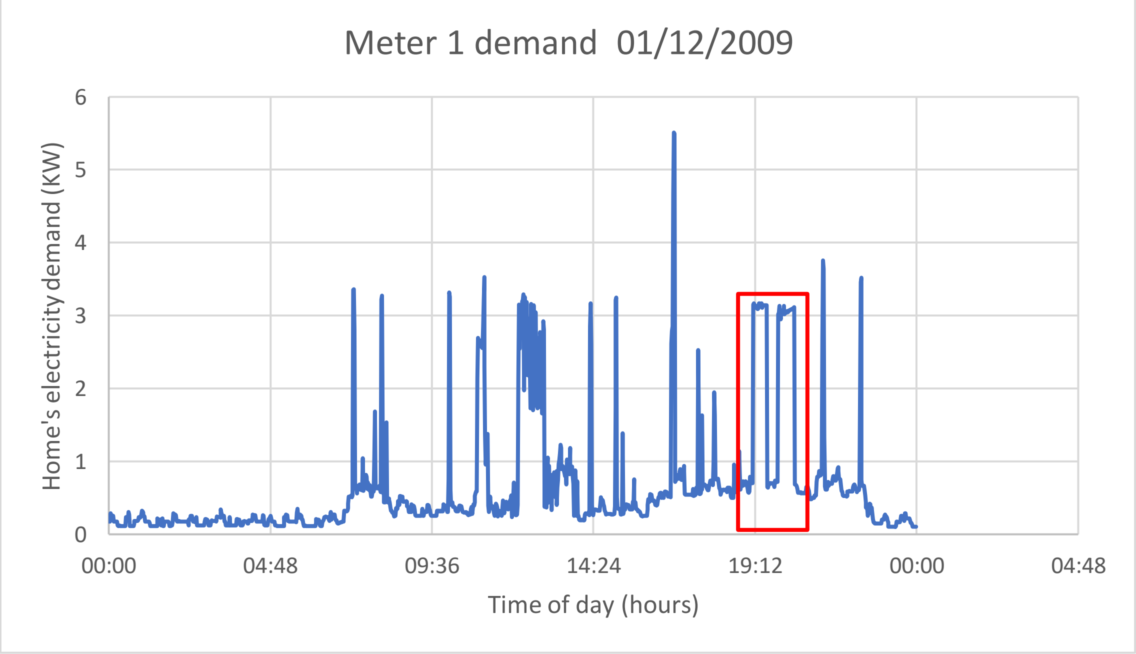


Figure 19: Individual home meter reading for Tuesday 1st of December. Meter 1 from dataset**.**

An example of an identified dishwasher energy signature (meter recording #1) is shown in Figure 19. dishwasher energy signature can be seen with the first cycle starting at 19:09 and lasting until 19:33 followed by a 20-minute gap after which the second cycle starts at 19:53 and lasts until 20:23. When the dishwasher cycles are running there is an identifiable energy spike (highlighted by the red box) resulting in the home's demand increasing past 3000 watts during the cycle periods.

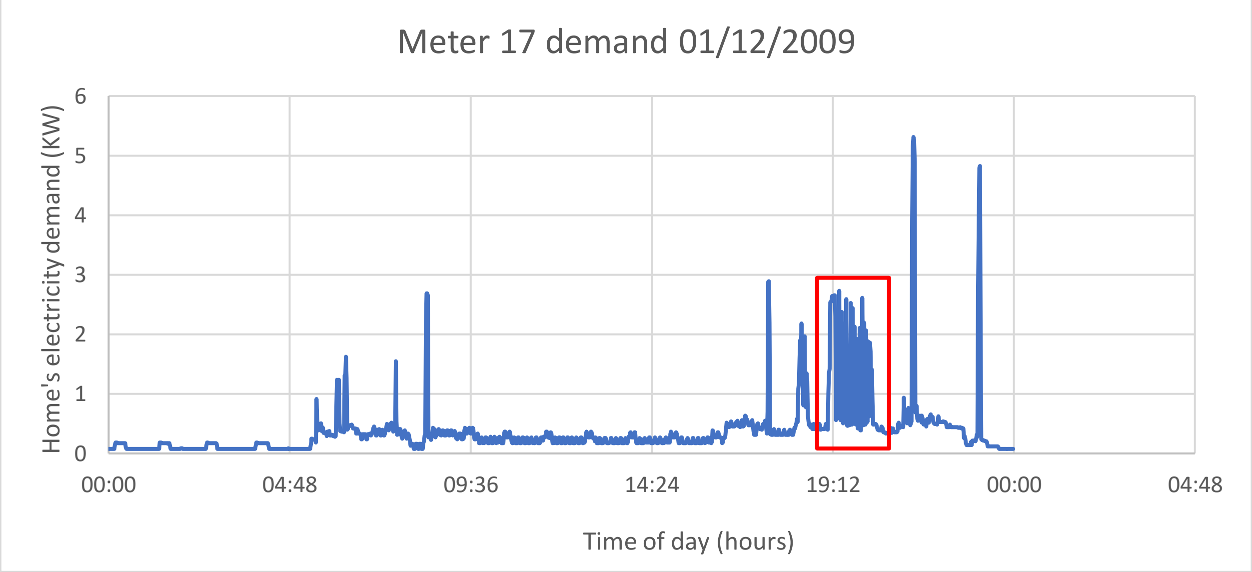


Figure 20: Individual home meter reading for Tuesday 1st of December. Meter 17 from dataset.

Finally, an example of a tumble dryer energy signature was identified from the home meter recordings (#17) and is shown in Figure 20. The tumble dryer energy signature can be seen with the cycle starting at 19:05 and lasting until 20:15. When the tumble dryer is in use there is an identifiable energy signature (highlighted by the red box) resulting in the home's demand alternating between 2000 watts and 200 (on top of the base load) lasting 70 minutes.

Having demonstrated an ability to identify distinctive energy signatures that correspond to specific appliances, it is possible to shift these energy loads for the purposes of better load management. This will be further explored in the latter part of this thesis.

4.2 Optimised management of domestic energy load for economy 7 tariff

4.2.1 Section introduction

Currently in the UK, the most notable demand response program for domestic housing is the economy 7 tariff. This program aims to reduce UK evening demand peaks by incentivising occupants to use high energy appliances in the hours after midnight through reduced electricity pricing. However, the overall national participation is underwhelming as seen in figure 8. As this is the demand response program currently in place and as a proof of principle, here previously identified energy signatures will be shifted to the time period covered by the economy 7 tariff in order to optimise energy load management.

4.2.2 Shifting washing machine energy loads

In the previous section, distinctive energy signatures that corresponded to washing machine usage were identified from individual home meter readings (Figures 16 and 17). The average energy consumption of washing machine use (2,000 W) was subtracted from the identified spike and this load was then moved into the time period covered by the economy 7 tariff. The energy appliance energy loads, when found in individual homes, were spread evenly over the economy 7 tariff time slot. This was done with the aims of reducing the daytime peaks while avoiding making a new early morning peak.

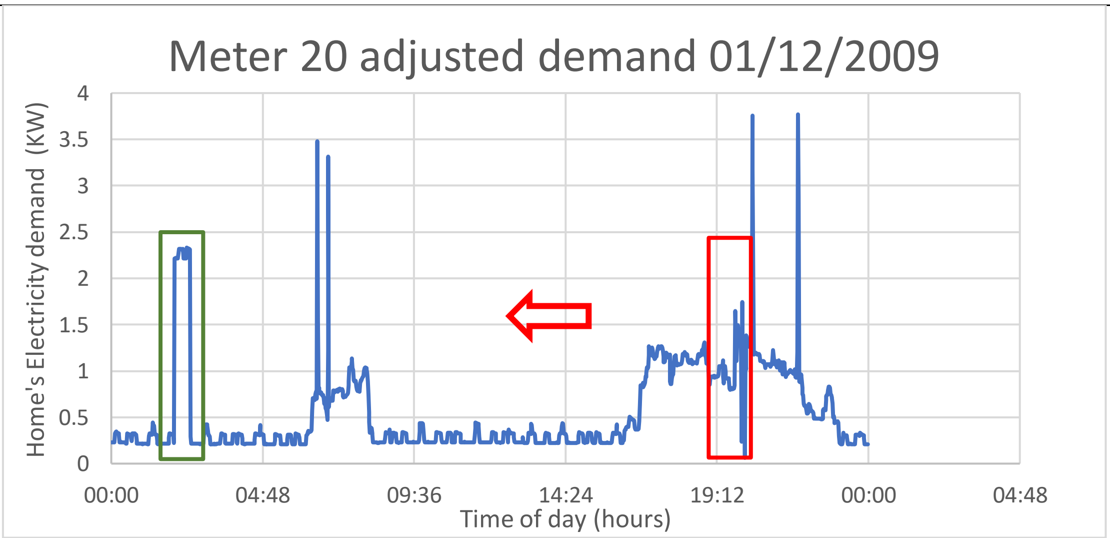


Figure 21: Individual home meter reading for Tuesday 1st of December after washing machine load shift has been applied. Meter 20 from dataset.

As shown in the example highlighted in Figure 21, shifting the predicted washing machine energy load identified in Figure 16 to the early morning reduces the home's evening spike peak from 3700 watts to 1700 watts. The energy load shift can be seen on figure 21 by the red box shoing the loads orignial location to the green box where the load has been shifted. Importantly, increased washing machine usage in the early morning instead of during peak demand in the evening would result in lower energy bills for the home occupants. Together, these examples demonstrate how load shifting can be applied to help better manage demand in accordance with the current economy 7 tariff.

4.2.3 Shifting dish washer energy loads

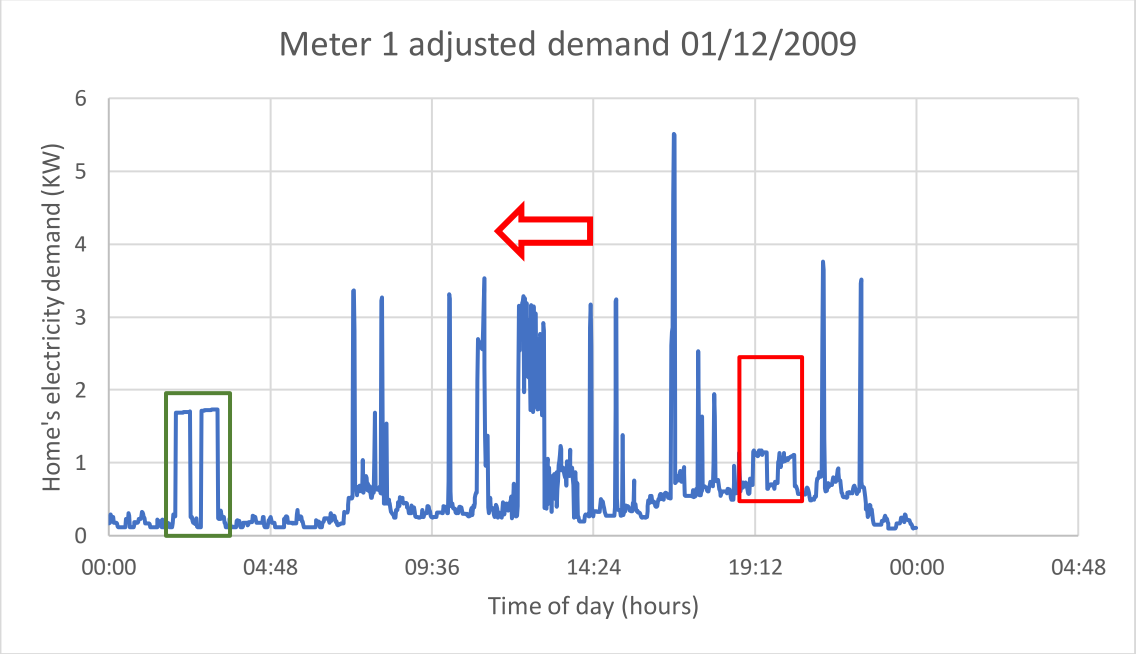


Figure 22: Individual home meter reading for Tuesday 1st of December after dishwasher load shift has been applied. Meter 1 from dataset.

In a similar manner to the previous section, energy loads corresponding to dish washer energy signatures were shifted from the evening during peak demand to the early hours of the morning. As shown in the example highlighted in Figure 22, both dishwasher cycles are moved to the early morning starting at 02:00. The shift has resulted in a reduction of energy between 19:09 until 20:23 and increased the energy usage in the early morning utilising the economy 7 tariff. Again, if this shift was maintained regularly, this would result in lower energy bills for the home occupants and reduced demand at peak times. It was noted that shifting the 1,600 watts from the identified dishwasher energy signature did not completely remove the two spikes occurring at 19:09 and 19:53. This may be due to the households dishwasher having a lower energy efficency rating than the appliance average. However, even if this represents an underestimate of the true energy load in this case, there was still significant improved load management.

4.2.4 Shifting tumble dryer energy loads

Finally, energy signatures corresponding to tumble dryer usage during evening were shifted to the early morning to ease peak demand. As shown in Figure 23:

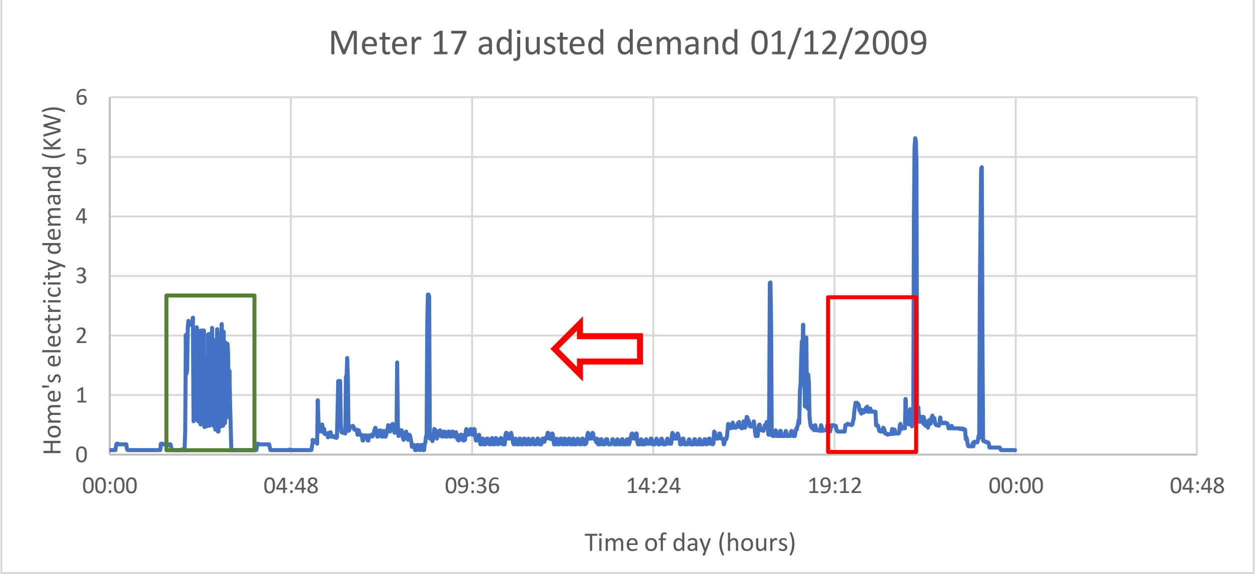


Figure 23: Individual home meter reading for Tuesday 1st of December after tumble dryer load shift has been applied. Meter 17 from dataset.

The shift resulted in a peak reduction at 19:19 reducing the watts from 2900 watts to 900 watts. The tumble dry energy load was shifted to 02:00 where the peak energy usage increased from 78 watts to 2078 watts.

4.2.5 Projected effect on appliance shifting on weekday demand

This section aims to show the results of the energy load management strategy outlined above on average weekday (Tuesday) demand. This strategy assumes possessing full control of the 3 types of washing appliances across all 12 surveyed houses. The effects of collectively shifting all their loads the early morning, low demand periods on average demand were then explored.

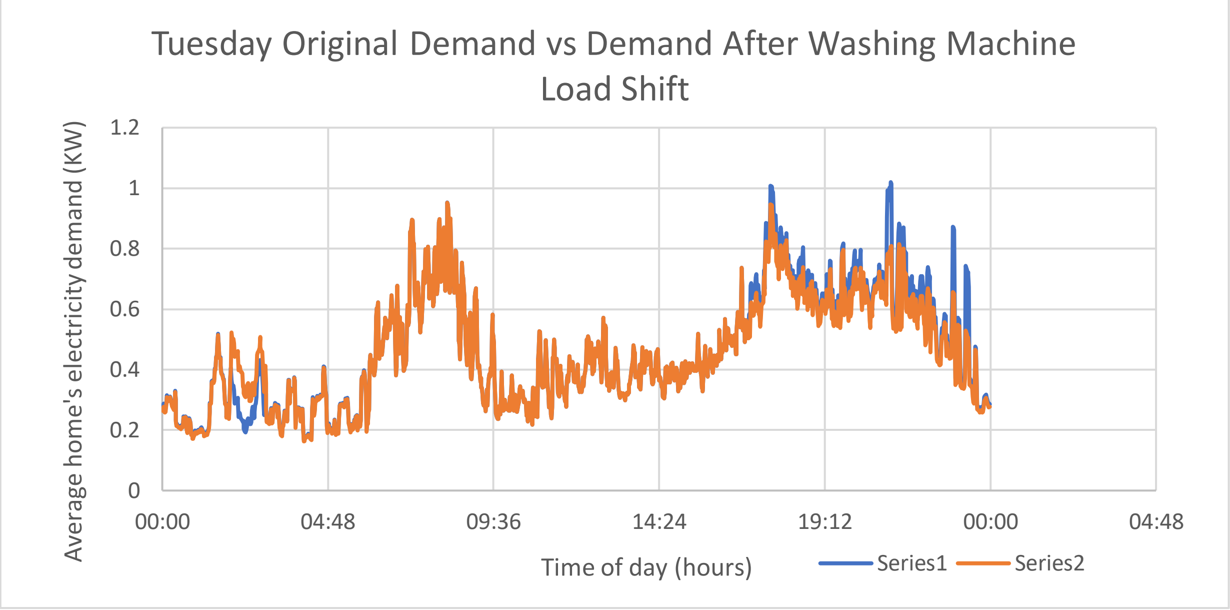


Figure 24: showing the original Tuesday demand average (series 1) and the demand average after washing machine evening loads have been shifted to the morning (series 2).

Firstly, six out of the predicted eight washing machine energy signatures were located and shifted to between 02:00 – 03:00. Figure 24 shows the the average demand of the 12 surveyed homes after any washing machine appliance usage that occurs during the evening peak is shifted to the early morning and Figure 24 shows a before and after comparison. As expected, the average evening demand is reduced whereas the average demand in the early morning between 02:00 and 03:00 is increased. The largest reduction after energy load shifting can be seen at the 21:00 evening peak from 1010 watts to 870 watts. The evening electrical demand average beteween 17:00 and 22:00 reduces from 707 watts to 660 watts. Additionally, the average demand in the early morning (01:00 – 04:00) increases from 285 watts before energy load shifting to 319 watts after. This represents a successful easing of peak demand and better utilisation of the economy 7 tariff.

After successful shifting of the washing machine loads, the dishwasher appliance loads were also shifted on top of the already augmented demand. In the 12 surveyed homes 5 of the 8 predicted dishwasher energy signatures were identified in the evening and shifted. As a result of dishwasher shifting the largest energy peak average during the evening was reduced from 940 watts to 890 watts and the average evening energy usage dropped from 665 watts to 653 watts after dishwasher appliance load shifts.

From the data of the 12 surveyed houses, 0 of the 4 predicted tumble dryer energy signatures were identified. Therefore, no tumble dryer loads could be shifted from the average Tuesday evening peak demand.

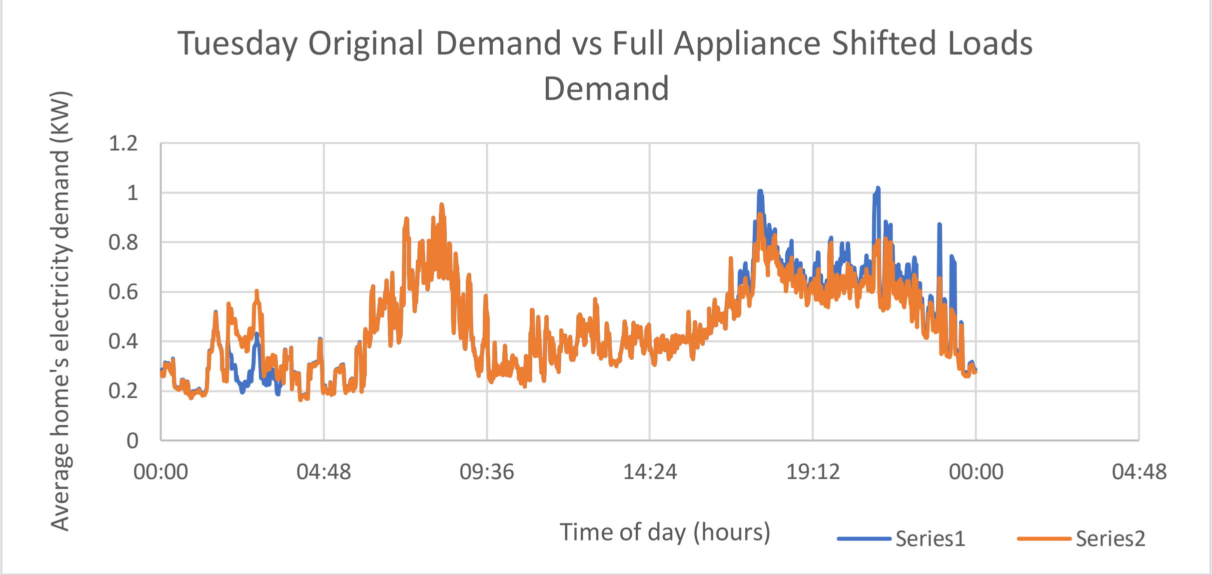


Figure 25: showing the Tuesday demand average (series 1) and the demand average after dishwasher evening loads have been shifted to the morning (series 2).

Figure 27 shows the fully optimised average demand compared to the original pre-shifted average demand. The all identified appliances had been collectively shifted, the two largest average evening peaks had been reduced. The first peaks lasting 6 minutes (17:37 – 17:43) was reduced from 1,005 watts to 890 watts and the second dominant evening average peaks lasting 7 minutes (21:02 -20:09) was reduced from 1,010 watts to 790 watts. In total, the whole evening average was reduced from 643 watts to 590 watts. Correspondingly, the early morning period in which the appliances were shifted to (i.e. to comply with the economy 7 tariff) increased its average energy usage from 285 watts to 350 watts. In summary, energy load management had been successfully applied to the average December Tuesday by shifting washing appliances use to the economy 7 tariff.

4.2.6 Projected effect on appliance shifting on weekend demand

Since weekday and weekend energy consumption are very different, the results of the energy load management strategy outlined above on an average Sunday were determined as a comparison. As in the previous section, this strategy assumes possessing full control of the 3 types of washing appliances across all 12 surveyed houses. The effects of collectively shifting all of their loads the early morning, low demand periods on average demand were then explored.

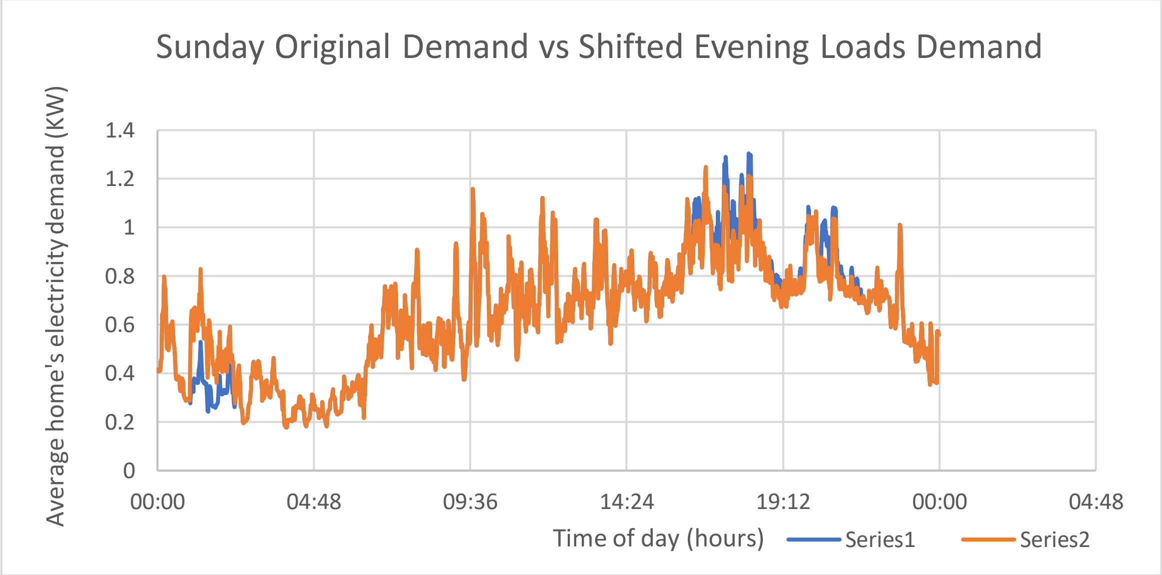


Figure 26: showing the Sunday demand average (series 1) and the demand average after washing appliances evening loads have been shifted to the morning (series 2).

For washing machines, 11 out of the 15 predicted energy signatures were identified in the evening and shifted to the morning. For clarity this was 15 load shifts in the 12 surveyed homes over all 4 Sundays in December. For the dishwasher 4 out of the 8 predicted energy signatures were identified in the evening and shifted to the morning. For the tumble dryer appliance 4 out of the 4 predicted energy signatures were identified in the evening and shifted to the morning. Together, as a result of shifting all these loads, the two largest average evening peaks were reduced (Figure 26). The first peak lasting 6 minutes (17:37 – 17:43) was reduced from 1,005 watts to 890 watts and the second dominant evening average peak lasting 7 minutes (21:02 - 20:09) was reduced from 1,010 watts to 790 watts. In total, the whole evening average was reduced from 643 watts to 590 watts. This was balanced by an increase in average demand during the early morning. In summary, energy load management had been successfully applied to the average December Sunday in by shifting washing appliance use to the economy 7 tariff.

The magnitude of the reduction is not significant enough to flatten the peak but that was not expected when only shifting three high energy consuming but relatively low usage appliances. Sunday experienced the smallest impact from the effect of load shifts on reducing the evening peak average. This is in spite of the fact that Sunday had the highest number of appliances removed. This suggests that Sunday features a higher diversity of appliance usage and a greater number of appliances are required to be enrolled in the strategy to make a significant difference.

In contrast, the low number of appliances shifts on Tuesday were able to lower the evening peak below the morning peak.

4.2.7 Section Summary

The results gained in this section demonstrate the effect that the selected appliance shifts have on both weekday and weekend peak demand and validate this technique as a means to better utilise the economy 7 tariff. However, ultimately this approach assumes universal cooperation and participation in the program, which is unfortunately unrealistic. An attempt to counter this aspect by shifting the loads evenly between the 01:00 and 03:00 so simulate a more relaxed participation.

Nevertheless, as a concept, this strategy illustrates how applying energy load management within individual homes can substantially ease peak collective energy demand. Furthermore, as this method has focussed on shifting the loads of only three washing appliances, it is likely that there is scope for further management.

In this section, energy load management has been optimised to fit with the current demand response program deployed in the UK, the economy 7 tariff. However, in the following sections, optimal load management will be explored in the context of a hypothetical, future, renewable dominant grid.

4.3 Predicting Energy Demand in a Future, renewable Dominant Grid

4.3.1 Section introduction

When considering the future grid, a large number of assumptions must be made. Therefore, the approach adopted in this thesis has been to analyse the current grid for characterisitics that can give clues to the influences of a future grid. Furthermore, the undoubted trend is for the continued adoption of renewable energy sources. For these reasons, national pumped hydro generation and wind generation was analysed for the insight they could provide. The results presented in this section will not supply a full comprehensive process of energy load management. Instead, this section aims to demonstrate the techniques that might be applied to optimise load management in such a future grid.

4.3.2 contribution of pumped hydro and wind power to grid

Wind turbines are assumed to be the predominant renewable energy generator of the future and will be analysed for its stochastic characteristics in the current grid. In contrast, pumped hydro is mostly used as a buffer providing insight into periods in which backup energy is required in the current grid.

Current pumped hydro and wind generation supply over the month of December 2019 are shown in Figures 27-31. Datasets on Pumped hydro generation supply and wind generation supply to the national grid were provded by G.B. National Grid Status (Data courtesy of Elexon portal and Sheffield University).

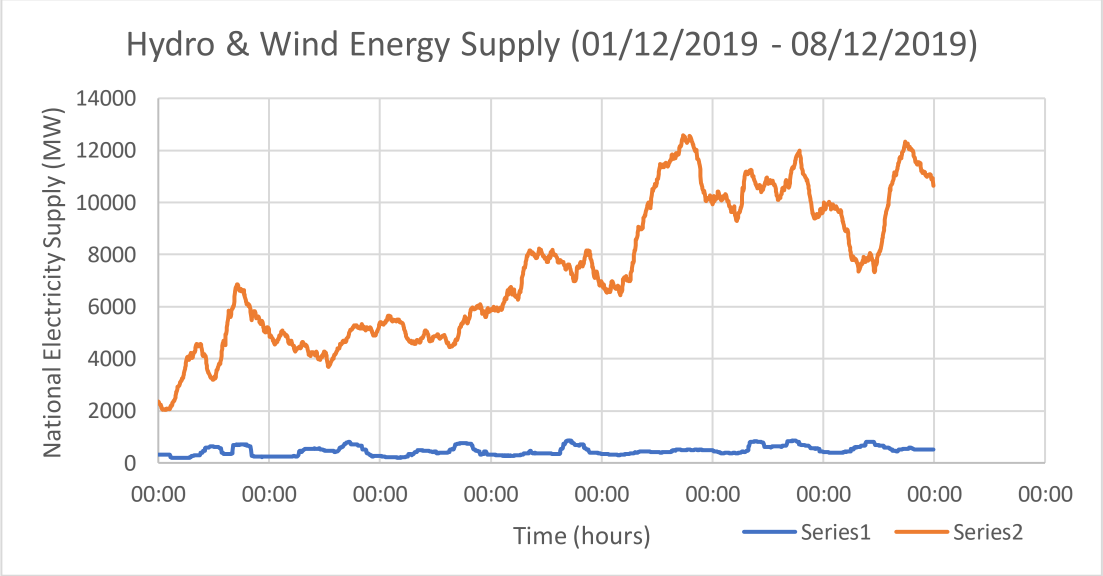


Figure 27 shows pumped hydro (series 1) and wind (series 2) contribution to the national energy supply between 01/12/2019 and 08/12/2019. Dataset provide by G.B. Natioanl Grid Status.

Figure 27 shows the weekd beginging with relatively low wind supply which eicreases towards the end of the week. A comprehensive demand system would benefit from occuants being insentivised to use there appliances later in the week if possible. The first 4 days show back up required during evening peak demand peroids therefore, the economy 7 tariff would aid the electric grid balance on these days.

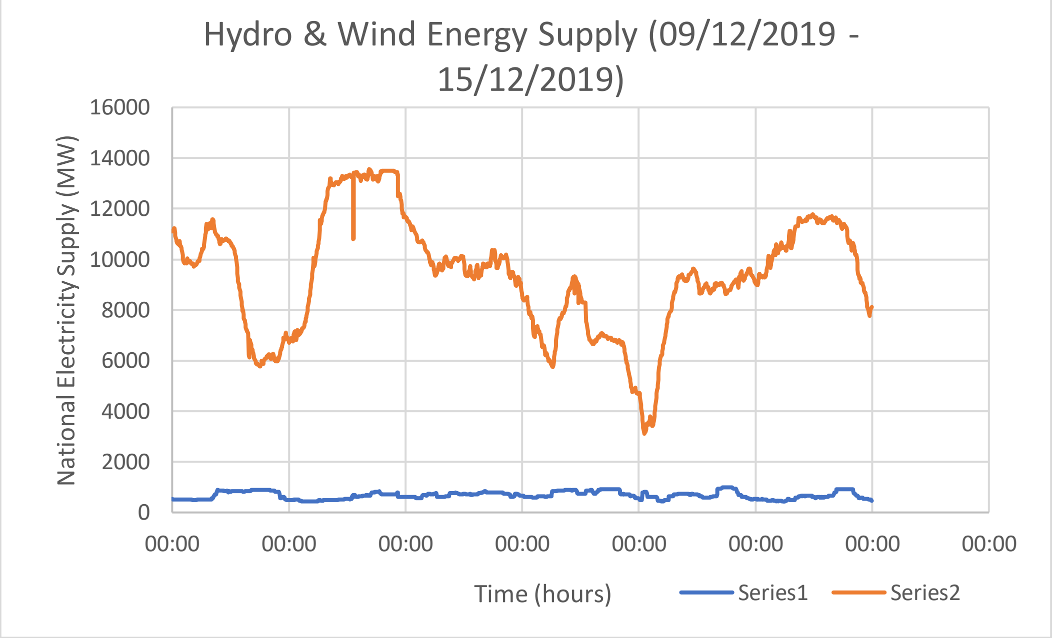


Figure 28 shows pumped hydro (series 1) and wind (series 2) contribution to the national energy supply between 09/12/2019 and 015/12/2019. Dataset provide by G.B. Natioanl Grid Status.

Figure 28 shows that the contribution from wind fluctuates between 2,000 megawatts and 8,000 megawatts for the first 4 days before experiencing a spike of increased wind energy reaching peaks above 12000 megawatts over the last 3 days. For the first 4 days pumped hydro reserves are required for the evening peak. During the days of high wind hydro peaks are less consistent. On the 9th, wind energy experiences generation highs of above 11,000 megawatts, after midday the production decreases to 6,000 megawatts at which point larger pumped hydo generation reserves are required to meet demand (Figure 30).

On the 13th and 14th, pumped hydro backups are required during the evening peak (Figure 30). It should be noted that these mentioned days would benifit from the current economy 7 tariff energy load management strategy for reducing the evening peak.

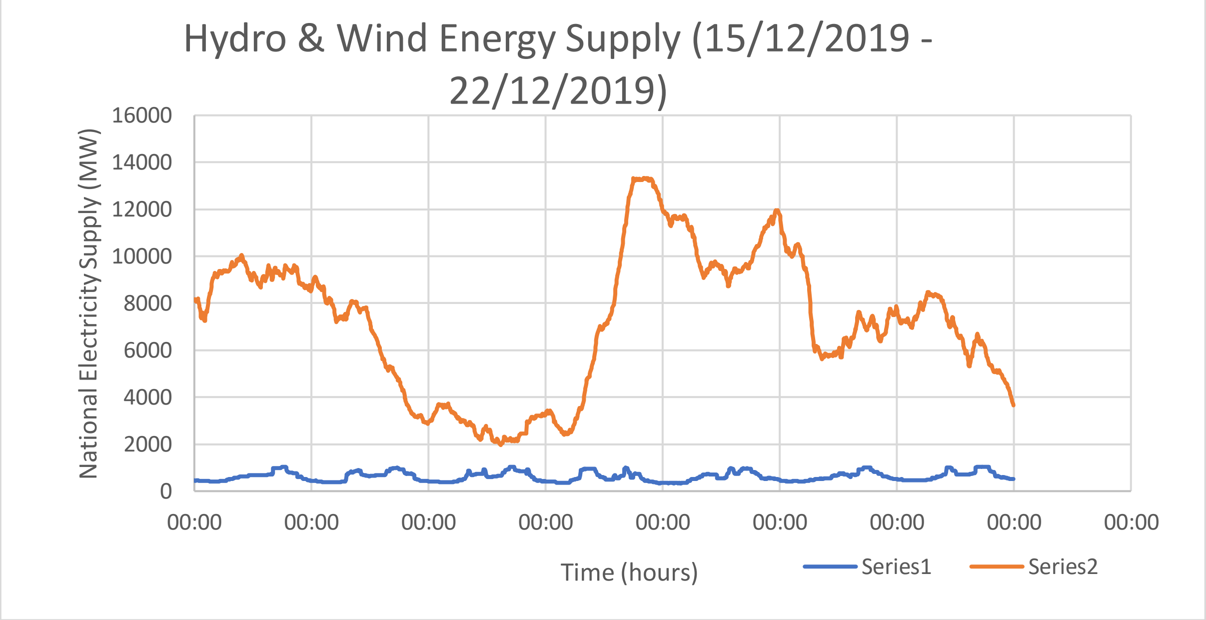


Figure 29 shows pumped hydro (series 1) and wind (series 2) contribution to the national energy supply between 15/12/2019 and 22/12/2019. Dataset provide by G.B. Natioanl Grid Status.

From the 18th to the 20th, these days experience low wind generation followed by days of high generation (Figure 29). This situation would require more complex demand mangement involving a week long strategy applying most appliance loads at the end of the week, which would be difficult to achieve solely through the current economy 7 tariff.

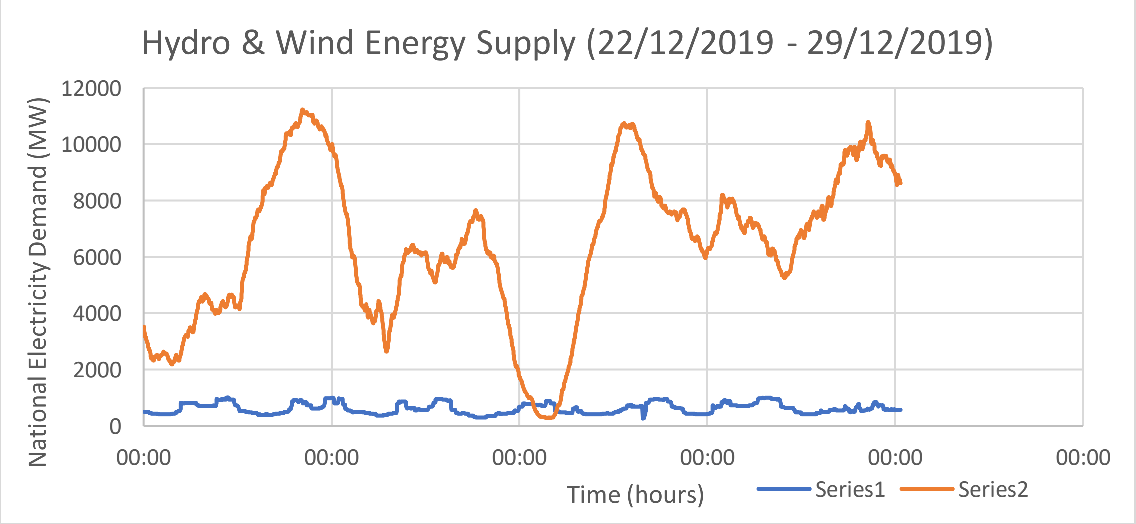


Figure 30 shows pumped hydro (series 1) and wind (series 2) contribution to the national energy supply between 22/12/2019 and 29/12/2019. Dataset provide by G.B. Natioanl Grid Status.

The energy strategy for this week would aim to apply appliance loads at the end of the 22nd or the end of the week, avoiding the wind energy generation low occuring during the early morning of the 24th. This is an example of where the renewable tariff policies will differ greatly from the current economy 7 tariff. On the 24th, appliances would preferably be applied during the evening peak demands avoiding shifts to the early morning (Figure 30). This weeks strategy would aim to maximise appliance usage at the beginnig of the week avoiding the end of the month.

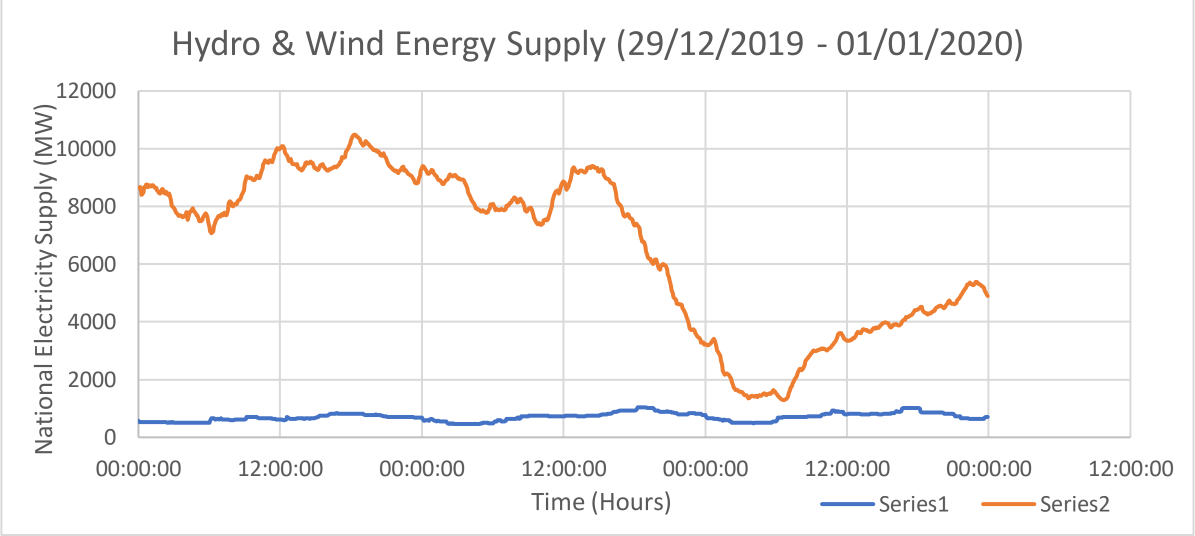


Figure 31 shows pumped hydro (series 1) and wind (series 2) contribution to the national energy supply between 29/12/2019 and 01/01/2020. Dataset provide by G.B. Natioanl Grid Status.

Between the 29th and the 1st a prefeable demand program would insentivise consumers to use appliances at the beginning of this period. On the 31st the economy 7 tariff participation would be disruptive.

The data shown in Figures 27-31 are limited due to the fact what the data shown only includes energy generation that is used by the grid. It does not give any indications to when wind turbines are shut down due to oversupply and when pumped hydro is reversed with the aims of consuming energy.

To counter this wind turbine oversupply limitation wind speed data was gathered over the same month (December 2019) and compared to give clues to when oversupply may be occuring. Wind speed figures were analysed to give a hint as to the amount of total wind energy generated with the aim of predicting periods of oversupply.

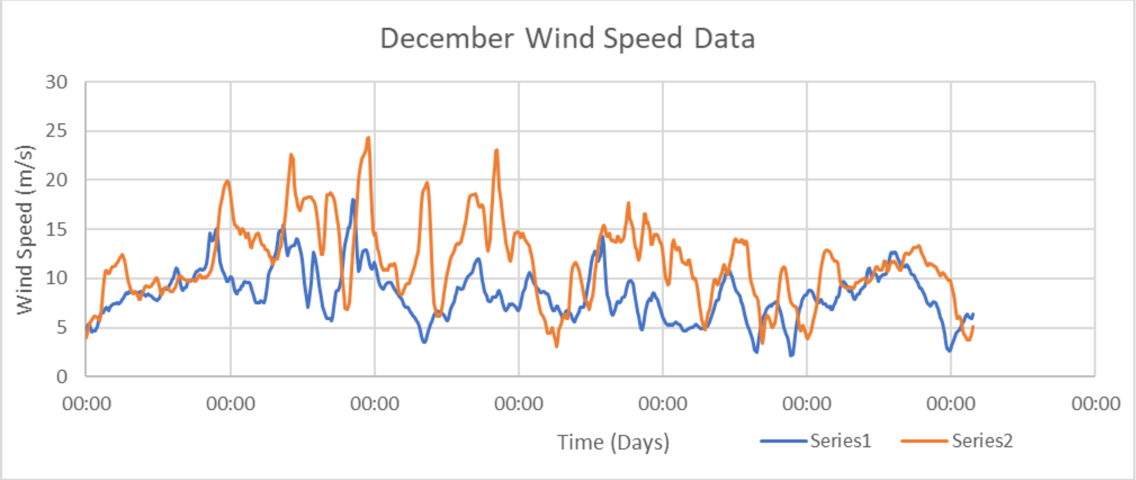


Figure 32 shows December 2019 wind profile provided by MERRA-2 (global) Data set, series 1 shows wind speeds at whitlee wind farm, series 2 shows wind speeds at dogger bank.

Between each 00:00 on the horizontal axis there is a 5 day period. Figure 32 shows both the wind speeds at Whitelee wind farm (the UK's largest onshore wind farm) and the wind speeds at Dogger bank in the north sea. Dogger bank aims to be the site of the largest offshore wind farm in the world and therefore, will have a large impact on the future renewable grid. Dogger bank experiences larger wind speeds but follows a very similar trend to Whitelee with about an 8 hour delay between the peaks of the two series. This suggest that despite being a singular coordinate of wind data, Whitlee wind farm can be used loosley as a reference point for UK wind turbine data.

The Whitlee wind farm data were used to cross analyse the national electrical wind supply data with the aim of idenfying the periods of wind oversupply. The first significant peak occured on 05/12/2019 lasting from 06:00 to 12:00. The wind speed experienced by the turbines were between 13.5 m/s and 15 m/s which is above rated speed for the standard onshore UK turbine. This means that most turbines experiencing the same wind speeds during this period would have been generating electricity at full capacity.

Figure 32 reflects this high wind generation however, despite this wind energy supply peak occuring during the morning demand no additional pumped hydro generation is required. This could suggest that this is a period of oversupply in which wind turbines are required to be curtailed. With the assumption that the previous statement is correct this would be an ideal senario to apply energy load management. A renewable orientated tariff or energy service controlled automated applainces would be shifted to this period.

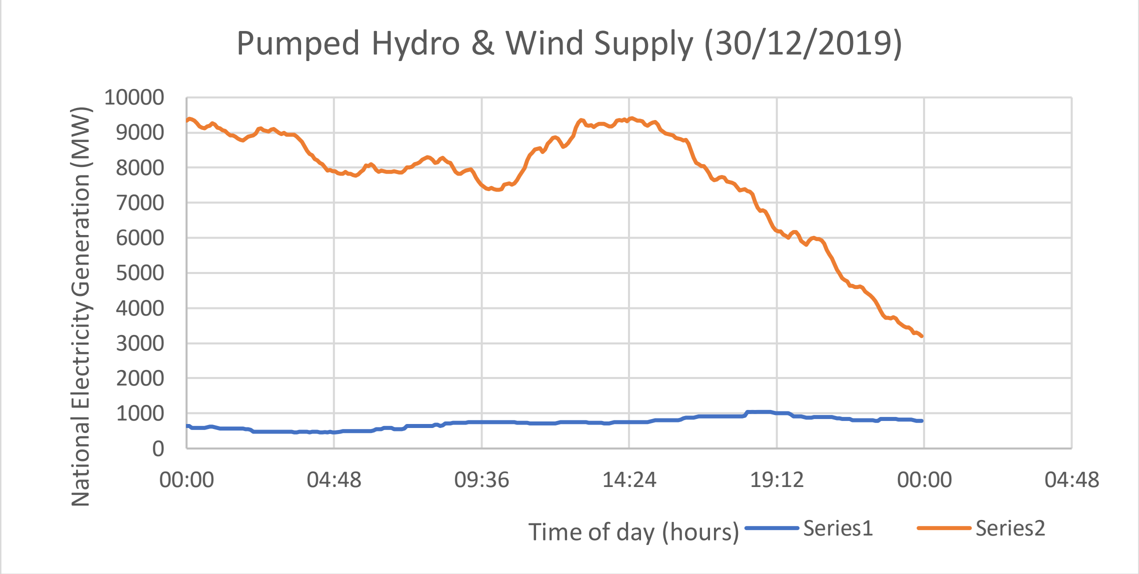


Figure 33 shows pumped hydro (series 1) and wind (series 2) contribution to the national energy supply on Tuesday the 30th of December 2019. Dataset provide by G.B. Natioanl Grid Status.

In figure 33 which highlights a singular day seen on in figure 31 showing the energy generation of pumped hydro and wind energy on the day 30/12/2019. The data of interest is the period between 04:00 and 06:00 which show a high level of wind production occurring early in the morning and low generation from the pumped hydro. When comparing the wind production to the daily energy demand the results can be seen in figure 34.

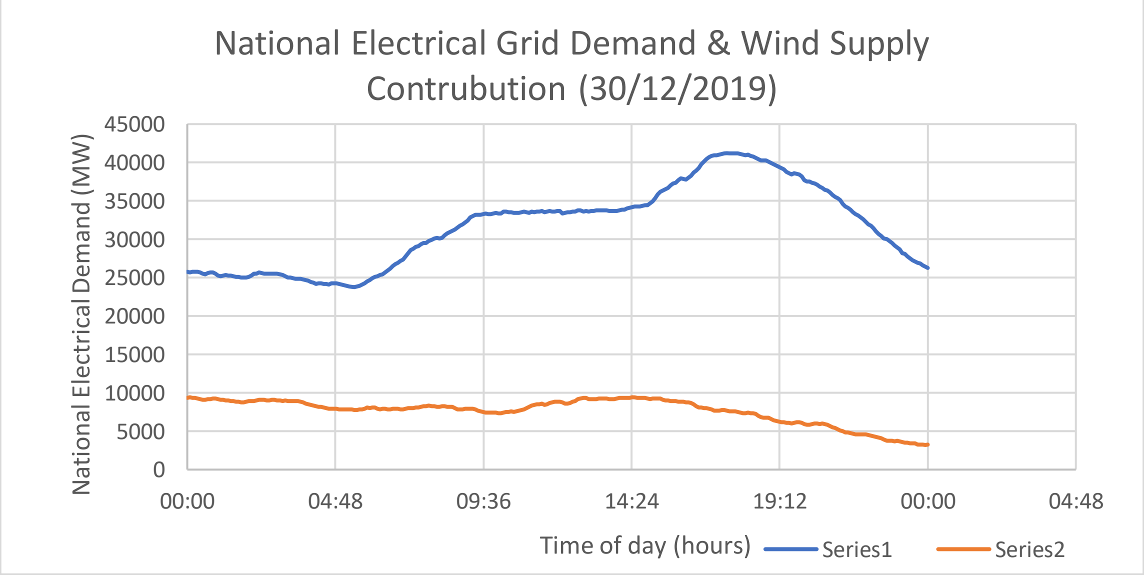


Figure 34: National demand (series 1) and wind supply contrubution (series 2).

Figure 34 shows the national UK demand in series 1 and the wind generation supply to the electric grid. Continuing from the previous figure the period of interest is between 04:00 and 06:00. During this period demand is at its lowest point during the day. However, in comparison the contribution from wind stays relatively level.

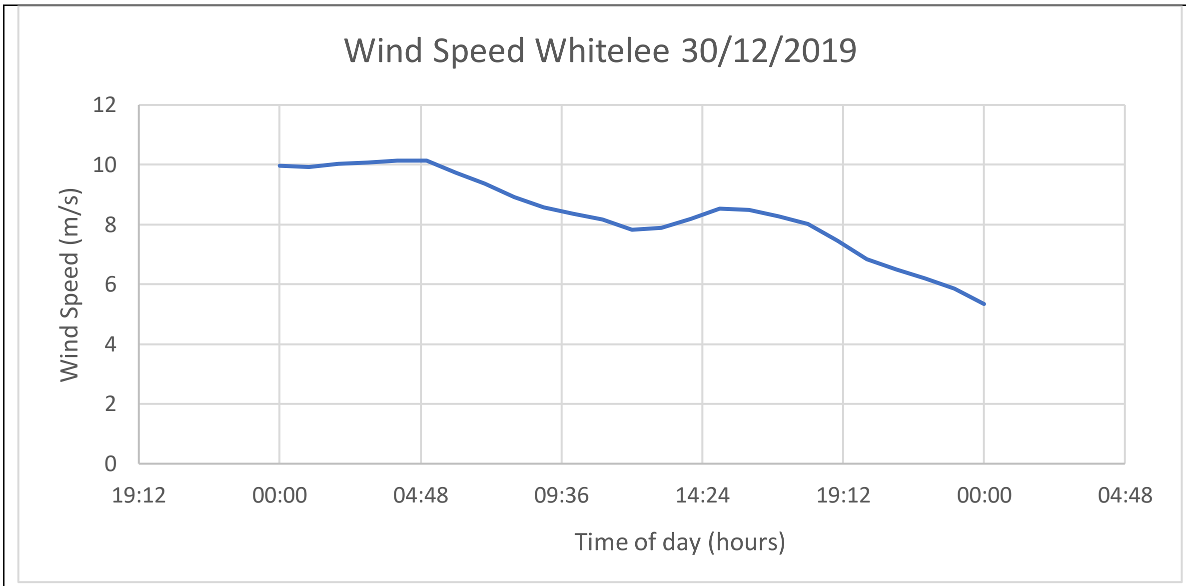


Figure 35. wind speed m/s experiences by a turbine at whitelee wind farm.

Figure 35 shows the wind speed on the same day. During the period of interest (04:00 – 06:00) wind speeds are reaching its highest point of the day at 10.1 m/s, just short of the standard turbine rated speed. throughout the rest of the day the wind speed declines. However, this decline in wind speed in not seen in the energy generation trend seen in figure 34. Therefore, the conclusion that can be drawn from figures 33 – 35 is that during the period of interest, wind turbines are required to be turned off due to low demand vs high energy supply.

The period between 04:00 and 06:00 is a perfect time to apply energy load management through appliance load shifts into this period.

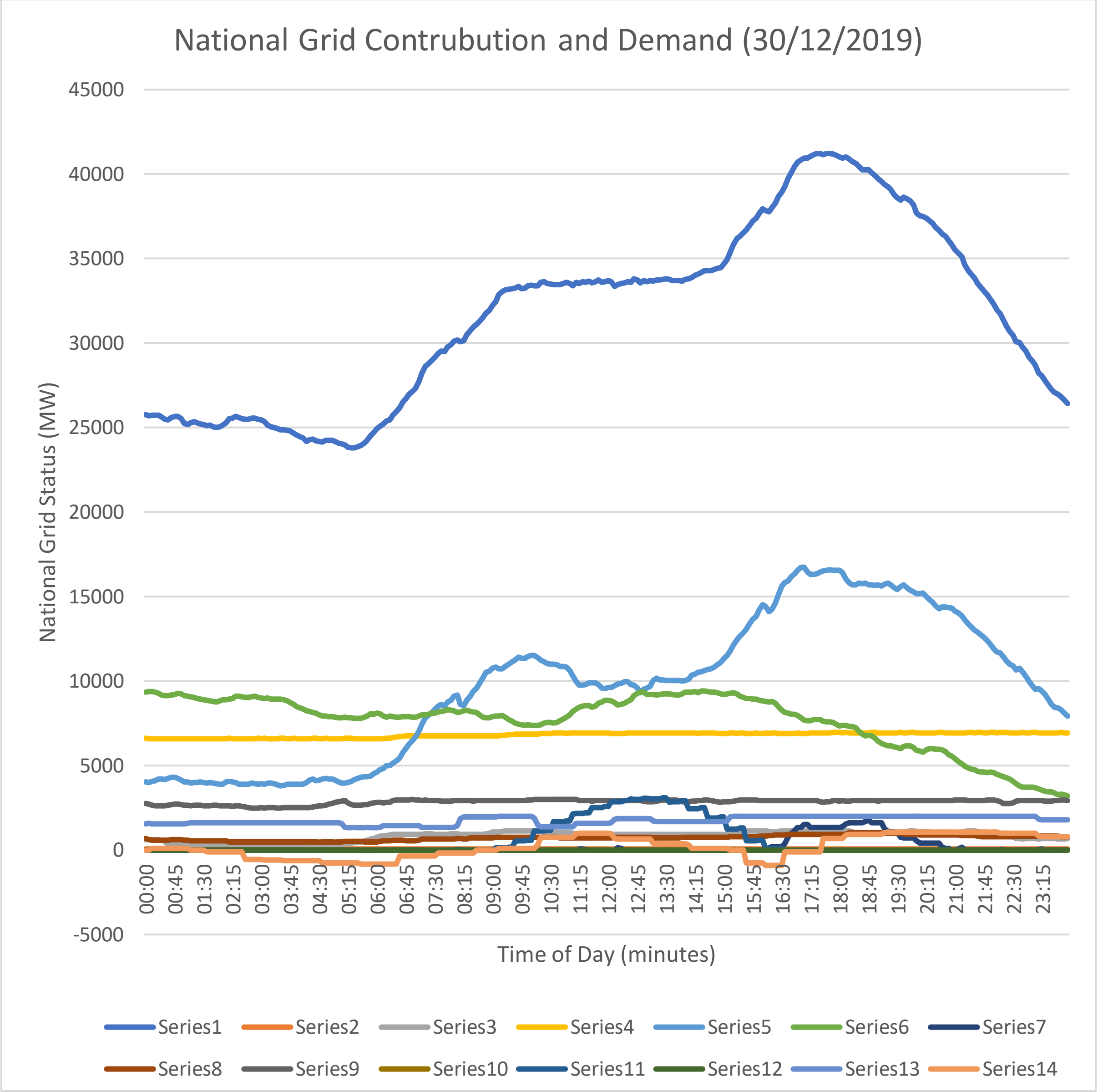


Figure 36: showing the national grids status on Tuesday the 30th of December 2019. Dataset provide by G.B. Natioanl Grid Status.

Series 1 = national demand, series 2 = grid frequency, series 3 = coal generation, series 4 = nuclear generation, series 5 = CCGT generation, series 6 = wind genration, series 7 = pumped hydro demand, series 8 = pumped hydro generation, series 9 = Biomass generation, series 10 = oil generation, series 11 = solar generation, series 12 = OCGT generation*, series 13 = French interconection, and series 14 = dutch interconection.

*OCGT generation refers to Open Cycle Gas Turbine which is another mode of gas powered back up generation.

Figure 36 is added for higher clarity and transparency of the national grid generation and demand results. The data shows the 3 main contributors being CCGT, nuclear, and wind. CCGT follows the trend of the demand which was expected due to the energy sources dispatchability. Nuclear provides a constant energy supply which was also expected of the fuel source. Figure 6's data does not show any data that conflicts with the prediction that wind oversupply occurs at 04:00. This data strengthens the claim as during the period between 04:00 and 06:00 there is 0 MW OCGT back-up energy supply, the Imported energy to France decreased by 277 MW and the exported energy to The Netherlands increases by 214 MW.

4.3.3 Section Summary

This section explored the current grid's renewable energy generation challenges by analysing wind power's periods of over and under supply. A period of wind oversupply was identified from the data. Despite the analysis being carried out on the current grid, the here aim was to highlight future challenges. The current grid is capable of handling the energy fluctuations resulting from wind energy. However, as the wind energy sector expands these fluctuations (particularly wind oversupply) will become more extreme. It is for this reason that demand management will become an even more important tool in maintaining stability to the energy grid's frequency.

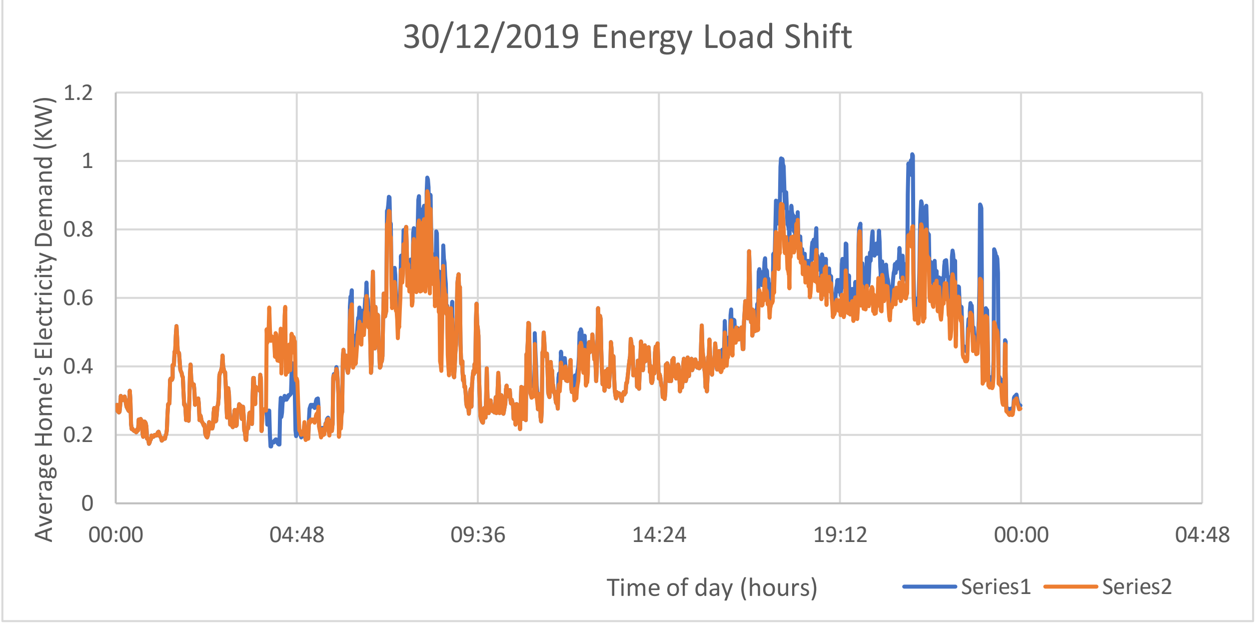
4.4 Optimised domestic energy load management for a future, renewable dominant grid

4.4.1 Section Introduction

In section 4.2, energy load management for three washing appliances was applied to help better utilise the current demand response program (economy 7 tariff). In section 4.3, the supply challenges of a renewable dominant grid were explored. Here, the outcomes of these two sections are combined to help devise a strategy for effective energy load management of a future renewable dominant grid. As before, this strategy assumes full control of the 3 washing appliances. It was explored how shifting the energy loads of these 3 washing appliances might aid stabilisation of a renewable grid, where energy supply is inherently variable.

4.4.2 Energy load management of a renewable dominant grid

In order to explore how energy shifting of 3 washing appliances could help the manage the demand in a renewable dominant grid, a single Tuesday in December was sought to serve as an example and a proof of concept. After analysing the pumped hydro, wind supply, and UK demand for Tuesdays in December in the previous sections, it was concluded that there was a period of oversupply occurring at 04:00 on Tuesday 30th of December 2019. As the following analysis was conducted on the supply and demand from this single day, any broad interpretation is limited. Instead, the chief interest was in validating this energy load management strategy as a successful strategy.



37: showing original Tuesday demand aversge (series 1) and demand average after appliance shifts to period of predicted wind over supply (series 2).

Figure 38 shows the daily average demand of Tuesday (30/12/2019) after all 3 washing appliance loads are shifted between 04:00 and 06:00 with the aim of aiding wind oversupply. Series 1 shows the original demand and series 2 shows the demand after energy load management is applied in accordance with the energy supply conditions of 30/12/2019. This resulted in and average increase between 04:00 and 05:30 (tumble dryer cycles lasting 1.5 hours) from 249 watts to 354 watts. This is a 42% increase on the domestic housing demand average during this period.

The most significant increase can be seen at 4:04 increasing from 170 watts in the original demand to 570 watts in the shifted demand. By shifting all the available appliances to one period we were able to create a new average energy demand spike which has a peak demand volume that is 57% of the days highest demand peak.

Domestic housing contributes 29% of the national demand. The resulting increase (42%) to the domestic demand average during the period of 04:00 to 06:00, if carried out nationally, would result in a 12% national grid increase. On the 30th of December 2019, the demand average during the period of 04:00 to 06:00 was 24177.4 MW. Therefore, if the program were developed and participated at a national level, the national grid would receive an average demand increase of

2956.6 MW between the period of 04:00 and 06:00. This demand increase would prevent up to 1285 2.3 MW wind turbines being curtailed.

Wind energy Curtailment is equal to 9.45% of total wind energy production, which corresponds to 4484.6 MWh/year.[55] The 3 washing appliances analysed in this thesis combined are responsible of a household mean of 8.4 KWh per week (437 KWh per year). This means theoretically it would require a minimum of 10262 out of 22.6 million UK homes to enrol in full cooperation to satisfy the wind oversupply issue using the load shifting of these 3 appliances. With the ability of full energy load management of these appliances there is mobile demand of 189 GWh per week across the whole UK.

Ultimately, this example demonstrates that energy load shifting can be successfully applied to aid oversupply arising from a renewable dominant grid.

5 DISCUSSION

5.1 Identifying Energy Loads.

The results use here, show an effective strategy of identifying appliance energy signatures using only a couple of parameters that were established. These appliances could be identified because of their high demand characteristics. With increased data and time, the same strategy could be applied to identify a large volume of appliance this would result in an increased energy load management potential in the domestic home. This results section was successful at completing its aims allowing further analysis to be carried out and demonstrating proof of the examined concept.

5.2 Appliance Load Shifting for Economy 7 Tariff

Having successfully identified high demand appliances through their energy signatures, this thesis next explored the ability to analysed the ability to shift the identified appliance energy loads into an early morning period. The results highlight that the strategy undertaken is a useful tool for energy load management. The strategy carried out utilised an already existing demand response program that is developed to aid the UK's current grid's economy 7 tariff.

The results show the that the presented method can have a positive effect on reducing the daily domestic demand peaks benefiting the national grid and the consumer. The limitations of the results are in some ways reflective of the limitations of the economy 7 tariff. For example, the purpose of the tariff is solely to reduce daily demand peaks and offers limited flexibility that is likely to be required by a more complex renewable grid. Additionally, to feasibly achieve the results automation will be required in order to insure reliability and consistency of participation.

5.3 Future Renewable Grid

The aims of this results section were to identify and analyse the challenges of the future renewable grid. The results used the characteristics of the current grid and the influential features renewable generation holds. The results showed the ability to identify energy signatures in meter readings. The results also gave insight to the impact on the average peak demand that their appliances can have after being shifted to a different period. Finally, the results showed the ability to identify periods of wind oversupply and shift energy loads into the same period to aid the issue.

The results were limited by the assumptions that are required when predicting the future, potentially leading to errors of accuracy. This limitation was mitigated by using current grid data to extrapolate the future challenges through a method of exaggeration. Additionally, the results were limited by the lack of data available for wind turbine curtailment periods. This meant that the predicted period of wind oversupply could not be verified and prevented further calculations of the magnitude of the energy generated during wind over supply.

However, when considering the future grid featuring expanded wind energy penetration, the likeliness and magnitude of wind oversupply statistically increase. With the assumption the predicted period is correct, this allowed the energy load management strategy to be applied as an example of the method.

Wind oversupply is a major challenge of the future renewable grid. The results offer a method of tackling the challenge in a cost-effective manner. Alternative solutions are: wind turbine curtailment, large-scale electrical storage, or increasing the national grid's exportable capacity with increased cable infrastructure. Each of these alternatives are very costly solutions in comparison to developing demand management policy and strategies. These alternatives discount the continuation of fossil fuel powered back-up generation as this solution does not meet the conditions of a renewable grid.

5.4 Appliance Shifting for the Renewable Grid

Finally, this thesis successfully demonstrated the strategies ability to apply energy load management in accordance to the needs of a renewable electric grid. The resulting calculations highlight the benefits of a strategy that utilises a small variety of switchable appliances. These results imply that by introducing a larger variety of domestic appliances into the strategy the benefiting effects will increase. More appliances can be introduced through larger understanding of domestic demand patterns and increased data supplying faster meter recordings, increased internet connectivity telling you what is turned on. The results supply a valuable method which can play an important role in stabilising a renewable grid.

5.5 Concluding Remarks

The results presented here establish the capabilities of energy load management of intensive energy consuming appliances. These results demonstrated the benefits and importance of energy load management's role in a renewable grid.

All the energy load shifting achieved in the results section was done on past data. The development of a new demand program would in reality require accurate weather and demand forecasting is vital for its ability to work successfully. Additionally, successful implementation assumes full cooperation, however, this is unlikely as the method will receive resistance through human behaviour as any change in human behavior is generally resisted. This highlights the issue of depending on occupants to voluntarily commit to the programme particularly when appliances are required at inconvenient times. Therefore, to maximise successful and dependable participation automation is essential. Automation would give energy services full control of the appliances allow energy load management to be applied even when the occupants are out of the home.

Realistically, the program is unlikely to receive full participation, the method has not considered the pragmatic impact of the selected appliance on human lifestyle. For example, the program might encounter resistance from occupants who will experience disruption from the noise of the appliance being turned on in the early hours of the morning. These limitations can be overcome though higher variety of domestic appliances involved in the demand management program. Larger availability of appliance in the program allow to cater more closely to the individuals comfort and requirements while maintaining the ability to satisfy the energy shifting requirements. Even without full national participation, the proposed method still supplies a beneficial function to the national grid as it transitions to a renewable grid.

6 FINAL REMARKS

6.1 Conclusion

This thesis supplies an effective strategy of energy load management in the domestic home through a small number of appliances. The UK's current demand management potential is lacking in comparison to other countries, but through applying the simple strategy laid out in the results section of this thesis, demand management can become an active part of national grid stabilisation. The future of the energy grid hosts many challenges which require solutions to provide stability to the national grid. As national energy generation moves forward with renewable targets national grid stability is risked. The energy load management strategy applied in this thesis will supply energy services with cost-effective methods of stabilising a renewable grid.

This conclusion has important implications, such as the potential effect the shift of one appliance load per home can have on the average domestic demand and the increased effects of multiple appliance energy management. The appliances selected in this thesis (the washing machine, the dishwasher, and the tumble dryer) were selected because of their ability to be utilised in a demand management setting. These appliances have great potential to ease the transition for domestic home occupants into an energy considerate lifestyle. The management of these switchable appliances has the potential of being applied across the UK with minimum infrastructure upgrades required as these appliances are flexible and simple timers can be used until internet linked automation provides smoother demand management.

Back-up generation and large energy storage methods require large capital investment and infrastructure construction. Wind turbine curtailments during periods of oversupply is a bottle-neck problem which will only become more costly as wind energy's capacity expands. Energy load management may be a vital solution and the strategy demonstrated in this thesis supplies the early steps for the transition to a renewable UK.

6.2 Limitations of this study

The limitations of this study concerning the data primarily consist of the usage of small data pools. The fact the analysis was carried out on a limited 12 surveyed homes may lead to inaccuracies in the data being representative of the national energy usage and demand and the same limitation in the time of use data may lead to similar inaccuracies occurring. Additionally, the data of the 12 homes used was carried out in 2009 leading to potential errors of representation accuracy i.e. much has already changed in energy consumption over the last decade.

When using energy generation data, this thesis was severely limited by wind turbine curtailment periods being commercially sensitive information and therefore not available for analysis. This limited the ability of accurate energy load shifting periods and hindered the ability of calculating the true effect the energy load management had of wind oversupply.

The method of energy load management was completed manually on excel which may result in human error when identifying the energy signatures and when applying energy load shifts. There is no current computer modelling software designed specifically for carrying out energy load management on the UK national demand, which in itself is a major limiting factor holding back the UK’s demand response.

To summarise, the work carried out in this thesis would be greatly improved through knowledge of wind curtailment periods, more recently acquired domestic demand data, and modelling software to automatically carry out energy load management.

Finally, this thesis was complete during the 2020 Covid-19 pandemic, which limited the usage of university facilities and resulted in a level of disruption and concern.

6.3 Direction for future investigations

This thesis supplies a method of energy load management of 3 switchable appliances. Further development can expand on the number of appliances which are enrolled into the demand management program to increase the effects and therefore, the benefits of energy load management. The 3 switchable appliances have great energy load management potential due to their rare time constraint importance in the occupant’s lifestyle, further domestic appliance enrolment will likely require research into different methods and tactics of load shifting in accordance to their usage. Furthermore, demand management methods can be researched and applied outside of the domestic demand. The world of energy load management presents an exciting opportunity to allow the UK to reach its ambitious renewable targets.

REFERENCES

1 V. T. Nguyen, T. Luan Vu, N. T. Le and Y. Min Jang, *9th Int. Conf. Inf. Commun. Technol. Converg. ICT Converg. Powered by Smart Intell. ICTC 2018*, 2018, 852–855.

2 M. Uehara, *Proc. - IEEE 29th Int. Conf. Adv. Inf. Netw. Appl. Work. WAINA 2015*, 2015, 457–462.

3 R. Bolton and T. J. Foxon, *Technol. Forecast. Soc. Change*, 2015, **90**, 538–550.

4 C. Li, X. Yu, W. Yu, G. Chen and J. Wang, *IEEE Trans. Smart Grid*, 2017, **8**, 250–261.

5 J. Viitanen and R. Kingston, *Environ. Plan. A*, 2014, **46**, 803–819.

6 T. Asakura, T. Genji, T. Yura, N. Hayashi and Y. Fukuyama, *IEEE Trans. Power Syst.*, 2003, **18**, 1196–1204.

7 P. Warren, *Renew. Sustain. Energy Rev.*, 2014, **29**, 941–951.

8 W. Murrell, L. Ran and J. Wang, *2014 IEEE Innov. Smart Grid Technol. - Asia, ISGT ASIA 2014*, 2014, 1–6.

9 S. Xie, X. Wang, C. Qu, X. Wang and J. Guo, *Int. Trans. Electr. energy Syst.*, 2013, **20**, 1–6.

10 T. Crosbie, *Energy Policy*, 2008, **36**, 2191–2199.

11 D. Li, W. Y. Chiu and H. Sun, *Microgrid Adv. Control Methods Renew. Energy Syst. Integr.*, 2017, 203–230.

12 S. Darby, *Build. Res. Inf.*, 2010, **38**, 442–457.

13 N. G. Paterakis, O. Erdinç and J. P. S. Catalão, *Renew. Sustain. Energy Rev.*, 2017, **69**, 871–891.

14 J. A. Short, D. G. Infield and L. L. Freris, *IEEE Trans. Power Syst.*, 2007, **22**, 1284–1293.

15 T. Chen, J. Guo, B. Chaudhuri and R. S. Y. Hui, *IEEE Trans. Smart Grid*, 2020, **3053**, 1–1.

16 C. Wang, C. Grebogi and M. S. Baptista, *Chaos*, , DOI:10.1063/1.4963764.

17 M. E. U. C. Eddie Proffitt, National Grid, *Major Energy Users' Counc.*, , DOI:10.1016/j.trd.2008.11.010.

18 J. W. Taylor and S. Majithia, *J. Oper. Res. Soc.*, 2000, **51**, 72–82.

19 T. K. Jason Palmer, Nicola Terry, , DOI:10.1002/bscb.19951040404.

20 I. Richardson, M. Thomson, D. Infield and C. Clifford, *Energy Build.*, 2010, **42**, 1878–1887.

21 E. & I. S. Department for Buisness, *Natl. Stat.*, 2019, 25–30.

22 G. Rentier, H. Lelieveldt and G. J. Kramer, *Energy Policy*, 2019, **132**, 620–632.

23 P. Tielens and D. Van Hertem, *Young Res. Symp. Electr. Power Eng.*, , DOI:10.1101/sqb.1974.039.01.121.

24 M. Dreidy, H. Mokhlis and S. Mekhilef, *Renew. Sustain. Energy Rev.*, 2017, **69**, 144–155.

25 J. S. K. Baker, R. Mould, C. Dalzell and C. W. Policy, *Common Weal Policy*.

26 R. J. Bass, W. Malalasekera, P. Willmot and H. K. Versteeg, *Energy*, 2011, **36**, 1956–1965.

27 and J. R. T. Bennet, Donald J., *The Elements of Nuclear Power . Harlow: Longman Scientific & Technical, 1989. Print.*, Longman Group Limited, 3rd edn., 1989.

28 J. R. Lovering, A. Yip and T. Nordhaus, *Energy Policy*, 2016, **91**, 371–382.

29 K. Y. Oh, W. Nam, M. S. Ryu, J. Y. Kim and B. I. Epureanu, *Renew. Sustain. Energy Rev.*, 2018, **88**, 16–36.

30 N. Gardner, B. J. W. Manley and J. M. Pearson, *Appl. Energy*, 1993, **44**, 165–174.

31 J. Sumner and C. Masson, *J. Sol. Energy Eng. Trans. ASME*, 2006, **128**, 531–538.

32 L. Fu, Y. D. Wei, S. Fang, G. Tian and X. J. Zhou, *Adv. Mech. Eng.*, 2018, **10**, 1–11.

33 D. MacKay, *Review of Sustainable Energy -- Without the Hot Air by David MacKay (2009)*, 2009.

34 D. Weisser and R. S. Garcia, *Renew. Energy*, 2005, **30**, 1299–1308.

35 I. A. Erinmez, D. O. Bickers, G. F. Wood and W. W. Hung, *IEEE Eng. Soc. Winter Meet.*, 1999, **1**, 590–596.

36 B. J. Constable and M. Ridley, 2017.

37 D. Grover, *Cent. Clim. Chang. Econ. Policy*.

38 V. Sutedy, S. Member, P. Wang, S. Member, L. H. Koh, S. Member, F. H. Choo and S. Member, 2015, 229–233.

39 E. McKenna and M. Thomson, *Energy. Sustain. Soc.*, 2014, **4**, 1–12.

40 S. P. Mansoor, D. I. Jones, D. A. Bradley, F. C. Ark and G. R. Jones, 1998, 646–650.

41 M. K. Chang, J. D. Eichman, F. Mueller and S. Samuelsen, *Appl. Energy*, 2013, **112**, 1–11.

42 B. Zhou, S. Liu, S. Lu, X. Cao and W. Zhao, *J. Eng.*, 2017, **2017**, 2146–2151.

43 A. Castillo and D. F. Gayme, *Energy Convers. Manag.*, 2014, **87**, 885–894.

44 D. Greenwood, N. Wade, P. Taylor and N. Heyward, 2015, 15–18.

45 S. D. Ramchurn, P. Vytelingum, A. Rogers and N. Jennings, *10th Int. Conf. Auton. Agents Multiagent Syst. 2011, AAMAS 2011*, 2011, **1**, 1–8.

46 D. P. Jenkins, S. Patidar and S. A. Simpson, *Energy Build.*, 2014, **76**, 605–614.

47 V. Hamidi, F. Li and F. Robinson, *Electr. Power Syst. Res.*, 2009, **79**, 1722–1726.

48 G. Strbac, *Energy Policy*, 2008, **36**, 4419–4426.

49 D. Angeli and P. A. Kountouriotis, *IEEE Trans. Control Syst. Technol.*, 2012, **20**, 581–592.

50 M. Filippini, L. C. Hunt and J. Zorić, *Energy Policy*, 2014, **69**, 73–81.

51 Data set found at UK DATA Service, https://www.ukdataservice.ac.uk/get-data.

52 R. V. Jones and K. J. Lomas, *Energy Build.*, 2016, **117**, 71–82.

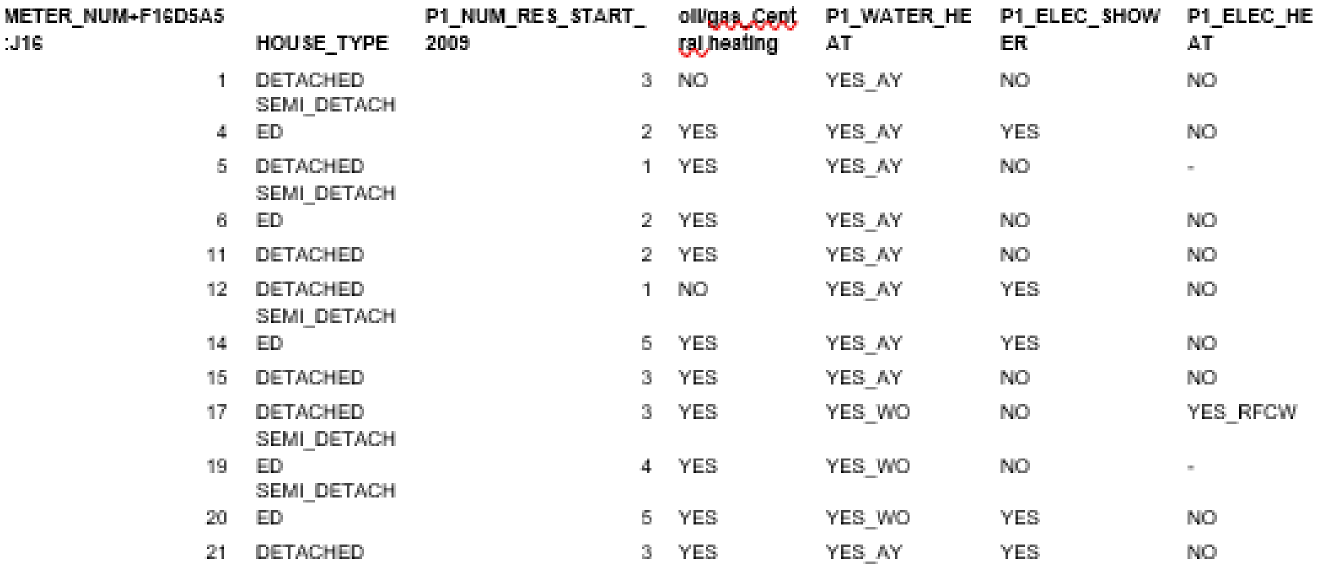
53 O. Parson, Disaggregated Homes web page found at: http://blog.oliverparson.co.uk/

54 C. Pakula and R. Stamminger, *Energy Effic.*, 2010, **3**, 365–382.

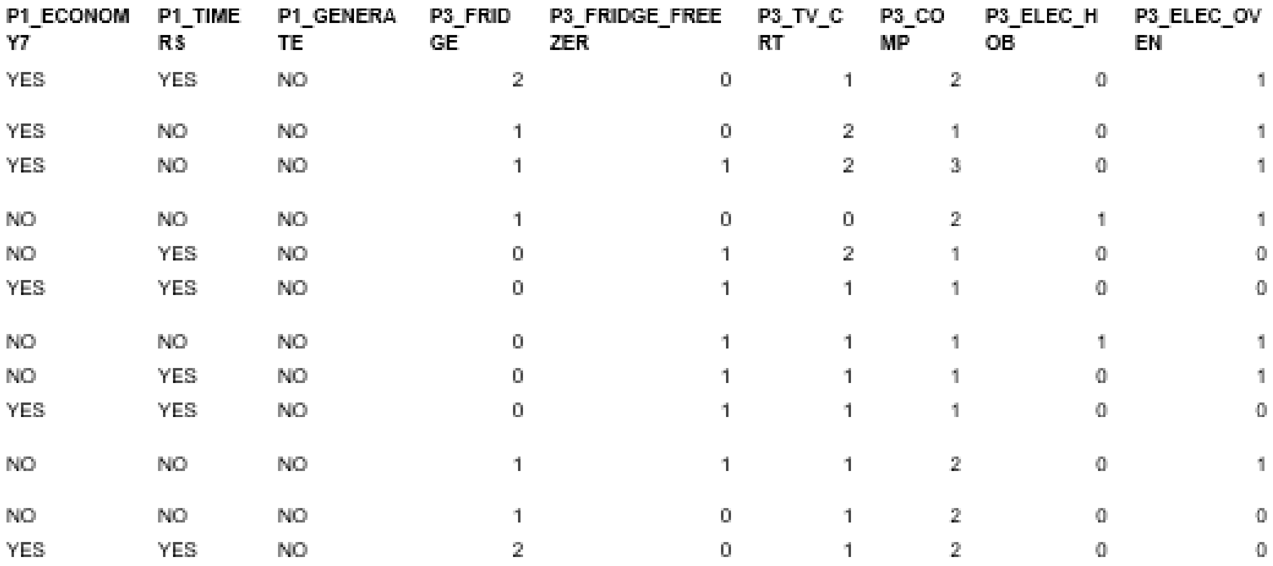
55 M. Ali, J. Matevosyan, J. V Milanović and L. Söder, *8th Int. Work. Large Scale Integr. Wind Power, Bremen*, 2009, 14–15.

APENDIX

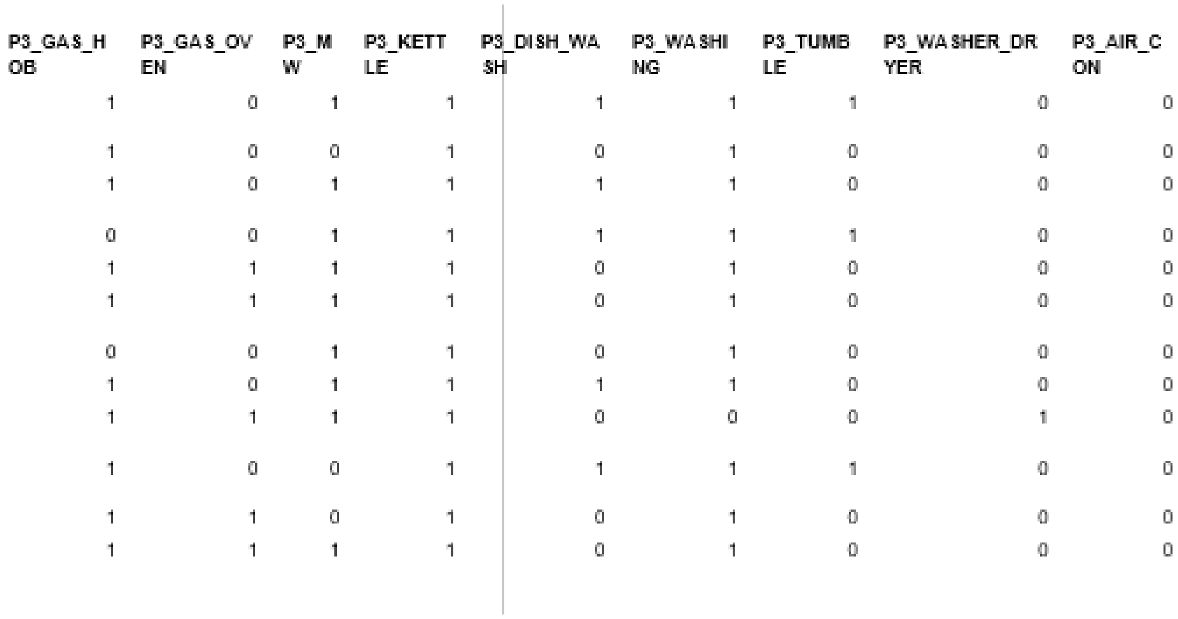
Table of surveyed metered home data: (0= no, 1= Yes)



METER_NUM+F16D5A5:J16	HOUSE_TYPE	P1_NUM_RES_START_2009	oil/gas_Central heating	P1_WATER_HEAT	P1_ELEC_SHOWER	P1_ELEC_HEAT
1	DETACHED	3	NO	YES_AY	NO	NO
4	SEMI_DETACHED	2	YES	YES_AY	YES	NO
5	DETACHED	1	YES	YES_AY	NO	-
6	SEMI_DETACHED	2	YES	YES_AY	NO	NO
11	DETACHED	2	YES	YES_AY	NO	NO
12	DETACHED	1	NO	YES_AY	YES	NO
14	SEMI_DETACHED	5	YES	YES_AY	YES	NO
15	DETACHED	3	YES	YES_AY	NO	NO
17	DETACHED	3	YES	YES_WO	NO	YES_RFCW
19	SEMI_DETACHED	4	YES	YES_WO	NO	-
20	SEMI_DETACHED	5	YES	YES_WO	YES	NO
21	DETACHED	3	YES	YES_AY	YES	NO



P1_ECONOMY7	P1_TIMERS	P1_GENERATE	P3_FRIDGE	P3_FRIDGE_FREEZER	P3_TV_CRT	P3_COMP	P3_ELEC_HOB	P3_ELEC_OVEN
YES	YES	NO	2	0	1	2	0	1
YES	NO	NO	1	0	2	1	0	1
YES	NO	NO	1	1	2	3	0	1
NO	NO	NO	1	0	0	2	1	1
NO	YES	NO	0	1	2	1	0	0
YES	YES	NO	0	1	1	1	0	0
NO	NO	NO	0	1	1	1	1	1
NO	YES	NO	0	1	1	1	0	1
YES	YES	NO	0	1	1	1	0	0
NO	NO	NO	1	1	1	2	0	1
NO	NO	NO	1	0	1	2	0	0
YES	YES	NO	2	0	1	2	0	0



P3_GAS_HOB	P3_GAS_OVEN	P3_MW	P3_KETTLE	P3_DISH_WASH	P3_WASHING	P3_TUMBLE	P3_WASHER_DRYER	P3_AIR_CON
1	0	1	1	1	1	1	0	0
1	0	0	1	0	1	0	0	0
1	0	1	1	1	1	0	0	0
0	0	1	1	1	1	1	0	0
1	1	1	1	0	1	0	0	0
1	1	1	1	0	1	0	0	0
0	0	1	1	0	1	0	0	0
1	0	1	1	1	1	0	0	0
1	1	1	1	0	0	0	1	0
1	0	0	1	1	1	1	0	0
1	1	0	1	0	1	0	0	0
1	1	1	1	0	1	0	0	0

Surveyed meter table legend:

House Type
Number of residents
Gas/oil fuelled central heating
Gas/oil water heater
Electric shower
Electric heaters*
Generate own electricity
Economy 7 Tariff
Appliances on timers
*APPLIANCES**
Electric oven
Electric hob
Gas oven
Gas hob
Microwave
Kettle
Dish washer
Washing machine
Washer dryer
Tumble dryer
Fridge
Fridge + Freezer
Freezer
TV
Computer
Air Conditioning

*regular usage