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Feasibility study of small-scale battery systems for domestic application

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Abstract

In response to the dual problem of, on the one hand, depleting and environmentally harmful conventional methods of power generation, and, on the other, the inherently erratic, unpredictable nature of their renewable, more environmentally friendly alternatives, this thesis highlights the implementation of home energy storage systems as a potential avenue through which this predicament could be mitigated. There are a number of different types of batteries that can be used as a home energy storage device, and this thesis will investigate which type of battery works best with which set of specifications, in relation to different locations and renewable technologies. In order to achieve this, the objectives of the thesis are: to provide an overview of energy storage; to carry out technical and economic analysis of the application of different types of energy storage devices, when used in a typical three-bedroom dwelling in both the USA and the UK; and to determine the optimum system for combining the use of energy storage with solar PV and wind technologies in both countries. Chapter 1 outlines the background to the problem in hand and introduces energy storage as a feasible solution. Chapters 2, 3 and 4 review the relevant literature regarding, respectively, energy storage in general, domestic energy use, and the integration of renewable energy technologies, namely wind and solar, with energy storage. As outlined in Chapters 5 and 6, the program HOMER Pro is then used to model a typical 3-bedroom household in San Francisco, USA and in Aberdeen, UK, in an attempt to find the most suitable type of battery system for each location. Wind and solar PV technologies will be tested for each location and each battery type (lithium-ion, flooded lead-acid, and tubular gel lead-acid), for both a stand-alone and grid-connected dwelling, in an attempt to identify the most beneficial route for residential renewable technology use. In many of the grid-connected simulations in both San Francisco and Aberdeen, the batteries do not appear to be fully utilised, whereas, as expected, in the stand-alone simulations, the batteries are much more widely used. However, with a lack of export revenue, it is clear that the economic feasibility is decreased in a stand-alone system. The overall conclusion of this thesis is that simulating the way in which batteries can be used in conjunction with renewable energy systems at the domestic level is an extremely complex pursuit. However, with continued developments in this field, home energy storage by means of batteries, could improve the use of renewable energy technologies in the domestic setting.

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1. Introduction

1.1. Overview

Amid growing concern over the environmentally harmful effects of conventional power generation methods, such as coal, oil and gas, together with their depleting supply, a great deal of legislation and targets have been instated worldwide, in an attempt to mitigate the negative implications of this issue. Over the years, this has led to the development of renewable energy technologies that make use of more readily available natural resources, such as solar irradiance and wind. However, these renewable resources also have the potential to be extremely volatile and difficult to predict. Technologies such as wind turbines and photovoltaics have relatively low efficiencies in comparison to conventional means of generating electricity, and, without storage, any electricity produced using these renewable methods can only be used at the time of generation. This complex polemic, with, on the one hand, the need to move away from conventional methods and, on the other, the unpredictable nature of renewable resources, has led researchers and scientists to strive to find a suitable replacement for conventional methods of power generation that can still provide a reliable and secure power supply to consumers. One of the most recent areas of research explores different ways of storing electricity, so as to overcome the intermittent nature of most renewable energy sources. (Brunet, ed., 2011, p. 2) The importance and legitimacy of this pursuit is confirmed by Huggins, who writes that "the need for energy storage will grow substantially in the future." (2010, p. 383) So, too, therefore, must its availability, its efficacy, and also our understanding of it.

The need for energy storage is further increased by the fact that different energy consumers can portray very different load patterns. For example, industry could require electricity 24 hours per day, while residences may only use it early in the morning and at night. This irregular demand makes it extremely difficult for electricity suppliers to provide a stable supply of electricity to every consumer (Huggins, 2010, p. 4), but the implementation of storage in this process could arguably significantly reduce the associated pressures. Indeed, a number of energy storage technologies have the ability to store electricity as it is generated, and then discharge it as and when required by the consumer.

As previously stated, energy storage is at the forefront of renewable energy research, motivated by the ambition to improve the availability and efficiency of renewable sources and to mitigate the negative consequences that might result from the continued use of and dependency upon the conventional means of power generation. One of the most widely used forms of energy storage involves the electrochemical process, using batteries such as lead-acid, lithium-ion and many more. (Zito, 2010, p. 34) Indeed, Zito notes that electrochemical cells such as these constitute one of the most hopeful methods by which electricity can be stored. (2010, p.21) While some of these technologies, such as the lead-acid battery, are not incredibly innovative and have been used for many years, (Brunet, ed., 2011, p. 71) the lithium-ion battery, for example, is a fairly new technology that has been primarily used for micro-scale applications such as mobile phones. (Beaudin et al., 2010, p. 307) One of the most interesting developments in lithium-ion batteries occurred in April 2015, when Tesla, an electric vehicle manufacturer, released plans to develop an energy storage device in the United States of America (USA) utilising lithium-ion batteries, entitled the 'Tesla Powerwall'. This product is aimed at consumers who already use, or plan to use, renewable energy technologies such as photovoltaic (PV) panels. Importantly, these storage systems are designed to be used, not only within industry, but also in the home. (TESLA, 2015) Indeed, a number of products of this kind exist, and a selection of the different battery types used within these systems will be examined in this thesis, namely lithium-ion, flooded lead-acid, and tubular gel lead-acid. Put simply, these home energy storage devices are batteries with the ability to store electricity generated from renewable sources, so that it is available for use whenever it may be required by the domestic consumer. It is stated throughout literature that effective energy storage technology will enable the renewable energy market to grow, (e.g. Ford & Burns, eds., 2012, p.1) raising the idea that this might be the answer to the problem of intermittency associated with renewable resources such as solar PV and wind power. As a result, the increased and widened use of energy storage could play a significant role in increasing the efficiency of domestic energy use, reducing the stress on the electric grid, and decreasing the reliance upon conventional methods of power generation.

1.2. Thesis Outline

With various different types of small-scale storage devices available, some with very similar technical specifications, it is perhaps difficult to know which type of device will work best for a specific dwelling and renewable system. This thesis will investigate the effects of different types of electrical home energy storage devices, when integrated with renewable energy technology, namely wind and solar power. In view of the fact that both the United Kingdom (UK) and the United States of America (USA) are arguably among the key players in the global pursuit of sustainability, and also given their differing climates due to geographical separation, it seems appropriate to compare residential renewable energy systems with energy storage in these two countries. Chapters 2, 3 and 4 will review the literature on, respectively, energy storage in general, domestic energy use, and the integration of residential wind and solar power generation with storage. As will be detailed in Chapters 5, and 6, an analysis tool, HOMER Pro, will then be used, in order to assess the efficiency of various types of home energy storage devices in relation to different sets of conditions. Each battery type (lithium-ion, flooded lead-acid, and tubular gel lead-acid) will be modelled for a typical three-bedroom dwelling in Aberdeen, UK, and San Francisco, USA, in both grid-connected and stand-alone formats, firstly, with a home PV system similar to those currently used in practice, and, secondly, with a small-scale wind turbine, in order to determine which type of storage device would provide the optimum renewable system for each domestic situation. All of this will serve to demonstrate that, provided that the most appropriate battery type is implemented for the particular specifications of the situation in hand, home energy storage technologies are highly viable as a potential avenue for mitigating the problems currently faced in relation to the intermittent, unpredictable nature of renewable energy technologies.

1.3. Thesis Objectives

- Provide an overview of small-scale batteries as a means of energy storage.

- Carry out technical and economic analysis of the application of different types of energy storage devices, when used in a typical three-bedroom dwelling in both the USA and the UK.

- Determine the optimum system for combining the use of energy storage with wind and solar PV in locations in both the USA and the UK for both grid-connected dwellings and stand-alone systems.

2. Energy Storage

2.1. Background

Motivated by the need to overcome the problems associated with continued use of conventional power generation, various scholars have highlighted energy storage as a key area of interest. (e.g. Beaudin, 2010; Fallahi, 2014; Zito, 2010) The need for storage is particularly evident in relation to renewable energy technologies, which, as noted in the Introduction of this thesis, generate electricity in haphazard daily patterns, dependent on natural resources. Storage, in this case, allows the energy to be utilised as and when it is required, and then stored when it is not, therefore reducing wasted energy as much as possible. (Huggins, 2010, p. 2)

In general, energy storage is not a particularly novel technology, given that, for example, lead-acid batteries have been in use for over 130 years and are still implemented today for many storage applications. (Beaudin et al., 2010, p. 306) Current research into energy storage, however, includes not only electrochemical batteries, but also technology such as liquid air, compressed air and pumped storage. These types of energy storage are primarily used for larger applications. Meanwhile, for domestic applications, and, in particular, stand-alone systems, batteries are more common than other technologies, (Brunet, ed., 2011, p.65) due, arguably, to the fact that, as highlighted by Cho et al., batteries are, "more suitable in terms of power and energy density, efficiency, weight, and mobility of the systems." (2015, p.98)

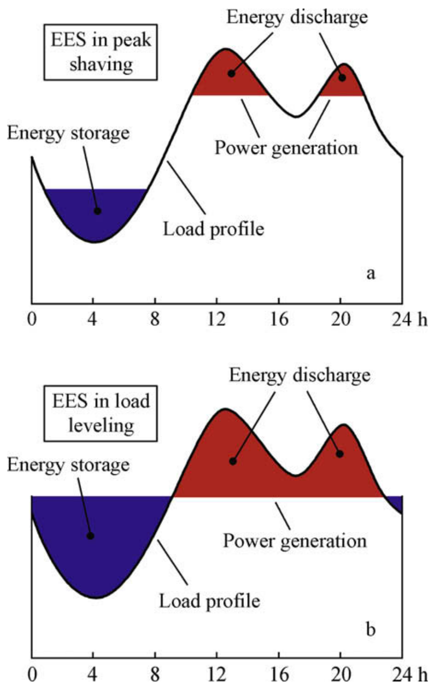


Figure 1 – Peak shaving and load levelling capabilities of energy storage system. (Chen et al. 2009, p. 292)

2.1.1. Advantages

According to Mattera, one of the principal advantages of the implementation of electrical storage is peaks shaving: the process of creating a smoother, more stable, supply of electricity to consumer. (Brunet, ed., 2011, p.78) Further areas that can benefit from storage, Mattera continues, include transmission support, demand management, current quality and security. (Brunet, ed., 2011, p. 78)

Indeed, Kaldellis writes, energy storage systems can be beneficial in a number of ways. For example, they can enable the exploitation of potentially wasted energy, increase autonomy and, therefore, improve the reliability of the energy supply. (2010, p. 12) Furthermore, the use of energy storage also helps to enhance the quality of power received by the consumer, and reduces the risks often associated with connections to the grid. (Kaldellis, ed., 2010, p.12)

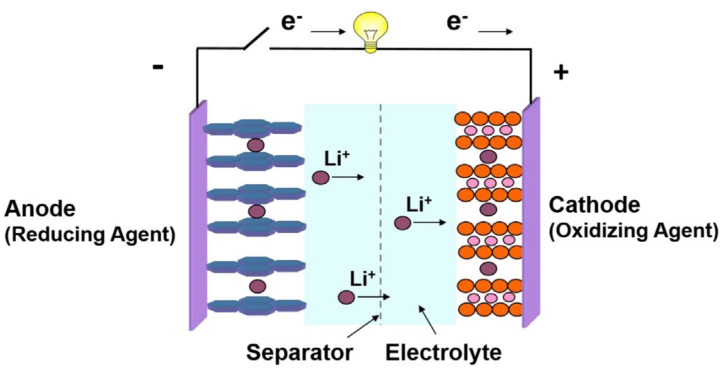
2.1.2. Disadvantages

One of the most significant disadvantages of energy storage is that their capital cost can be high. (Kaldellis, ed., 2010, p.13) Another important aspect of energy storage, as outlined by Kaldellis, is that, in some cases, in the construction of storage systems, energy use is required, meaning that negative environmental effects remain a partial problem, albeit generally minimal. (2010, p.13) One of the greatest drawbacks of the use of batteries, Zito maintains, is that their lifetime can be reasonably limited, which can be directly associated with their reversibility. (2010, p. 55) As the number of cycles increases, more and more chemical changes take place, allowing for physical changes, such as the reduction of mechanical strength, among others, to occur. (Zito, 2010, p. 55)

2.2. Batteries

2.2.1. Electrochemical Process

Figure 2 - Electrochemical Process of Lithium-ion (Cho et al. 2015, p. 90)



One of the most popular methods of energy storage is the implementation of batteries, which make use of the electrochemical process, whereby an electrochemical cell, containing a cathode and an anode, stores electrical energy and then releases it as and when required by the consumer. Put simply, an electrochemical cell, lithium-ion for example, contains an anode, a cathode and an electrolyte. During charging, the anode oxidises, and electrons are given off, through the electrolyte, to the cathode, as shown above, in Figure 2.

In the case of lithium-ion cells, this process is reversible, leading to the overall reaction equation shown below. (Cho et al. 2015, p. 90)

$$LiC_6 + CoO_2 \rightleftharpoons C_6 + LiCoO_2$$

2.2.2. Important Features

There are many key specifications of batteries that determine the quality of storage, some of the most important of which are capacity, round-trip efficiency, self-discharge, lifetime and number of cycles, depth of discharge, charge rate, discharge rate and, finally, cost.

Capacity – This is dependent on the amount of electricity that can be discharged during a specific period. It is one of the first characteristics that must be determined for a given system, in order to ensure that the appropriate amount of electricity is stored and discharged for later use, ensuring that there is enough electricity for the loads required. (Brunet, ed., 2011, p.174)

Round-trip efficiency – This is the ratio of energy output from the battery and energy input to the battery. It is used to determine how successful the storage device is during charging and discharging, as well as to establish its ability to store energy, since losses are also considered within this value. This efficiency is one of the most crucial features of a storage device, given that a low efficiency can mean that, due to significant losses, it is unlikely that it would be worthwhile adding storage to the system. (Kaldellis, ed., 2010, p.38)

Self-discharge – This is the average loss of capacity per month in storage. It is a feature that varies from battery to battery, and can also be influenced by other characteristics. Temperature can affect the self-discharge drastically, which means that the location in which a battery is kept is crucial, in order to prevent overheating.

(Brunet, ed., 2011, p. 188) The concept of self-discharge can generate a degree of uncertainty in how much is thought to be in the store, as the losses are difficult to predict. (Brunet, ed., 2011, p. 174)

Lifetime and Number of Cycles – These two features are dependent on each other. The number of cycles applies to the number of times the battery is charged and discharged, the magnitude of which varies, based on how much energy is required and how quickly. This plays a huge role on the overall lifetime of the battery. As detailed, above, in the disadvantages of batteries, as the number of cycles increases, more changes take place in the battery and various aspects of it are weakened, such as mechanical strength, thereby decreasing its lifetime. (Brunet, ed., 2011, p.175; Zito, 2010, p. 55)

Depth of Discharge – This is the maximum amount of electricity that can be used from the energy storage capacity, ensuring that the use of electricity is controlled and suitable. (Kaldellis, ed., 2010, p. 39) According to Fusalba and Martinet, in the case of lead-acid batteries, if the daily depth of discharge is limited, the lifetime can be improved, provided that the system is prevented from overcharging. (Brunet, ed., 2011, p.188) This is obviously an important aspect of battery systems, since, if the lifetime can be prolonged by ensuring that the system is operating effectively, then the feasibility will be improved.

Charge Rate – This is the battery's ability to take in the electricity required. The charge rate determines how much electricity can be put into the storage and how quickly it can be achieved. This feature is dependent on the storage capacity, as, if the store were to already be full, then it would not be possible for it to absorb any more electricity.

Discharge Rate – This is a battery's ability to release the electricity that is stored. A battery's discharge is an extremely important feature for all applications, as it determines how much, and how quickly, electricity is available to the load. (Kaldellis, ed., 2010, p.38) Different applications require different discharge response times. For example, for grid stability, short-term discharge of less than one minute is required.

On the other hand, when in use with renewables such as PV systems, the discharge time needed can take between minutes and hours. (Ford & Burns, eds., 2012, p.5)

Cost – Arguably the most significant factor of batteries is their cost, as this will play a huge role in the feasibility of including batteries in a particular system. In the case of residential energy storage, when connected to the grid, the savings from reducing imported electricity will be compared with the overall cost of the storage system. However, the reduced exported electricity must also be considered in the calculation. Charging and storing energy reduces the exports, leading to the need to weigh-up what is more beneficial: storing or exporting electricity.

2.2.3. Types of Batteries

Detailed below are the types of battery that will be studied in this thesis, all of which can be applied to residential energy storage and stationary applications: lithium-ion, flooded lead-acid, and tubular gel lead-acid.

Lithium-Ion

Lithium-ion batteries typically consist of a graphite anode, a lithium oxide cathode, and a liquid electrolyte in between, commonly hexafluorophosphate mixed with carbonate solution. (Brunet, ed., 2011, p.195) These batteries were first commercialised in 1991, and, ever since, have been extremely popular, especially in small electronics, such as mobile phones. (Beaudin et al. 2010, p. 307) They have also started being used in electric vehicles, due to their extremely beneficial attributes, such as high efficiency, long life cycles, high depth of discharge, high energy density and high power density. (Chen et al., 2009, p. 298) Another advantage of lithium-ion batteries is that they have a low self-discharge rate, meaning that very little is lost when the battery is charged in comparison to other batteries. (Kaldellis, ed., 2010, p.56) It is outlined in the literature that lithium-ion is particularly suitable for applications requiring security or peak-shaving, due to its high energy density. (Brunet, ed., 2011, p. 79) Some of the disadvantages of lithium-ion batteries include the requirement of protection circuits, due to the relative immaturity of the technology, in order to keep the voltage and current within safe limits. (Kaldellis, ed., 2010, p.56) One of the biggest disadvantages is outlined by Cho et al., who state that, when in use for large applications such as residential energy storage, lithium-ion batteries can have a high capital cost of upwards of $1000/kWh. (2015, p. 86) However, the new lithium-ion home energy storage device manufactured by Tesla is $3000 for a 7kWh battery, therefore <$450/kWh. This is considerably lower than the value stated by Cho et al., implying that the capital cost is reducing as the lithium-ion technology progresses. (TESLA, 2015)

Lead-Acid

Lead-acid batteries are one of the oldest types of electrochemical batteries, and one of the most widely used for small-scale storage applications. (Beaudin et al., 2010, p. 306) In this type of battery, the positive electrode is lead dioxide and metallic lead is the negative electrode. When discharging, a double-sulphate reaction takes place, allowing for electrode reactions of lead oxidation and lead dioxide reduction to occur. (Cho et al., 2015, p.88) This process is reversible during charging, allowing the battery to be charged and discharged.

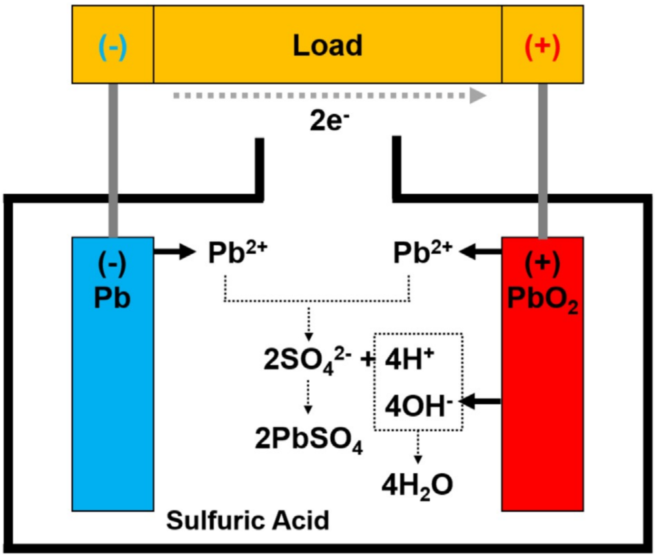


Figure 3 – Lead-Acid Battery (Cho et al. 2015, p.88)

When the cell is almost fully charged, lead sulphate will be converted back to lead or lead oxide and the water will be converted to sulphuric acid, ready for the process to be repeated. More current passing through will create hydrogen at the negative electrode and oxygen at the positive electrode. When these gases are released, this results in a loss of water from the electrolyte, the two electrodes are submerged in. This type of process is defined as a "traditional cell design" known as a "flooded" lead-acid battery. (All: Moseley & Garche, eds., 2014, p. 202) After much research, it was found that this release of gases could cause an explosive hazard, and so scientists tried to develop a sealed battery. The main improvement of lead-acid batteries came when the valve-regulated lead-acid battery was invented. This type of battery makes use of an 'internal oxygen cycle', this cycle then consumes some of the electrical energy delivered to the cell and then is converted into heat instead of chemical energy. One of the designs that converts electrical energy by means of the oxygen cycle is where the electrolyte is "immobilised" as a gel, which allows oxygen transfer to continue, leading to the gas release from the cell being controlled. (All: Moseley & Garche, eds., 2014, p. 203)

Some of the advantages of lead-acid include low capital cost, high efficiency and reliability. (Chen et al., 2009, p. 297) However, its short lifetime, due to the short number of cycles available, means that energy management application is one of the shortcomings of this battery type. (Chen et al., 2009, p. 297) Nevertheless, this flaw has not stopped the lead-acid battery from being widely circulated. For example, as Beaudin et al. state, they have been used as storage for 75% of new solar power systems in China. (2010, p. 306)

2.3. Home Energy Storage

According to Kaplan, a system including home energy storage and a power system is extremely complex. (Ford & Burns, eds., 2012, p. 140) However, it is also stated by Fusalba and Martinet that, "electrical storage allows good management of electric networks both in terms of supply and demand and also in terms of quality." (Brunet, ed., 2011, p. 176) This demonstrates that, if the complexity of these systems were to be overcome, the implementation of electrical storage would have the potential to help improve the problems associated with supply and demand matching. Through the implementation of home energy storage, the homeowner would benefit from using the stored energy as opposed to paying for imported electricity from the grid. Not only this, but the energy storage could also be used to store cheap off-peak electricity from the grid and then release it back when the price increases. (Zhao et al., 2015, p. 549) This is one of the great advantages of having storage. However, effective management is also required, in order to determine exactly the best time to do so. This is particularly difficult in the case of energy storage integrated with renewable technologies, such as wind and solar systems, as will be described in greater detail in Chapter 4.

There are various different storage systems available on the market, which will differ greatly in terms of efficiency at storing electricity for later use in a household. Tesla, manufacturer of the proposed energy storage system, 'Powerwall', due for commercial release in 2016, has listed several key benefits to be enjoyed by the consumer following the installation of an energy storage device: (TESLA, 2015)

- Load-shifting
- Increasing self-consumption of solar power generation
- Back-up power

All of these factors allow the consumer to increase the control they have over their power supply. First of all, load-shifting capabilities permit the consumer to charge their storage with cheap off-peak electricity from the grid and then release the electricity back to the grid when the price has increased. Furthermore, increasing the self-consumption of solar power generation decreases the amount of electricity wastage that could occur without storage. For example, if there were to be a surplus of electricity generated by a home solar power system and the grid did not want to take it, then, without storage, this electricity would simply be wasted, which would, in turn, decrease the financial benefits of installing a solar system in the first place. Finally, back-up power is one of the most important features of a storage device, as this means that there is less chance of difficulties arising from problems associated with grid, such as blackouts and power quality issues. Due to a lack of full dependency on grid electricity, if problems such as these were to occur, then electricity in storage could be used until the situation was resolved. Therefore, the ability to provide back-up to the grid would result in the improved security and reliability of an electrical supply.

One area that requires a substantial amount of attention, when an energy storage device is included within a home system, is the increased necessity for energy management, so as to determine the right times to store energy as it is generated, and when to use ready-stored energy. There are vast amounts of literature on energy management systems, with a most prominent area being the research and development of smart grids. (e.g. Connor et al., 2014; Hill et al., 2012) This type of energy management system has been developed with the aim of helping people to become more aware of their energy use, in turn reducing the amount of electricity used, and thereby, in theory, lowering carbon emissions and reducing consumers' electricity bills. (Bouhafs et al., 2014, p. 56) A management system with the ability to control when energy storage is needed, by knowing how much energy is required when a particular appliance is turned on, could greatly improve the feasibility of a home energy storage system.

However, with systems such as these, there are many different factors affecting the effectiveness of their functionality, for example manufacturers' willingness, or lack thereof, to provide smart appliances that can be used to monitor energy use. Another example of this is consumer behaviour, which can be extremely difficult to predict. These two factors are among many others that could be improved in order to facilitate the more widespread use of energy management strategies. With wide reference to the relevant literature, it becomes clear that, as technology develops, monitoring energy management could become easier, and thus, home energy storage could be better utilised to meet more controlled loads.

3. Domestic Energy Use

Energy use can be categorised into four different sectors: residential, industrial, transport and services. (Boyle, 2012, p.11) In the most recent report by the Department of Energy and Climate Change (DECC), it is stated that domestic electricity consumption has increased for the first quarter of 2015, to account for over 35% of all electricity consumption in the UK. (DECC, 2015) This level of consumption makes the domestic sector the highest consumer of electricity in the UK, with an increase of 2% in electrical sales from last year. (DECC, 2015) In the USA, this value is much the same, with residential electricity consumption upwards of 35% of total electricity end use in 2014. (EIA, 2015) As a large portion of electricity is still generated using conventional methods, such as coal and gas, this level of electricity consumption plays a part in the continued use of such resources. (DECC, 2015) If more renewable energy systems were in place at the domestic level, therefore, then the stress on fossil fuel-based electricity generation could be relieved. (EIA, 2015).

Currently, in the UK, when connected to the grid, domestic consumers of electricity will pay an import tariff of roughly 15p/kWh. (SSE, 2015) However, consumers that invest in residential renewable energy systems, for example wind or solar PV, can also export surplus electricity that they do not require to the grid for a selling price. In the case of solar panels, the consumer will be paid for the amount of electricity exported back to the grid and also for the amount of electricity generated by renewables, based on the UK's renewable energy feed-in-tariff, which can lead to high savings in some cases. (Energy Saving Trust, 2015) The Energy Information Administration (EIA) states that feed-in-tariffs are not widely used in the United States. However, other policies such as Renewable Portfolio Standards (RPS) are used to enhance the deployment of renewable technology, in the hope of reducing use of conventional power generation. (EIA, 2015) Currently, however, in both countries there are no incentives of this nature for the implementation of energy storage systems, which in no way helps to increase the economic feasibility of such projects.

There are two areas that can influence domestic energy use immensely, which are well discussed throughout literature, one being occupant behaviour, and the other being the use of appliances. There have been many studies covering both of these aspects, which have produced substantial evidence of their impact on energy use. One of the most difficult challenges involved in matching demand with supply in the case of domestic loads is that it is often very difficult for utility companies to predict the pattern of energy use. As already alluded to in the Introduction to this thesis, different consumers can portray very different patterns of energy use, dependent on many factors such as location, type of house and type of appliances used among others. (Yao & Steemers, 2005, p. 664) Mansouri et al. state that, if the behavioural aspect of energy use were to be studied, a more efficient handling of energy could result. (1996, p. 277-278) In order to make this projection a reality, however, Karatasou et al. note that studies of behavioural patterns, which can result in energy savings and a reduction in all CO2 emissions, still require further research in order to be able to support policy making. (2014, p. 145) To this end, they state that a more "methodological approach" would be required, so as to properly assess the effects that the behaviour of consumers can have on energy use. (Karatasou et al., 2014, p.138) Despite this shortcoming involving the lack of full understanding of the behavioural patterns of domestic energy consumers, researchers have not been stopped in the development of load models, in order to try and predict energy use, so as to enable the more accurate modelling of electricity supply and demand. An early example of such a model is that of Yao and Steemers, who, in 2005, developed an approach devised to generate energy load profiles for homes in the UK. The program created gives a breakdown of energy consumption, based on specific input data, such as house information, appliance usage and location. (Yao & Steemers, 2005, p. 670) It is clear that the development of programs such as these would greatly improve the understanding and prediction of occupant energy consumption, and also the simulation of proposed renewable residential developments, generating, as a result, far more realistic results.

4. <u>Wind and Solar Generation Integrated with Storage</u>

"*Small-scale implementation of renewable energy systems in the form of micro-wind turbines or photovoltaic (PV) installations coupled with energy storage systems provide the ability to supply power to commercial buildings and/or residential dwellings while offsetting grid consumption*." (Nair & Garimella, 2010, p.2124)

4.1. Overview

Concerns are expressed throughout the literature regarding the contribution towards climate change made by the conventional means of electricity generation. (e.g. Beaudin et al., 2010, p. 302) This has led to progressive research into renewable energy systems, such as photovoltaics (PV) and wind, whose effects on the environment are far less harmful. Renewable energy sources are highly beneficial. Not only do they release very few carbon emissions, with the majority of their pollution occurring only during the manufacturing stages, but also, true to their name, they are, unlike their conventional predecessors, available in an virtually limitless supply. However, as renewable electricity sources such as these depend on the availability, and thus the inevitable variability, of natural resources, the resulting power outputs obtained can fluctuate immensely, rendering processes of energy management extremely difficult. Indeed, relying on erratic sources such as these to supply electricity to consumers increases the uncertainty regarding meeting demands, which can, in turn make the system far less reliable. (Behzadi and Niasati, 2015, p. 538) This chapter will discuss the main features of solar and wind electricity generation and explore how, by including energy storage, the shortcomings of these technologies could be diminished.

4.2. Solar

Solar cells make use of the photovoltaic effect, which converts light energy into electricity. The first solar cell, Boyle informs us, was used in 1958 to power a radio transmitter in a space satellite. (2012, p. 76) Despite a multitude of subsequent developments in photovoltaic technology, he continues, over half a century later, the efficiency of state-of-the-art solar cells is still only in the region of 20-30%. (Boyle, 2012, p. 77) However, this relatively low efficiency has not stopped the widespread use of PV cells in both grid-connected and stand-alone solar power systems.

The intermittent efficiency of PV cells can be explained by the fact that the sun only shines during the day, and that, therefore, at certain points during the night, the photovoltaic system can boast absolutely no power output at all. Not only this, but there are obviously also periods, even during daylight hours, where the level of irradiance is lower, due to weather events such as significant cloud cover. The sporadic nature of solar PV systems results in power output fluctuations, leading to challenges in achieving power quality and reliability. (Hill et al., 2012, p.850) Hill et al. assert further that the power output of a PV system could change by up to 80% in a matter of seconds, when a cloud covers over the PV panels. This makes the output of PV systems extremely difficult to predict, and can even lead to voltage swings and frequency variations, which can be harmful to parts of the system, and, in some cases. reduce its life expectancy. (Hill et al., 2011, p.852) Mattera states that both stand-alone and grid-connected photovoltaic systems require energy storage to overcome this problem of a variable power output, and to increase, consequently, the likelihood that problems resulting from this predicament might be reduced. (Brunet, ed., 2011, p.65) On top of this, Hill et al. also discuss the importance of location in tying a battery storage system to the grid, facilitating the amelioration of both the power quality and the transmission of the renewable energy output of large-scale systems, such as solar PV. (2011, p.852) It can be easily deduced from the relevant literature, referred to herein, that there is great need for coupling PV systems with battery storage systems, in order to improve the quality and reliability of the power output, the details and benefits of which were outlined in Chapter 2.

PV systems can either be connected to only the grid, to both an energy storage system and the grid, or to a stand-alone energy storage system with no connection to the grid. Naturally, each of these situations can pose different implications for the consumer. When PV systems are connected to only the grid, the grid acts a form of storage whereby, when there is an abundance of output from the solar cells, the demand will be matched and any surplus will be exported to the grid for an export price. If there is a deficit however, electricity will need to be purchased from the grid, generating an additional expense for the consumer, on top of their initial capital investment in the PV system. However, if energy storage is utilised when still connected to the grid, by means of batteries for example, energy management, as previously detailed, is much more complex. It has to be decided whether or not it is appropriate to store surplus electricity for later use, or whether to export it for financial gain. Stand-alone systems, without connection to grid, meanwhile, have the advantage of removing the dependency on the grid and, therefore, of reducing the likelihood of the associated negative implications, such as blackouts and power quality issues. However, this also means that, if there are periods of large outputs of PV generation and the storage is at full capacity, then any unused electricity will be wasted, where it could, in an alternative set-up, have been exported to the grid for income. That being said, in many remote areas, connections to the grid with such systems are complicated, and, for this reason, in a number of cases, stand-alone PV systems are much more appropriate.

4.3. Wind

The utilisation of wind energy is one of the fastest growing areas of electricity generation in the world. (Such & Hill, 2012, p.1) More and more wind farms are being built worldwide, with their development bolstered by years of research and development. (Liang et al., 2012, p.1) However, as encountered with PV application, the intermittency of the wind itself can lead to fluctuating power output from wind turbines. It is stated throughout the literature that this can lead to problems of power quality and reliability, due to changes in frequency and voltage. (e.g. Such & Hill, 2012, p.2) There has been a substantial amount of research based around alleviating negative implications associated with sporadic wind turbine power output, one area of which involves the investigation into battery energy storage systems.

Liang et al. note that, “the connection between wind energy and power grid should be more flexible and stable.” (2012, p.1) As previously mentioned, the principal difficulty with increasing the capacity of wind energy is the resulting problems involving the uncertainty of output. The intermittent nature of wind power output can be regarded as being a consequence of rapid changes in wind speeds, creating large variations, which are also extremely difficult to predict. An example of the problems associated with varying wind turbine power output is outlined by Ela and Kirby. In

Texas, in February 2008, they write, a load increase occurred at the same time as a large and unexpected drop in wind power output and the loss of a conventional generator. This resulted in the Electric Reliability Council of Texas (ERCOT) cutting a large load, so as to reduce the frequency to a normal level. (Ela & Kirby, 2008) This event is highlighted by Beaudin et al. as a perfect exemplification of one of the reasons why the use of large-scale wind power in certain systems ought, arguably, to be limited. (2010, p.302) It occurred because the level of wind power output was expected to be higher than it actually was, and this lower wind output happened at exactly the same time as an unexpected increase in load. However, the event also emphasises the uncertainty and risk associated with the large-scale use of an intermittent source of energy. This case study was an extreme case where everything that could have gone wrong, did, indeed, go wrong. In fact, it also highlights the benefits that an energy storage system could have, if integrated within such a system. Whether it be a large-scale, or in the form of residential systems, these storage systems could be used as a back-up, in order to reduce the requirement of utility companies, in this case, of ERCOT, to cut a large load and thereby inconvenience their consumers. Congruently, Parfomak discusses the operational impacts of wind power generation on the grid, including frequency regulation requirements, load following requirements and transmission requirements, which could be reduced, they claim, with the help of electrical storage. (Ford & Burns, eds., 2012, pp. 4-5)

Energy storage systems, as already recognised in this thesis, can provide different functions in order to improve the varying outputs of renewable sources of power generation such as wind energy. Lu et al. suggest that energy storage, when used in conjunction with wind generation would improve the security of supply from the grid, and would be capable of levelling wind power's irregular output. (2008, p. 2) Such & Hill confirm this, as shown in Figure 4, by including a megawatt-scale battery energy storage system: 'XP Power'. Here, the power output of a wind farm is regulated, as shown in the

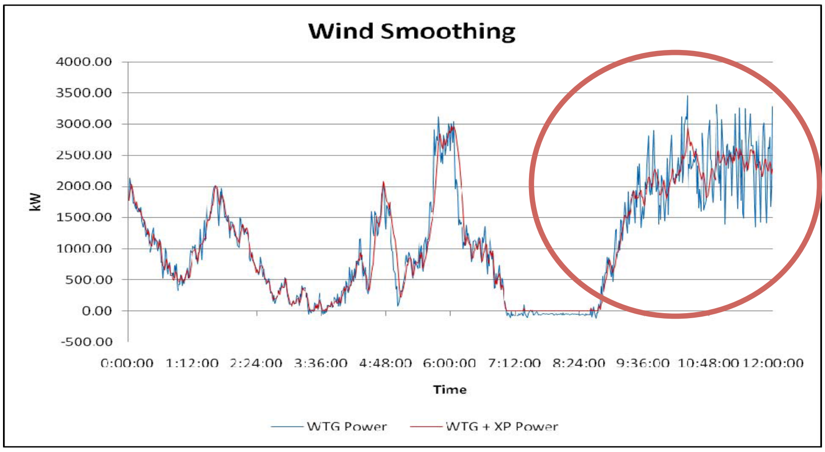


Figure 4 – Energy Storage capabilities of smoothing wind output. (Such & Hill, 2012, p .3)

circled section. (Such & Hill, 2012, p. 3)

When using battery storage systems in order to stabilise the fluctuating power output of wind generation, there are many different characteristics that must first be determined, including power rating, capacity, discharge time, efficiency, cost and many others. (Kaldellis, ed., 2010, pp. 37-40) Furthermore, Such & Hill assert that, when utilising energy storage as a means for controlling power output, one key aspect is ensuring that the battery is always at an appropriate state of charge. (2012, p.3) This is because the power output generated by wind turbines is so irregular that there are extremely large deviations, meaning that batteries are required to be charged and discharged in uneven patterns, which could, in turn, lead to a decreased lifetime. (Such & Hill, 2012, p.3)

All in all, it is clear from the literature that battery energy storage systems can indeed be useful to wind farms, in order to reduce the intermittent nature of this resource. However, this mainly applies to large-scale wind farms, as opposed to the case of the intermittency challenges of solar PV, which can also be applied to small-scale residential systems. However, a study of a "zero energy house" has, in fact, been performed using simulation software, with two small 5kW wind turbines to generate electricity, which resulted in total generation of over 6000kWh. (Wang et al., 2009, p. 1222) On top of this, some, smaller, wind turbines are also available for residential use. Kingspan Wind, manufacture small wind turbines in the UK, with their KW6 wind turbine the most appropriate for domestic use. (Kingspan Wind, 2015) Indeed, Bergey, a US wind turbine company, also manufacture small wind turbines for rural domestic application. (Bergey, 2015) However, the negative environmental and social impacts associated with the widespread use of residential wind systems in built-up areas, such as, visual and noise impacts, and the consequent lack of public support, would arguably nevertheless be highly likely to prevent their application. Despite this, for this thesis, it has been decided that small-scale wind turbines will be assessed with batteries and compared with solar PV.

5. Methodology

5.1. Overview

With a view to fully understanding the effectiveness of various types of energy storage systems, the Hybrid Optimization of Multiple Energy Resources program (HOMER) was used in order to model each storage system with electrical demand and selected renewable supplies in both USA and UK. HOMER is an analysis tool that allows the user to input data in relation to what type of system they want to model. Using complex algorithms, HOMER simulates the designed system and generates results for specified sensitivity cases and also shows the user the optimum system design for the data inputted. The program has also been highlighted in literature as being one of the 'preferred tools' in energy modelling. (Chmeil and Bhattacharyya, 2015, p. 581) This tool has also been used by various scholars to model small-scale renewable energy systems. (Khare et al., 2015; Mokeheimer et al., 2015; Shahinzadeh et al., 2015) This makes HOMER one of the most suitable programs for the modelling of energy storage systems, as its battery calculation methods are very thorough and succinct.

5.2. Location

In order to compare the efficiency of different types of batteries for domestic application in both the USA and the UK, it is appropriate to simulate models in locations in both countries. This is especially important given the fact that, when dealing with renewable technologies such as solar PV and wind turbines, different locations will obviously have different levels of solar irradiance and wind. HOMER is able to carry out this function because the program can source the necessary information from 'NASA Surface meteorology and Solar Energy' data. (HOMER, 2015) The wind data for use with wind turbines is based on monthly averaged values between the years of 1983 and 1993, and the solar data is based on monthly averaged global horizontal irradiance during the period from 1983 to 2005. For simulations, the USA location will be San Francisco and the UK will be Aberdeen. Illustrated below is the climate data extracted from HOMER for wind speeds and solar global horizontal irradiance, which will be crucial in the output of wind turbines and solar PV systems in the simulations.

San Francisco

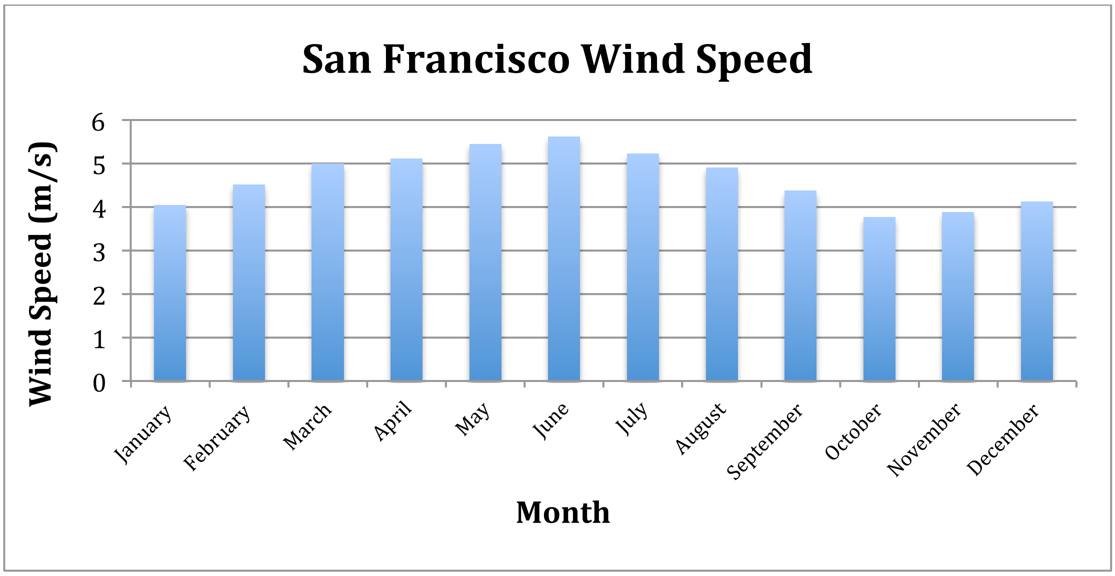


Figure 5 - San Francisco Wind Speed data

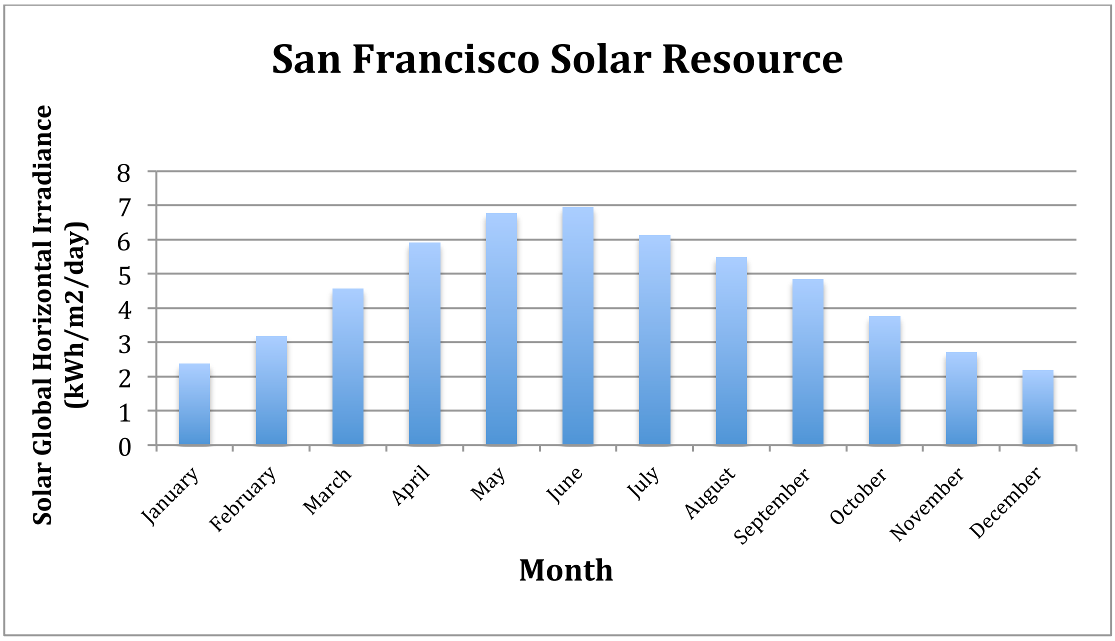


Figure 6 - San Francisco Solar Resource data

Aberdeen

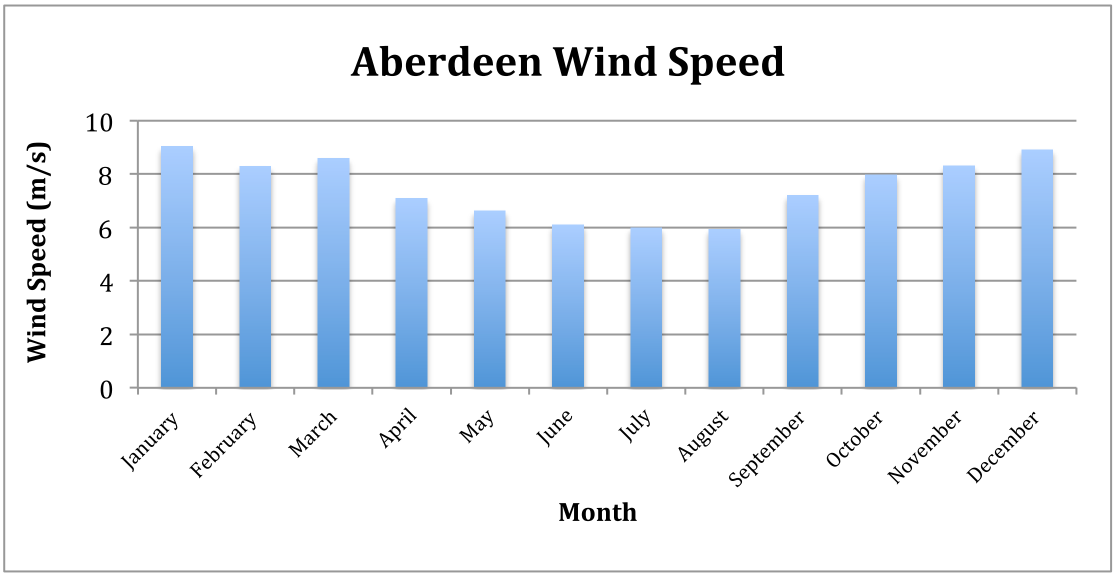


Figure 7 - Aberdeen Wind Speed Data

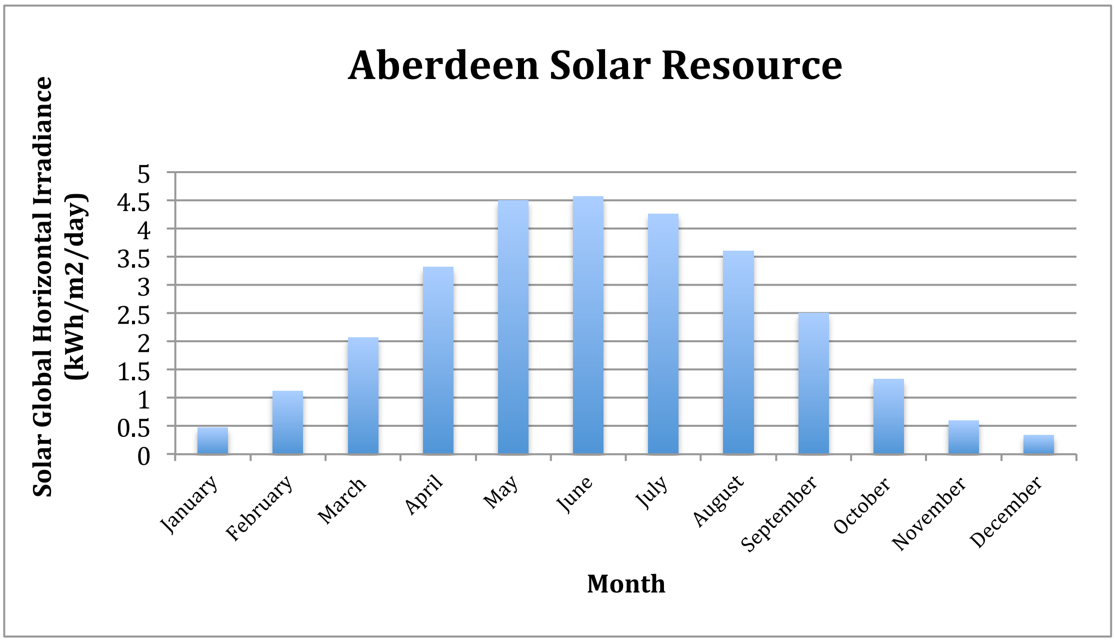


Figure 8 - Aberdeen Solar Resource Data

5.3. Demand

When simulating any renewable energy system, a realistic demand profile is extremely important. This is particularly the case in residential simulations, given that, as previously mentioned, the use of appliances and consumer behaviour are extremely difficult to predict. For this reason, accurate half-hourly data for demand profiles for a typical 3-bedroom house in UK was used, with an energy usage of 5.79kWh/day and a peak power of 0.58kW. (Merit, University of Strathclyde, 2015) This data was retrieved from Merit, a demand/supply matching tool used to simulate renewable energy systems, which uses real data to determine demand profiles for specific types of buildings.(Born et al., 2001, p.1) The resulting demand profile is shown in Figure 9.

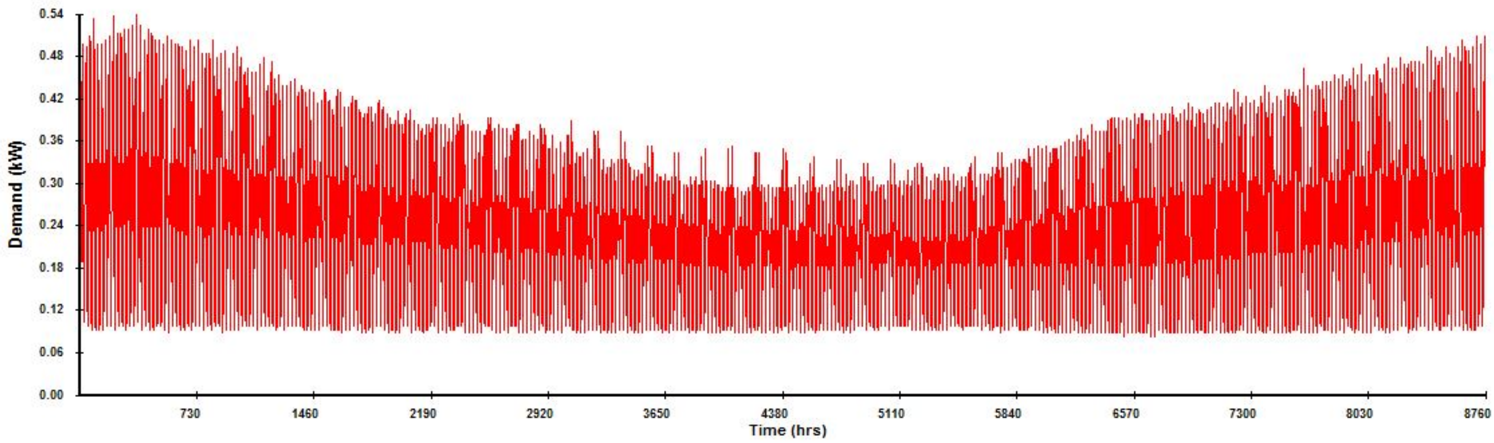


Figure 9 - Demand Profile for typical three-bedroom house in the UK

For simulations in the USA, the demand data was also retrieved from Merit for a typical household, with an energy use of 13.70 kWh/day and 1.22 kW peak power. (Merit, 2015) The demand data used for simulations in both, the USA and the UK, are absolutely critical in determining the amount of supply required and therefore the capacity of energy storage. With accurate data derived from Merit, this is the most suitable demand data possible in order to achieve the best understanding of the functionality of different types of batteries used within a domestic context.

5.4. Supply

There are many different technologies that can be used for residential simulations within HOMER. However, since solar PV is arguably the most popular system for residential supply, this will be used first. For this supply, there are a number of manufacturers who provide PV panels. It is stated by the Energy Saving Trust, that the average size of a domestic system is 4kWp, and for this reason it is the chosen size that will be used in the modelling of residential PV systems for this project. (Energy Saving Trust, 2015) The characteristics used for solar PV panels are based on typical systems that are available for homeowners, available within HOMER.

For the wind turbine simulations, there are various options available that are built into HOMER, but, to make the simulations as realistic as possible, a wind turbine available in the UK, manufactured by Kingspan Wind, will be used. Fortunately, Kingspan Wind have been willing to provide data for one of their wind turbines principally aimed at residential applications, KW6 turbine, with a peak power of 6.1kW. (Kingspan Wind, 2015) The power curve for the KW6 can be seen below.

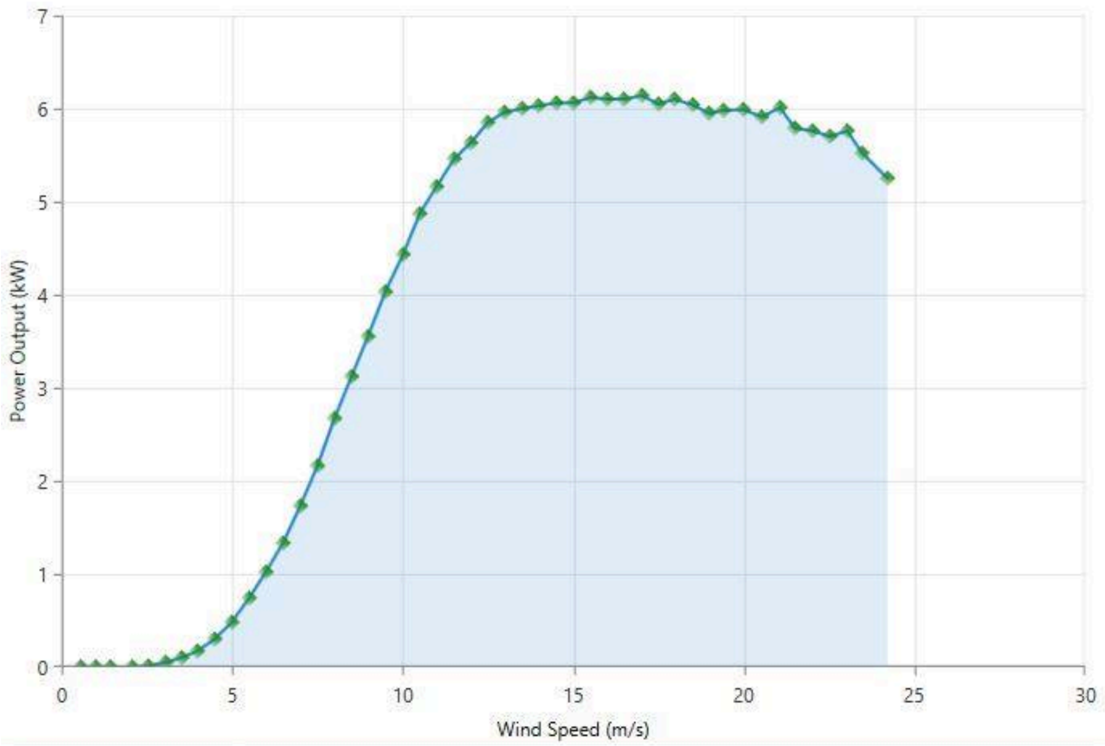


Figure 10 - KW6 Wind Turbine Power curve ***(data courtesy of Kingspan Wind)***

5.5. Inverter

When using a battery in a residential renewable energy system, it is necessary to have an AC/DC inverter, as household appliances and other loads run on alternating current and battery systems require direct current. For the simulations carried out for this thesis, a typical inverter system will be used, based on products available on the market. The chosen inverter for the grid-connected simulations will be the SMA product, 2.5 kW Sunny-Boy. (SMA Sunny Boy Inverter 2.5kW, 2015) For the stand-alone simulations, the chosen inverter will again be an SMA product, this time, the 3.3 kW Sunny-Island Inverter. (SMA Sunny Boy Inverter 3.3kW, 2015)

5.6. Energy Storage System

It has already been stated in the introduction that the aim of this thesis is to compare and assess some of the different battery types used in energy storage systems, for their effectiveness in improving residential energy use. For this reason, it is crucial that these systems are simulated correctly to achieve the most accurate results as possible. As described in Chapter 2, there are many different characteristics of batteries that determine their success at storing energy. These characteristics are the critical components that must be inputted into HOMER, in order to accurately simulate batteries. The types of batteries being assessed are lithium-ion batteries: SAFT Intensium Home, LG Chem and Juicebox Energy; flooded lead-acid batteries: Trojan IND29-4V and Trojan IND17-6V; and one tubular gel lead-acid battery: Discover 6VRE-2400TG.

One of the most important variables in modelling batteries is the capacity value. In HOMER, this can be inputted, either by entering capacity values for different discharge currents – creating a capacity curve – or by selecting an idealised storage model for a particular nominal capacity. The latter is not as accurate as the former. However, for the batteries used in the storage systems being assessed, it would not have been possible to include a kinetic battery model, as each battery would have to be thoroughly tested. Other key factors that had to be inputted for each battery system were the maximum charge and discharge currents, nominal voltage, lifetime and number of cycles to failure. For the residential battery systems under comparison, these characteristics are detailed in the specification sheets available in the Appendix.

Energy Storage System	Battery Type	Round Trip Efficiency (%)	Min. State of Charge (%)	Max. Charge Current (A)	Max. Discharge Current (A)	Nominal Capacity (Ah)	Nominal Voltage (V)	Float Life (years)
SAFT Intensium Home	Lithium-ion	**96**	**20**	**82**	**160**	**84**	**48**	**20**
Juicebox Energy	Lithium-ion	**98**	**20**	**80**	**140**	**172**	**50**	**10**
LG Chem	Lithium-ion	**95**	**20**	**38**	**38**	**126**	**52**	**10**
Discover 6VRE-2400TG	Tubular Gel Lead-Acid	**85**	**20**	**93**	**234**	**200**	**6**	**18**
Trojan IND29-4V	Flooded/Wet Lead-Acid	**81**	**20**	**271**	**242**	**1618**	**4**	**20**
Trojan 17-6V	Flooded/Wet Lead-Acid	**81**	**20**	**155**	**208**	**925**	**6**	**18**

Table 1 - Battery Characteristics

In the case of the simulations carried out for this project each time-step was one hour. With the key data for each battery shown above, HOMER carries out many complex algorithms assessing, for the grid-connected simulations, at each time-step, the amount of power that the battery systems can absorb, and whether power should be absorbed by the battery or exported to the grid. This is also the case in relation to consumption. At each time-step, HOMER decides, either to import power from the grid, or that the battery is capable of supplying enough power to the loads.

5.7. Economic Aspects

In order to assess economic feasibility as well as technical feasibility of each type of battery energy storage system, reliable data first had to be found for each component of the systems that made up the simulations. Due to the confidentiality of some of the products' prices, in some cases, the cost had to be estimated based on literature and other sources. In this section, each component's cost is detailed, along with the grid import costs and export prices used for grid-connected simulations.

Firstly, looking at the cost of solar panels, the size of a typical home solar PV system is identified by the Energy Saving Trust as 4 kWp. They then go on to state that the cost of such a system would range between £5,000 and £8,000. (Energy Saving Trust, 2015) For this reason, the cost of the 4kWp PV system used in the analysis was £6,500.

The wind turbine used in the simulations, as previously noted, is the Kingspan Wind KW6 turbine. Fortunately, Kingspan were willing to provide a range of data for this project and, in a meeting with the manufacturer, a total price including installation of the wind turbine was identified as £32,000.

As previously detailed in section 5.5., two types of inverter had to be used in the modelling process, one for grid-connected, and one for off-grid simulations. For the grid-connected simulations, the 2.5kW SMA Sunny Boy inverter was used, which has a retail price of £632.14. (Wind and Sun, 2015) For the stand-alone simulations, the price used for the 3.3kW Sunny-Island inverter was £2,000. (Wind and Sun, 2015)

Arguably the most important factor in assessing the economics of employing energy storage systems is the cost of the batteries themselves. There are many papers throughout the literature that provide a range of costs for different battery types. However, a paper by Anuphappharadorn et al. is one of the few to give one specific value for $/kWh of lithium-ion and lead-acid batteries based on their findings. (2014, Table 1, p. 354) A cost of 600 $/kWh is given for lithium-ion and of 120 $/kWh for lead-acid. (Anuphappharadorn et al., 2014, Table 1, p. 354) As the simulations in both the USA and the UK are being economically assessed in GBP, this price had to be converted into pounds sterling. In order to find the price of each type of battery device, as the cost was determined by nominal capacity (kWh), the nominal capacities (Ah) of each battery had to be converted to kWh. The calculations of which are shown in the table below, detailing the expected costs of each battery for the given costs in GBP, based on an estimated exchange rate of 0.649.

Battery Type	Type of Battery	Nominal Voltage (V)	Nominal Capacity (Ah)	Capacity (kWh)	Cost ($)	Cost (£)
SAFT Intensium Home	Lithium-ion	48	84	4.03	2580	**1674**
Juicebox	Lithium-ion	50	172	8.60	5160	**3349**
LG Chem	Lithium-ion	52	126	6.55	3930	**2550**
Discover 6VRE-2400TG	Tubular Gel Lead-acid	6	340	2.04	530	**345**
TrojanIND29-4V	Flooded/Wet Lead-acid	4	1618	6.47	776	**504**
TrojanIND17-6V	Flooded/Wet Lead-acid	6	925	5.55	666	**432**

Table 2 - Estimated Battery Costs

For the grid-connected simulations, import costs and export prices had to be used, in order for HOMER to assess whether it was economically appropriate to store electricity or whether to export it to the grid. In the USA simulations, the import cost used was 8 p/kWh, taken from the EIA website as a typical electricity price. (EIA, 2015b) For the export price in the USA simulations, a price of 5 p/kWh was used as an estimate, based on the built-in export price within HOMER. (HOMER, 2015) (EIA, 2015c)

In order to simulate residential renewable systems connected to the grid in the UK, an import price of 15p/kWh was taken from utility provider SSE. (SSE, 2015b) For the export price, a value of 4.85p/kWh was taken from the Energy Saving Trust website, as a typical value for residential PV systems and wind turbines. (Energy Saving Trust, 2015b) An assumption made in the economic assessment of each simulation is that there is no feed-in-tariff involved.

5.8. Simulations

Initially, a typical 3-bedroom household connected to the grid in San Francisco, USA and Aberdeen, UK will be assessed, in order to find the most suitable type of energy storage battery for each situation. This will evaluate the effectiveness of each type of storage system with two types of renewable electricity supply individually, firstly, a home solar PV system of 4 kWp, and secondly with a residential wind turbine of 6.1kWp. These results will then be compared to understand the most beneficial route for residential renewable technology use at said locations in both countries whilst connected to the grid. Both locations will then be simulated for the same system but without being connected to the grid. The main technical outputs of the simulations will be type of dispatch used, autonomy, annual throughput, renewable fraction, electrical production and, most importantly, state of charge (SOC). The economic results will demonstrate grid interaction of each system type, operating cost, initial capital and finally net present cost. The full meaning of these output parameters are detailed in full below.

Firstly, the type of dispatch used in the system is the way in which HOMER strategically decides what the best way, and therefore best combination of supplies, is to serve the load. By using a load following type of dispatch, a generator produces enough power to meet a load. The function of charging the batteries in this type of dispatch is not performed by a generator, but by renewable supplies. For this type of dispatch, HOMER serves the load with cheapest option of power sources for each time step. Cycle charging, uses the exact same step initially, but then, allows the generator or grid to operate at full power to meet a load, and surplus electricity will be used to charge batteries. The output of autonomy, is the ratio of the battery bank size to the electric load. This value for each battery is the same for all San Francisco simulations and all Aberdeen simulations. It is therefore only noted in initial results Table 3 and Table 6. The annual throughput is the total amount of energy that was charged and discharged by the battery in kWh/year. This output illustrates how much the battery has been used in the simulation and is extremely important in the lifetime of the batteries, as this is strongly dependent on the number of cycles, as stated in Chapter 2. The renewable fraction, determines how much renewable power sources such as, in this case, solar PV systems and wind turbine systems, have been used to produce electricity for the load. This is fully dependent on the solar and wind resource given for the simulated climate, and so the results vary greatly in Aberdeen and in San Francisco. The grid interaction for the grid-connected simulations is crucial, as this depicts whether or not the storage is being used, based on the money that can be saved by exporting electricity to the grid, rather than storing it. The operating cost is based on the value of all costs and revenues other than the initial capital cost. In the systems simulated, this includes, replacement costs of batteries, PV panels and wind turbines, if they are encountered in the project lifetime, maintenance costs. Net present cost is the present value of all the costs of installing and operating that component over the project lifetime, minus the present value of all the revenues that it earns over the project lifetime. HOMER calculates the net present cost of the entire system. Costs that are included in the analysis are, capital costs, replacement costs, maintenance costs, fuel costs, emissions penalties, import costs and export revenues. (All: HOMER, 2015) Once the simulations were carried out for each battery type for grid-connected application in both San Francisco and Aberdeen, it was then appropriate to determine each battery's capability of functioning independently of the grid. For some of these simulations, a generator was required in order to compensate for the intermittent nature of solar PV system and wind turbine output. The generator used in these cases, was an automatically sized generator built-in to the HOMER program, which is sized according to the load required to be met. The key technical outputs, similar to that of grid-connected simulations, were type of dispatch, autonomy, annual throughput, renewable fraction, production and also in this case, excess electricity. The significant results from the economic analysis are similar to that of the grid-connected case, the operating costs, initial capital costs and net present cost.

Each model was simulated in hourly time-steps, for a project lifetime of 15 years. In order to determine the most suitable form of dispatch, both load following and cycle charging were selected to determine which one would result in the optimum result, these will be further explained later in this thesis. HOMER gives the optimum results in order of the net present cost. This is included in the results section of this investigation, however, it is important to note that the technical outputs of each simulation are of equal importance in order to determine the most suitable battery both in terms of economic and technical feasibility.

6. Results

6.1 Grid Connected

6.1.1. San Francisco

6.1.1.1. Home Solar PV System

Battery Type	Dispatch	Autonomy (Hours)	Annual Throughput (kWh)	Ren Fraction (%)	Production (%)	
					PV	Grid
6VRE-2400TG	CC	2.86	3.53	63.32	68.90	31.10
IND17-6V	CC	7.78	5.91	63.32	68.91	31.09
IND29-4V	CC	9.07	6.93	63.32	68.91	31.09
SAFT	LF	5.65	7.70	63.34	68.90	31.10
LG Chem	LF	9.18	376.19	62.54	70.61	29.39
Juicebox	CC	12.05	6.88	63.27	68.85	31.15

Table 3 - San Francisco Home Solar PV System (grid-connected) Technical Results

Battery Type	Operating cost (£)	Initial capital (£)	Grid Interaction (kWh)		Net Present Cost (£)
			Import	Export	
6VRE-2400TG	-22.98	7477.14	2979.52	3122.90	7252.19
IND17-6V	-25.14	7564.14	2979.52	3122.14	7318.14
IND29-4V	-25.90	7636.14	2979.51	3121.90	7382.61
SAFT	-38.75	8806.14	2978.60	3123.85	8426.84
LG Chem	80.32	9682.14	2969.28	2927.00	10468.29
Juicebox	100.29	10481.14	2985.35	3128.85	11462.74

Table 4 - San Francisco Home Solar PV System (grid-connected) Technical Results

Discover 6VRE-2400TG

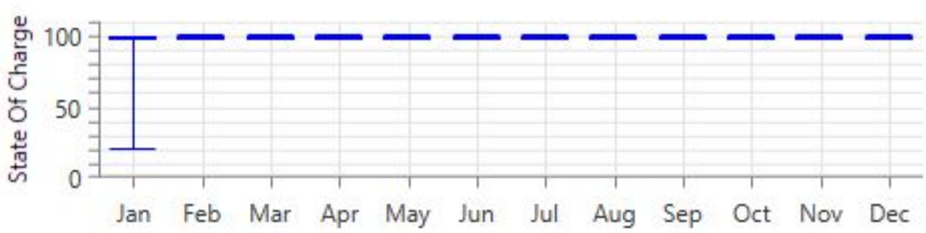


Figure 11 - Discover 6VRE-2400TG SOC for PV (grid-connected) System in San Francisco

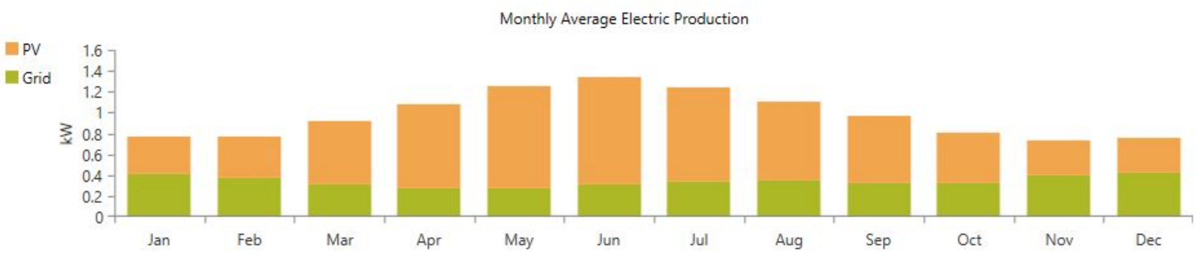


Figure 12 – Electricity Production for Discover 6VRE-2400TG with PV (grid-connected) System in San Francisco

TROJAN IND17-6V

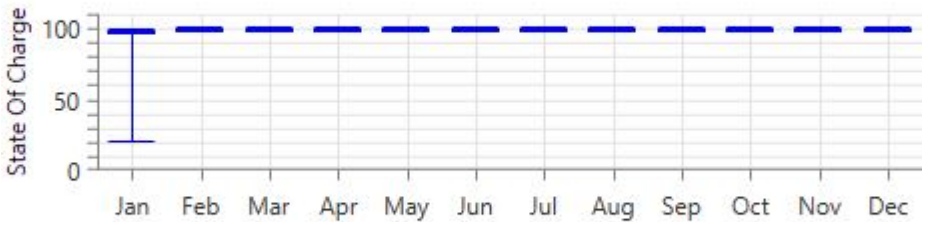


Figure 13 – Trojan IND17-6V SOC for PV (grid-connected) System in San Francisco

TROJAN IND29-4V

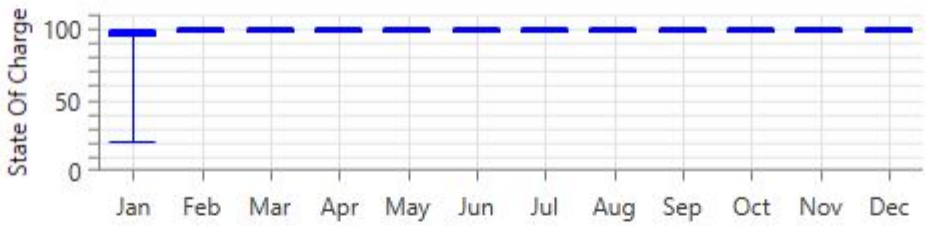


Figure 14 – Trojan IND29-4V SOC for PV (grid-connected) System in San Francisco

SAFT Intensium Home

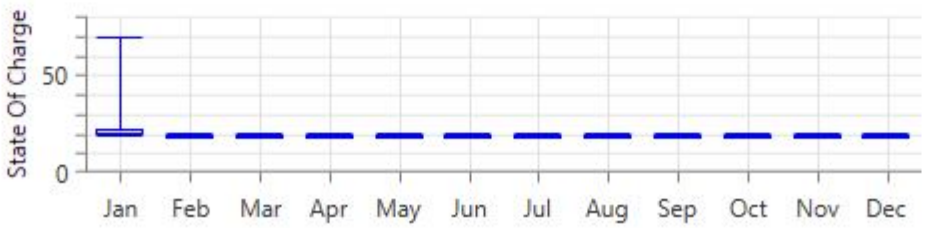


Figure 15 – SAFT Intensium Home SOC for PV (grid-connected) System in San Francisco

LG Chem

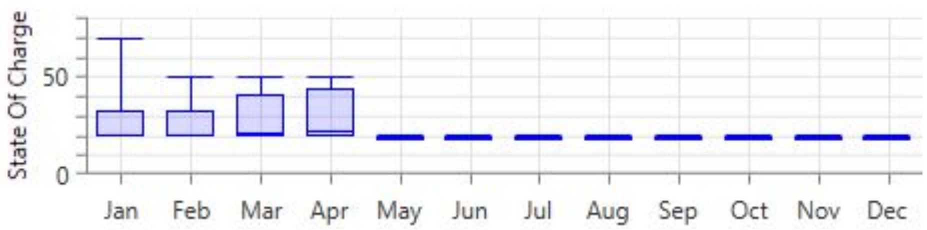


Figure 16 – LG Chem SOC for PV (grid-connected) System in San Francisco

Juicebox Energy

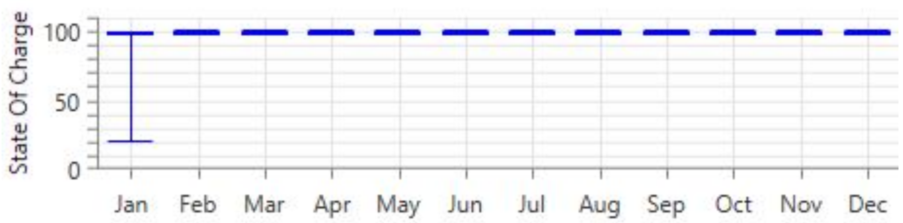


Figure 17 – Juicebox Energy SOC for PV (grid-connected) System in San Francisco

This simulation resulted in a PV output of 5597 kWh, which has been used in conjunction with the grid to meet a consumption of approximately 8000 kWh. Referring to Figures 11-17, it is evident from the state of charge profiles that each battery system is not being properly utilised. The Discover 6VRE-2400TG, Trojan IND17-6V, Trojan IND29-4V and Juicebox batteries are charged to 100% in January and are then hardly discharged, if at all. The case for the SAFT Intensium Home battery, meanwhile, is the reverse, with this battery remaining at its minimum state of charge of 20% for the entire year. LG Chem is the only battery that has been of some use for the system, as illustrated by its high value of annual throughput in comparison to the other technologies, detailed in Table 3. It is clear in Figure 16, however, that this battery is only used from January to April, after which, like the SAFT Intensium Home battery, it is kept at its minimum state of charge, 20%. A further simulation was constructed after this test, in order to determine the operating costs with no PV system or batteries, with the load being solely met by the grid. This resulted in an operating cost of £400 per year, which was the payment for imported electricity. It is clear, from the negative operating costs for the four battery types contained in Table 4, that the PV system could generate an annual income. This is the result of exported electricity, another reason against the use of storage systems, because, rather than storing any 'extra' electricity, it makes more economic sense to export it for revenue. This also explains the use of the LG Chem battery, since its exports are lower than those of the other battery systems, as highlighted in Table 4. It is evident from Table 4 that the use of lead-acid batteries will result in the best net present cost over the project lifetime of 15 years, given that lead-acid batteries are substantially cheaper than lithium-ion.

6.1.1.2. Home Wind System

Battery Type	Dispatch	Annual Throughput (kWh)	Ren Fraction (%)	Production (%)	
				Wind	Grid
6VRE-2400TG	CC	3.53	70.38	70.38	29.62
IND17-6V	CC	5.91	70.38	70.38	29.62
IND29-4V	CC	6.93	70.37	70.38	29.62
SAFT	CC	2116.85	72.90	73.60	26.40
LG Chem	LF	376.66	70.39	70.52	29.48
Juicebox	CC	6.88	70.33	70.33	29.67

Table 5 - San Francisco Home Wind System (grid-connected) Technical Results

Battery Type	Operating cost (£)	Initial capital (£)	Grid Interaction (kWh)		Net Present Cost (£)
			Import	Export	
6VRE-2400TG	173.05	32977.14	2564.02	3655.64	34670.87
IND17-6V	170.90	33064.14	2563.90	3654.70	34736.81
IND29-4V	170.14	33136.14	2563.89	3654.41	34801.31
SAFT	156.67	34306.14	2185.67	3065.04	35839.49
LG Chem	268.68	35182.14	2547.28	3602.95	37811.80
Juicebox	296.32	35981.14	2569.78	3661.63	38881.35

Table 6 - San Francisco Home Wind System (grid-connected) Economic Results

Discover 6VRE-2400TG

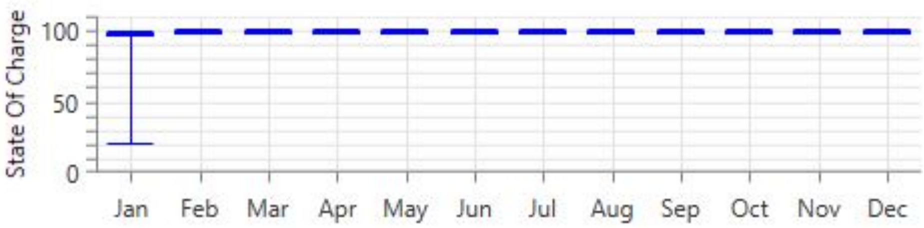


Figure 18 - Discover 6VRE-2400TG SOC for Wind (grid-connected) System in San Francisco

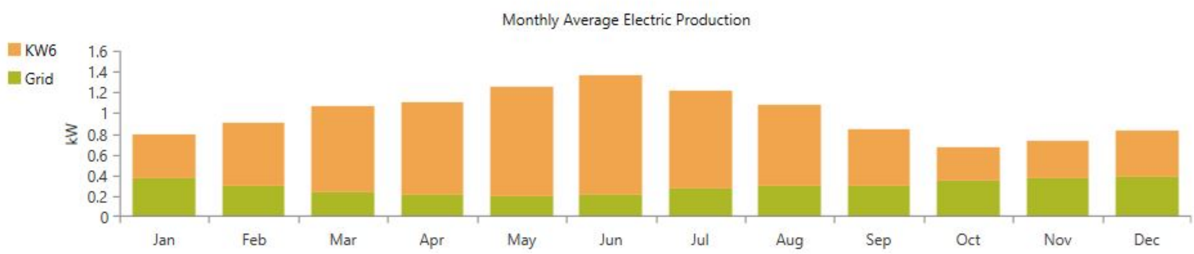


Figure 19 – Electricity Production for Discover 6VRE-2400TG with Wind (grid-connected) System in San Francisco

TROJAN IND17-6V

Figure 20 – Trojan IND17-6V SOC for Wind (grid-connected) System in San Francisco

TROJAN IND29-4V

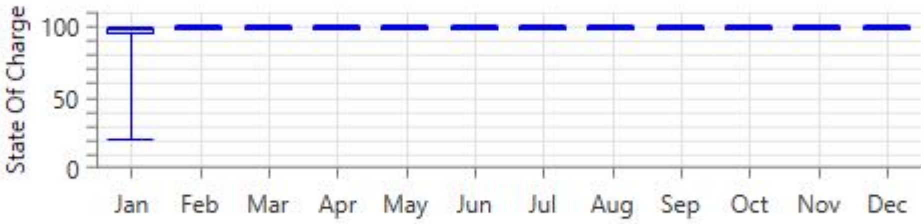


Figure 21 – Trojan IND29-4V SOC for Wind (grid-connected) System in San Francisco

SAFT Intensium Home

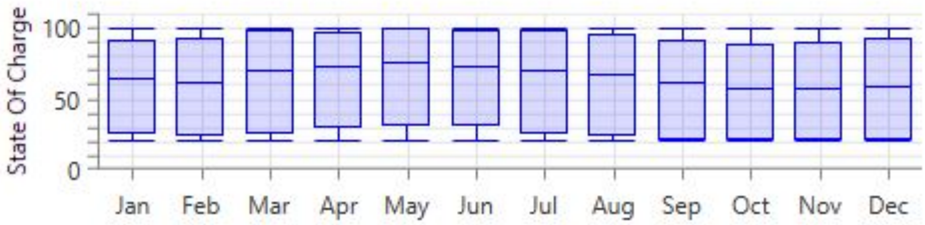


Figure 22 – SAFT Intensium Home SOC for Wind (grid-connected) System in San Francisco

LG Chem

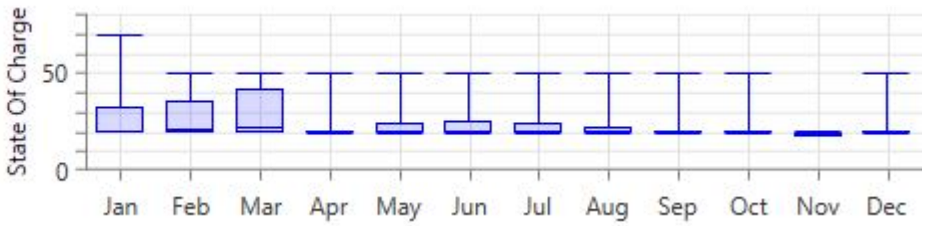


Figure 23 – LG Chem SOC for Wind (grid-connected) System in San Francisco

Juicebox Energy

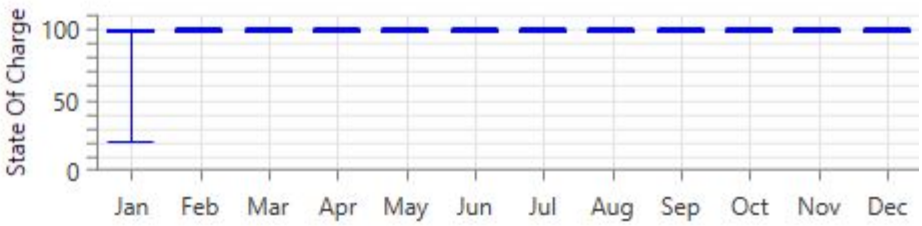


Figure 24 – Juicebox Energy SOC for Wind (grid-connected) System in San Francisco

This simulation resulted in a wind output of 6092 kWh: slightly higher than the output of the PV system in the previous model. This seems to be an appropriate result, since the wind turbine has a higher peak power output than the solar PV system. This case is similar to the last, in that the batteries are not being used to their full potential, given that it is more economically beneficial for the consumer to export the electricity rather than store it. As was witnessed in the previous simulation, here, the Discover 6VRE-2400TG, Trojan IND17-6V, Trojan IND29-4V and Juicebox batteries are also all charged to 100% state of charge and then not discharged for the remainder of the year. However, the SAFT Intensium Home battery differs much more significantly from the others in this case than it did in the last. This time, the optimum type of dispatch for the system is cycle charging, whereby the battery is charged and discharged monthly, resulting in a high annual throughput in comparison to the other batteries. LG Chem is also used in the same way as the last simulation, resulting in a similar annual throughput. All the battery types result in a higher net present cost than that witnessed with the PV simulations, which is heavily dependent on the high capital cost of the wind turbine itself. The revenue experienced in the previous system, due to export income, cannot not be matched in this case, due to the fact that the maintenance costs of the wind turbine, estimated at £500 a year, result in annual operating costs.

Referring to both types of systems used in a typical grid-connected dwelling in San Francisco, there are several conclusions that can be drawn. It can be understood from the results that a residential wind turbine system is more appropriate than solar PV in this case, due to a higher amount of energy produced over each year. However, this is largely down to the fact that the wind turbine has a greater peak power output. The large net present cost of wind turbine systems demonstrates that, without any form of financial incentive, this would not be economically feasible, whereas the PV system for all batteries results in revenue, meaning that not as large a subsidy would be required to generate high levels of revenue with this technology. In terms of battery systems, it is evident that they are not being used to their full potential, due to the fact that importing electricity is a reasonably cheap option. That said, for the wind system, the SAFT Intensium is the most suitable battery system, in that, despite a higher net present cost, this battery is being used over all months, meaning that the use of energy storage is of benefit to this model.

6.1.2. Aberdeen

6.1.2.1. Home Solar PV System

Battery Type	Dispatch	Autonomy (Hours)	Annual Throughput (kWh)	Ren Fraction (%)	Production (%)	
					PV	Grid
IND29-4V	LF	21.47	830.98	84.34	85.66	14.34
IND17-6V	LF	18.41	779.68	83.34	84.69	15.31
6VRE-2400TG	LF	6.77	684.38	82.10	83.25	16.75
SAFT	CC	13.37	1238.25	78.60	80.11	19.89
LG Chem	CC	21.73	1299.94	82.34	83.70	16.30
Juicebox	CC	28.52	6.88	70.85	72.16	27.84

Table 7 - Aberdeen Home Solar PV System (grid-connected) Technical Results

Battery Type	Operating cost (£)	Initial capital (£)	Grid Interaction (kWh)		Net Present Cost (£)
			Import	Export	
IND29-4V	-106.48	7636.14	561.56	1473.46	6409.81
IND17-6V	-99.62	7564.14	606.35	1527.51	6416.83
6VRE-2400TG	-82.53	7477.14	674.97	1657.62	6526.61
SAFT	-107.76	8806.14	832.41	1776.00	7565.06
LG Chem	-12.83	9682.14	653.28	1586.76	9534.36
Juicebox	75.93	10481.14	1293.72	2324.47	11355.69

Table 8 - Aberdeen Home Solar PV System (grid-connected) Economic Results

TROJAN IND29-4V

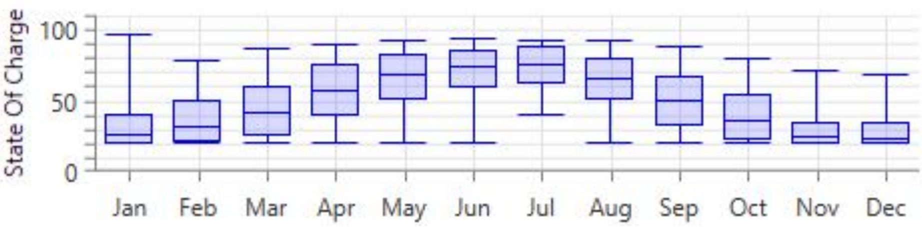


Figure 25 – Trojan IND29-4V SOC for PV (grid-connected) System in Aberdeen

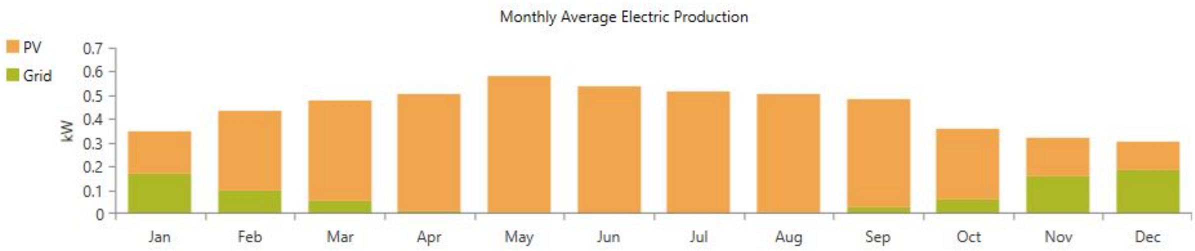


Figure 26 – Electricity Production for Trojan IND29-4V with PV (grid-connected) System in Aberdeen

TROJAN IND17-6V

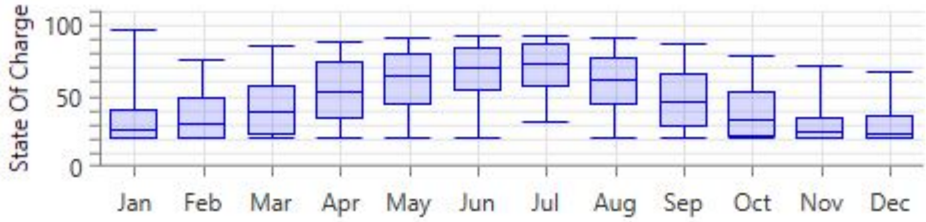


Figure 27 – Trojan IND17-6V SOC for PV (grid-connected) System in Aberdeen

Discover 6VRE-2400TG

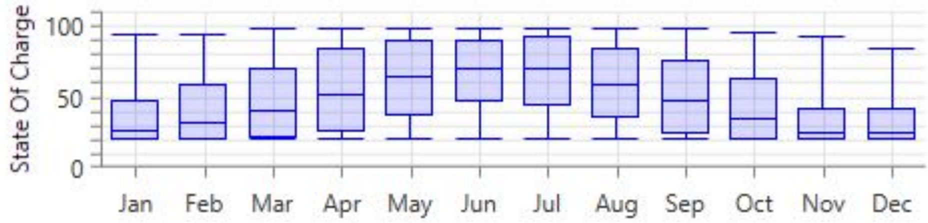


Figure 28 – Discover 6VRE-2400TG SOC for PV (grid-connected) System in Aberdeen

SAFT Intensium Home

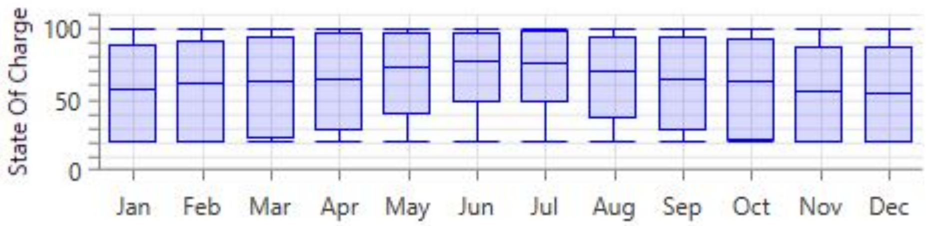


Figure 29 – SAFT Intensium Home SOC for PV (grid-connected) System in Aberdeen

LG Chem

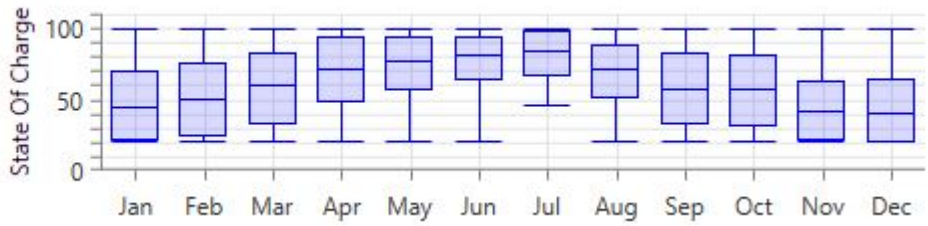


Figure 30 – LG Chem SOC for PV (grid-connected) System in Aberdeen

Juicebox Energy

Figure 31 – Juicebox Energy SOC for PV (grid-connected) System in Aberdeen

The PV output of the Aberdeen grid-connected simulation was 3354 kWh, substantially less than the PV output of the San Francisco simulation of 5597 kWh, which makes sense, due to the much more extensive solar resource available in California than in North-East Scotland. The PV generation plays a big part in meeting the consumption in the summer months, as is illustrated in Figure 26. However, even with the lower PV output, almost all batteries are better utilised in this simulation than in those performed for San Francisco. This could be down to a number of factors, and is arguably primarily due to the high import cost of 15p/kWh used for the Aberdeen simulations, meaning that it would more economical for the consumer to store the electricity as much as possible, as opposed to importing energy from the grid. The use of the batteries could also be due to the fact that the load to be met in the Aberdeen simulation is much lower than the load required in the San Francisco model, in which less needed to be discharged at one time. Both the SAFT Intensium Home and the LG Chem batteries have a high annual throughput, this time in the cycle charging type of dispatch. The Juicebox battery system is the only type that is not being fully utilised. Comparing the lithium-ion SAFT Intensium Home battery in this case to the other lead-acid batteries, it is clear from the state of charge graph in Figure 29 that this battery is being charged fully and then discharged until empty. As previously noted, this is healthy for the battery as it means that it is experiencing full cycles, rather than discharging when the battery is at a low state of charge, which, as demonstrated in Figures 25, 27 and 28, is the case for the lead-acid batteries during the winter months. Comparing these results to the San Francisco PV results, it is apparent that, here, the batteries are better utilised, meaning that it is more economically beneficial, given the UK's import/export rates, to implement storage to meet the load. Here, the lead-acid batteries result in the lowest net present cost, but, with a higher annual throughput, the SAFT Intensium Home lithium-ion generates greater revenue.

6.1.2.2. Home Wind System

Battery Type	Dispatch	Annual Throughput (kWh)	Ren Fraction (%)	Production (%)	
				Wind	Grid
6VRE-2400TG	LF	360.00	99.96	99.96	0.04
IND17-6V	CC	377.21	100.00	100.00	0.00
IND29-4V	CC	377.86	100.00	100.00	0.00
SAFT	LF	2435.95	98.26	98.28	1.72
LG Chem	CC	713.66	98.29	98.29	1.71
Juicebox	CC	6.88	98.24	98.24	1.76

Table 9 - Aberdeen Home Wind System (grid-connected) Technical Results

Battery Type	Operating cost (£)	Initial capital (£)	Grid Interaction (kWh)		Net Present Cost (£)
			Import	Export	
6VRE-2400TG	-719.92	32977.14	7.93	16633.16	24685.55
IND17-6V	-725.39	33064.14	0.00	16603.65	24709.53
IND29-4V	-726.37	33136.14	0.00	16602.91	24770.21
SAFT	-701.32	34306.14	328.51	16789.79	26228.77
LG Chem	-597.16	35182.14	326.86	16958.12	28304.41
Juicebox	-571.24	35981.14	337.04	17042.31	29401.93

Table 10 - Aberdeen Home Wind System (grid-connected) Economic Results

Discover 6VRE-2400TG

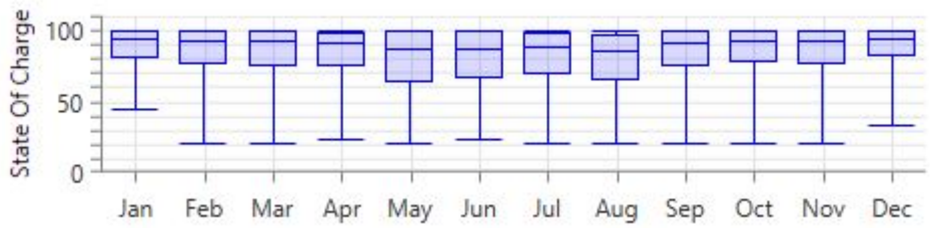


Figure 32 – Discover 6VRE-2400TG SOC for Wind (grid-connected) System in Aberdeen

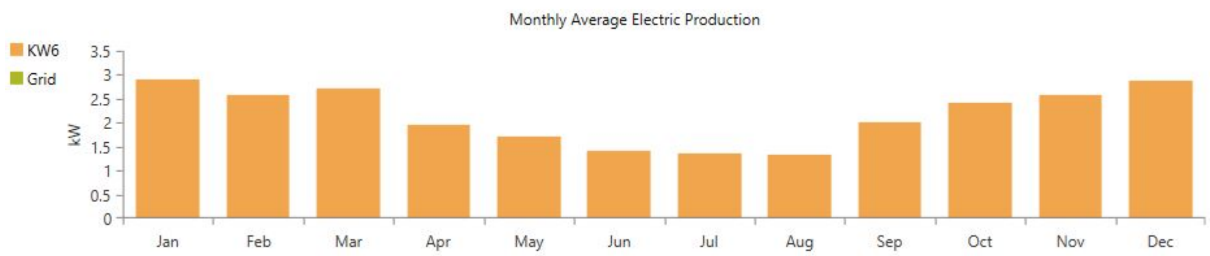


Figure 33 – Electricity Production for Discover 6VRE-2400TG with Wind (grid-connected) System in Aberdeen

TROJAN IND17-6V

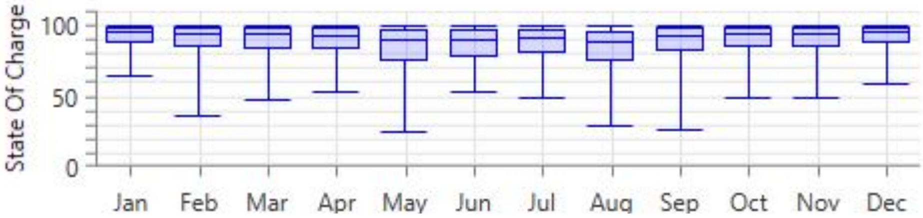


Figure 34 – Trojan IND17-6V SOC for Wind (grid-connected) System in Aberdeen

TROJAN IND29-4V

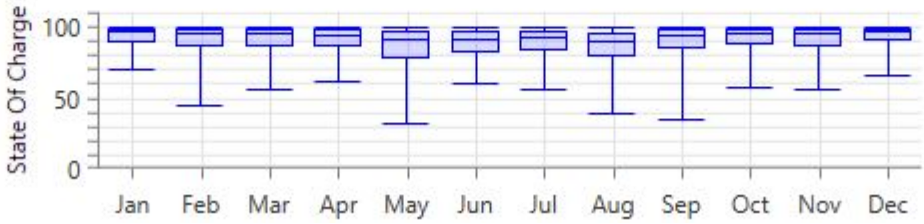


Figure 35 – Trojan IND29-4V SOC for Wind (grid-connected) System in Aberdeen

SAFT Intensium Home

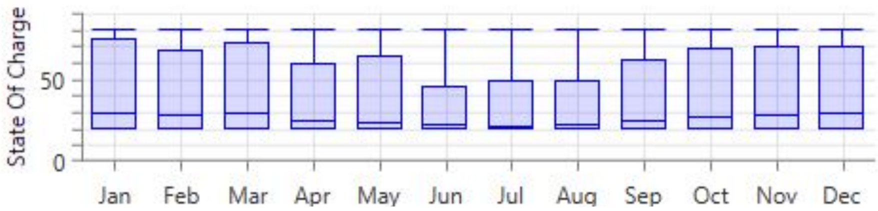


Figure 36 – SAFT Intensium Home SOC for Wind (grid-connected) System in Aberdeen

LG Chem

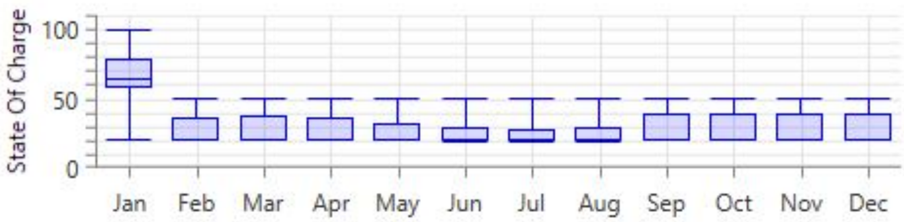


Figure 37 – LG Chem SOC for Wind (grid-connected) System in Aberdeen

Juicebox Energy

Figure 38 – Juicebox Energy SOC for Wind (grid-connected) System in Aberdeen

The abundant wind resource available in Scotland is strongly highlighted in this case, as the simulation resulted in a wind output of 18,819kWh per year. As illustrated in Tables 9 and 10, this amount of electricity generation helps towards a renewable fraction of 100% and no imported electricity in the case of the Trojan IND29-4V. Since the consumption is relatively low in the case of the Aberdeen models, there is scope for a large amount of electricity to be exported to the grid as a source of income, so as to counteract the high capital cost of the wind turbine. As shown in Table 10, each type of battery configuration results in revenue from exports, despite the annual maintenance cost of the wind turbine of £500. It is illustrated in Figures 32, 34 and 35 that the lead-acid batteries are operated, in this configuration, from a 100% state of charge, as there are only some cases per month where the state of charge of any of these batteries is below 80%. Meanwhile, in the case of SAFT Intensium Home battery, the state of charge varies greatly from month to month, with more widespread use in the winter months. Again, the Juicebox battery has an extremely low annual throughput in this case, resulting in the highest imports/exports, which also lessens the revenue in relation to the other types of batteries. This endows the Juicebox battery with the highest net present cost over the whole project lifetime. These results emphasise the profuseness of Scotland's wind resource, and that, if more residential wind turbines were to be used in connection to the grid, there is great scope for an income stream. As previously mentioned, these results are not taking into account any feed-in-tariff schemes. However, with this policy currently in place in reality, it is clear from these results that a substantial income could be generated, through both the exportation of electricity to the grid, and also the receipt of money for generating electricity by means of wind power technology.

In the case of a residential renewable energy system in Aberdeen, it is clear that there is great potential for both a PV system and a wind turbine system. To be sure, wind energy results in a higher net present cost. However, with the help of feed-in-tariffs, this result could be easily offset, creating a good source of revenue each year. From the results of the simulations detailed and explained above, the wind resource in Aberdeen is clearly better than the solar resource, meaning that this type of system would be favourable. Both types of systems, however, with the help of financial incentives, could work well. The SAFT Intensium Home battery is particularly good in both cases, boasting a high annual throughput.

6.2. Stand-alone

6.2.1. San Francisco

6.2.1.1. Home Solar PV System

Battery Type	Dispatch	Annual Throughput (kWh)	Excess Electricity (kWh/yr)	Ren Fraction (%)	Production (%)	
					PV	Generator
IND29-4V	CC	1915.07	2606.81	44.47	66.80	33.16
SAFT	CC	1924.89	2909.99	43.81	66.50	33.42
IND17-6V	CC	1962.04	2740.86	40.43	65.20	34.73
Juicebox	LF	1826.12	1730.38	72.88	80.40	19.50
6VRE-2400TG	CC	1699.43	3094.45	36.86	63.90	36.07
LG Chem	LF	1465.01	2094.93	65.17	76.30	23.73

Table 11 - San Francisco Home Solar PV system (stand-alone) Technical Results

Battery Type	Operating cost (£)	Initial capital (£)	Net Present Cost (£)
IND29-4V	1053.92	9704.00	20019.11
SAFT	947.25	10874.00	20145.02
IND17-6V	1098.54	9632.00	20383.81
Juicebox	861.92	12549.00	20984.96
6VRE-2400TG	1289.47	9545.00	22165.53
LG Chem	1113.85	11750.00	22651.63

Table 12 - San Francisco Home Solar PV system (stand-alone) Economic Results

TROJAN IND29-4V

Figure 39 – Trojan IND29-4V SOC for PV (stand-alone) System in San Francisco

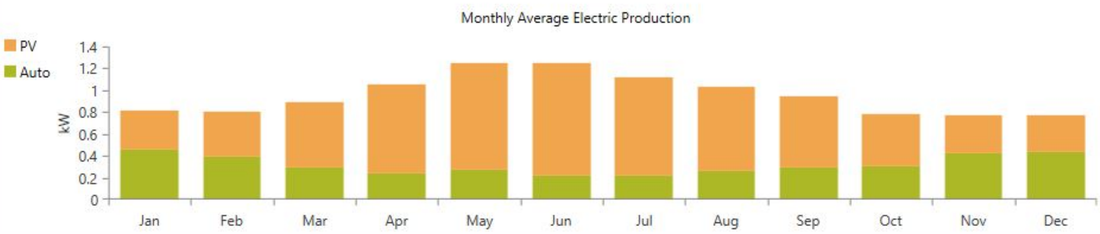


Figure 40 – Electricity Production for Trojan IND29-4V with PV (stand-alone) System in San Francisco

SAFT Intensium Home

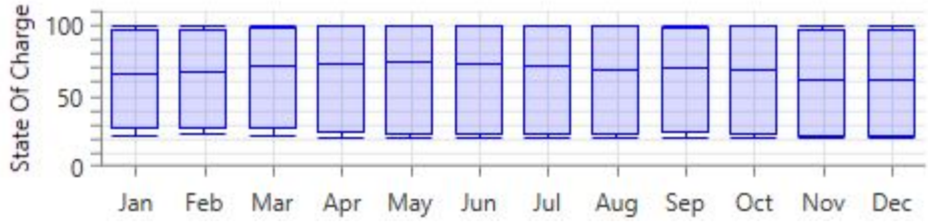


Figure 41 – SAFT Intensium Home SOC for PV (stand-alone) System in San Francisco

TROJAN IND17-6V

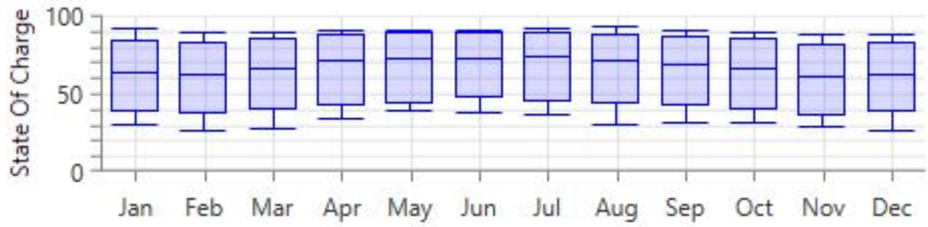


Figure 42 - Trojan IND17-6V SOC for PV (stand-alone) System in San Francisco

Juicebox Energy

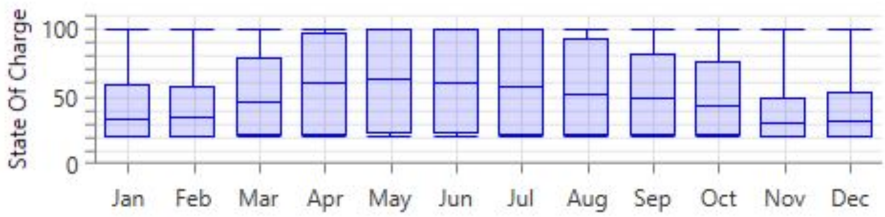


Figure 43 – Juicebox Energy SOC for PV (stand-alone) System in San Francisco

Discover 6VRE-2400TG

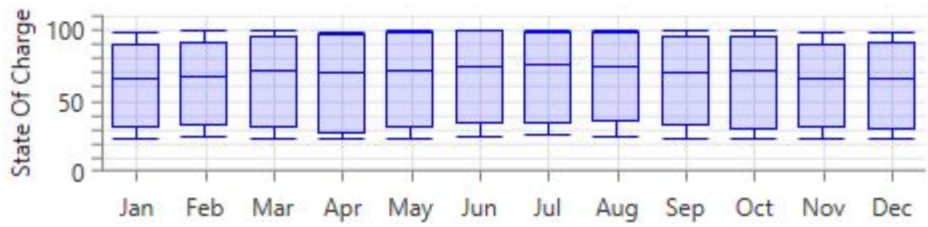


Figure 44 – Discover 6VRE-2400TG SOC for PV (stand-alone) System in San Francisco

LG Chem

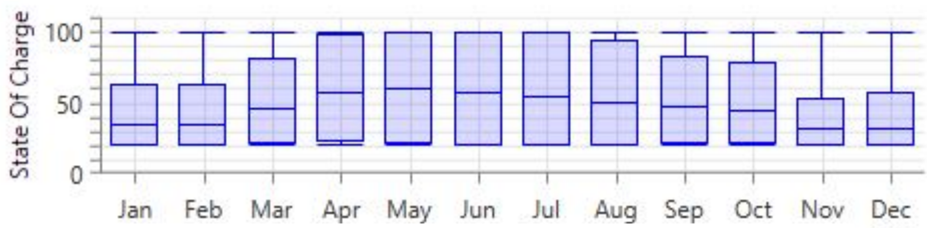


Figure 45 – LG Chem SOC for PV (stand-alone) System in San Francisco

In this simulation, it is clear, from Figure 39-45, that each type of battery is used thoroughly throughout the year, each operating at differing states of charge. This case results in the Juicebox battery, which was hardly utilised in the grid-connected simulations, having the highest penetration of renewable power generation, with a renewable fraction of 72%. A number of problems arise from not being connected to the grid. These include the fact that there are large amounts of excess electricity that could have been exported to the grid for a source of income. The Juicebox and LG Chem batteries proved, in this simulation, to be the most suitable for making the most of the PV output. On top of this, functioning in the load following type of dispatch means that the amount of excess electricity generated is substantially lower than in any of the other cases. Another interesting point to note is that the SAFT Intensium Home battery's state of charge varies greatly over all months, whereas, in the case of the Juicebox and LG lithium-ion batteries, their state of charge only varies in this way in the summer months, then varying only little during the winter, as illustrated in Figure 43 and 45. All in all, the net present costs of each system are much higher than in the case of the grid-connected PV system in San Francisco, down to the fact that, in addition to the cost of fuel for running the generator as well as the operation and maintenance costs of the generator, there is a lack of revenue from grid exports. This said, however, if renewable incentives like those currently in place in the UK were to be included in the model, the net present cost could be massively reduced, and if there were to be storage incentives put in place, an even bigger economic difference could be made.

6.2.1.2. Home Wind System

Battery Type	Dispatch	Annual Throughput (kWh)	Excess Electricity (kWh/yr)	Ren Fraction (%)	Production (%)	
					Wind	Generator
IND29-4V	CC	1714.29	2880.69	48.80	70.40	29.60
SAFT	CC	1726.37	3154.78	49.50	70.70	29.32
IND17-6V	CC	1767.12	3003.74	45.90	69.20	30.76
6VRE-2400TG	CC	1551.50	3148.88	46.50	69.50	30.50
LG Chem	CC	1916.30	2913.38	52.90	72.10	27.90
Juicebox	CC	1988.42	2740.80	57.20	74.10	25.97

Table 13 - San Francisco Home Wind system (stand-alone) Technical Results

Battery Type	Operating cost (£)	Initial capital (£)	Net Present Cost (£)
IND29-4V	1186.67	35204.00	46818.37
SAFT	1097.55	36374.00	47116.10
IND17-6V	1257.47	35132.00	47439.25
6VRE-2400TG	1317.35	35045.00	47938.32
LG Chem	1130.59	37250.00	48315.50
Juicebox	1069.23	38049.00	48513.94

Table 14 - San Francisco Home Wind system (stand-alone) Economic Results

TROJAN IND29-4V

Figure 46 – Trojan IND29-4V SOC for Wind (stand-alone) System in San Francisco

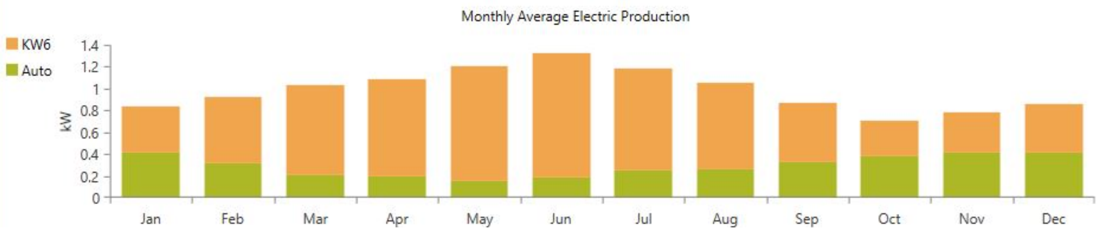


Figure 47 – Electricity Production for Trojan IND29-4V with Wind (stand-alone) System in San Francisco

SAFT Intensium Home

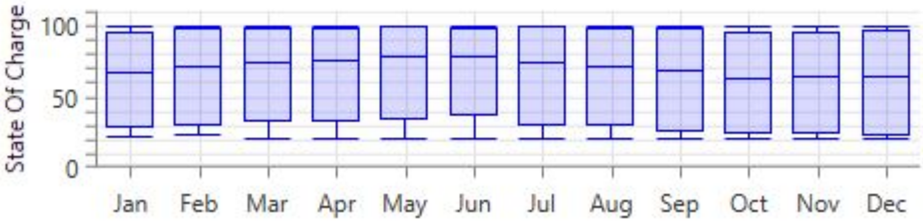


Figure 48 – SAFT Intensium Home SOC for Wind (stand-alone) System in San Francisco

TROJAN IND17-6V

Figure 49 – Trojan IND17-6V SOC for Wind (stand-alone) System in San Francisco

Juicebox Energy

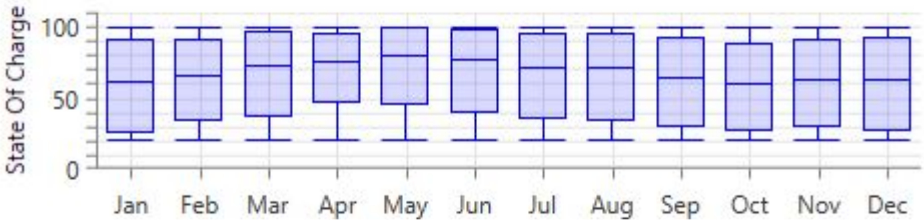


Figure 50 – Juicebox Energy SOC for Wind (stand-alone) System in San Francisco

Discover 6VRE-2400TG

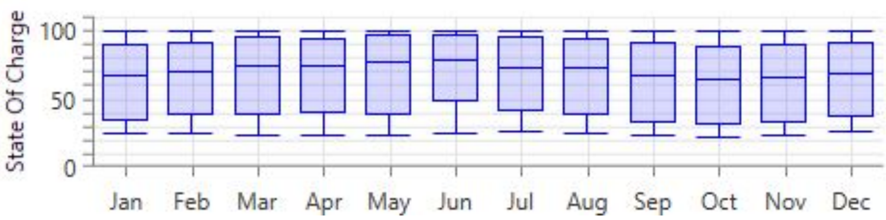


Figure 51 – Discover 6VRE-2400TG SOC for Wind (stand-alone) System in San Francisco

LG Chem

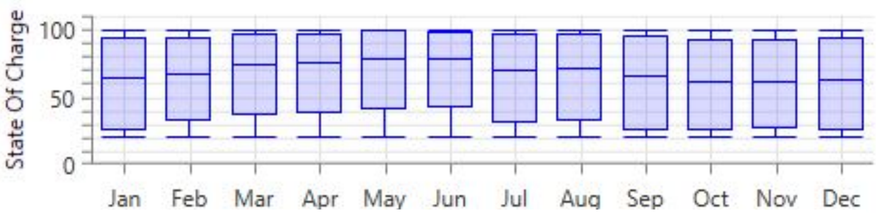


Figure 52 – LG Chem SOC for Wind (stand-alone) System in San Francisco

This type of system, again, leaves every type of battery model with excess electricity that is not being used or exported back to the grid, resulting in a loss of revenue, which in no way helps towards the economic feasibility of any battery system. For these simulations, it is clear that the batteries, once again, are being used thoroughly throughout the year. Each battery experiences a largely varying state of charge from month to month, which implies that the batteries are being charged almost to capacity, then discharged until empty. The results also show that the optimum type of dispatch in this case is cycle charging, which is used by every battery type in this simulation. One aspect that is particular noteworthy in this case, is that the net present costs are extremely high for all battery types. This is due to the lack of export revenue and also to the high capital costs of the wind turbine. However, despite having the highest net present cost, the Juicebox battery has the highest renewable fraction, which is clearly down to the fact that it boasts the highest annual throughput of all the battery types. Despite the use of each different battery system, it is clear that, without incentives or any feed-in-tariff, it would not be economically feasible to have such a system, due to the high costs incurred.

Comparing both San Francisco stand-alone systems, it is clear that, without any sort of feed-in-tariff or incentives, is it not viable to use a renewable system such as wind or PV to generate all electricity for the dwelling, as, with each of the battery systems, a generator is still required to match the load. In both of these cases, the Juicebox battery has one of the highest annual throughputs and renewable fractions, and the lowest excess electricity and operating costs. This is particularly surprising, considering that, in the grid-connected cases, this type of battery was hardly used at all. In general, all of the batteries are better utilised in the case of stand-alone dwellings in San Francisco, as most were hardly used at all in the grid-connected simulations. In both the wind and PV stand-alone systems, it is clear that the Juicebox battery is the most feasible option, and, if there were storage incentives, its economic feasibility could be greatly enhanced.

6.2.2. Aberdeen

6.2.2.1. Home Solar PV System

Battery Type	Dispatch	Annual Throughput (kWh)	Excess Electricity (kWh/yr)	Ren Fraction (%)	Production (%)	
					Solar	Generator
IND29-4V	LF	872.68	1568.04	72.03	85.02	14.98
IND17-6V	LF	825.95	1626.06	69.75	83.99	16.01
6VRE-2400TG	LF	736.72	1751.01	66.40	82.53	17.47
Saft	CC	1039.45	1989.09	53.75	77.43	22.57
LG Chem	CC	1129.16	1785.29	63.79	81.42	18.58
Juicebox	CC	1143.63	1705.34	69.87	84.05	15.95

Table 15 - Aberdeen Home Solar PV system (stand-alone) Technical Results

Battery Type	Operating cost (£)	Initial capital (£)	Net Present Cost (£)
IND29-4V	222.68	9324.00	11888.68
IND17-6V	259.77	9252.00	12243.92
6VRE-2400TG	324.76	9165.00	12905.44
Saft	220.31	10494.00	13031.44
LG Chem	248.35	11370.00	14230.32
Juicebox	223.54	12169.00	14743.64

Table 16 - Aberdeen Home Solar PV system (stand-alone) Economic Results

TROJAN IND29-4V

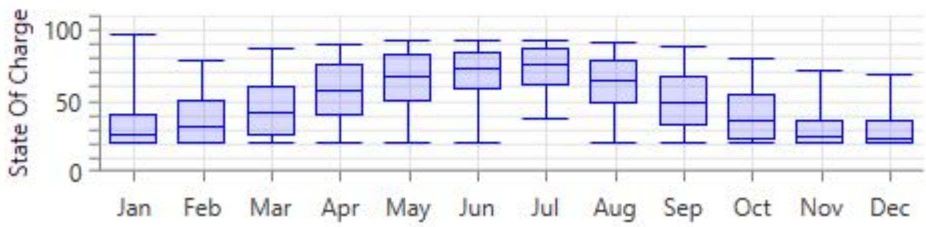


Figure 53 – Trojan IND29-4V SOC for PV (stand-alone) System in Aberdeen

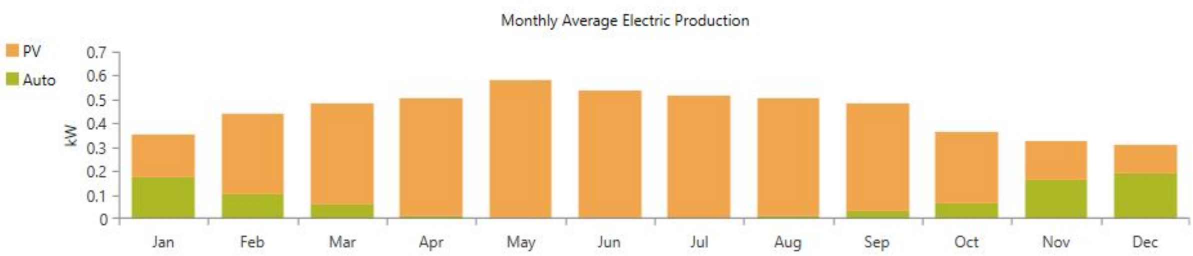


Figure 54 – Electricity Production for Trojan IND29-4V with PV (stand-alone) System in Aberdeen

SAFT Intensium Home

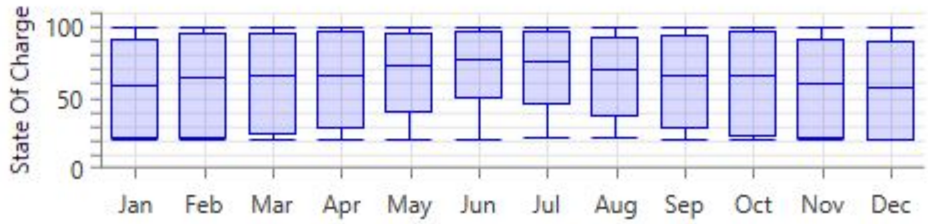


Figure 55 – SAFT Intensium Home SOC for PV (stand-alone) System in Aberdeen

TROJAN IND17-6V

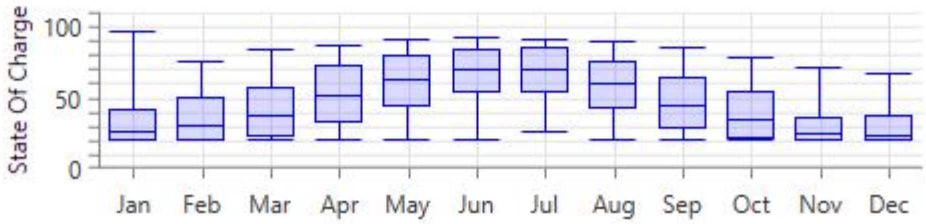


Figure 56 – Trojan IND17-6V SOC for PV (stand-alone) System in Aberdeen

Juicebox Energy

Figure 57 – Juicebox Energy SOC for PV (stand-alone) System in Aberdeen

Discover 6VRE-2400TG

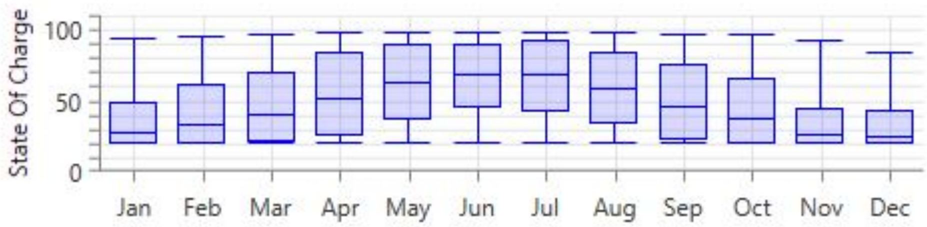


Figure 58 – Discover 6VRE-2400TG SOC for PV (stand-alone) System in Aberdeen

LG Chem

Figure 59 – LG Chem SOC for PV (stand-alone) System in Aberdeen

The Aberdeen stand-alone solar PV simulation, in comparison to the San Francisco simulation, in general, has a much higher renewable fraction. This means that the generator is used much less here than in the San Francisco case. The operating costs, as well as the amount of excess electricity, are much lower in this case, which will be heavily reliant on the fact that the level of electricity required to meet demand is much less for Aberdeen than San Francisco. In this case, the batteries do not demonstrate as varying levels of state of charge as witnessed in the stand-alone San Francisco simulations, apart from SAFT Intensium Home, which has given similar results for both locations in most cases. The greater degree of consistence observed in the state of charge levels for Aberdeen is probably due to the fact that less electricity is discharged from the capacity, because of the smaller load. Furthermore, the lower operating costs result in a much lower net present cost than witnessed in the San Francisco simulations. One interesting aspect of this simulation is that the optimum results for these batteries types result in load following dispatch for all lead-acid batteries, and in cycle charging dispatch for all lithium-ion batteries. The cycle charging feature results in more use of the generator in the case of SAFT Intensium Home and LG Chem batteries.

6.2.2.2. Home Wind System

Battery Type	Dispatch	Annual Throughput (kWh)	Excess Electricity (kWh/yr)	Ren Fraction (%)
IND17-6V	CC	384.97	16532.51	100.00
IND29-4V	CC	385.82	16531.43	100.00
LG Chem	CC	356.15	16605.83	100.00
Juicebox	CC	350.76	16618.86	100.00

Table 17 - Aberdeen Home Wind system (stand-alone) Technical Results

Battery Type	Operating cost (£)	Initial capital (£)	Net Present Cost (£)
IND17-6V	79.80	34432.00	35351.12
IND29-4V	78.87	34504.00	35412.38
LG Chem	176.28	36550.00	38580.29
Juicebox	204.76	37349.00	39707.26

Table 18 - Aberdeen Home Wind system (stand-alone) Economic Results

TROJAN IND17-6V

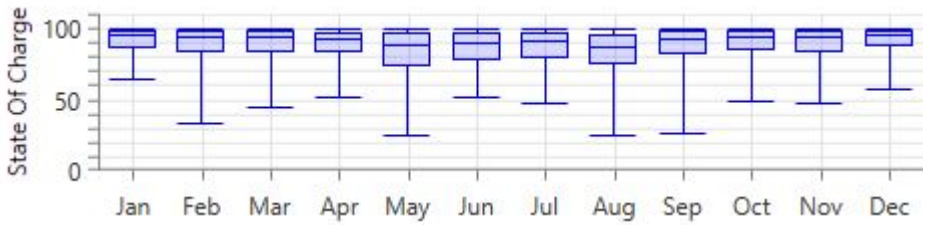


Figure 60– Trojan IND17-6V SOC for Wind (stand-alone) System in Aberdeen

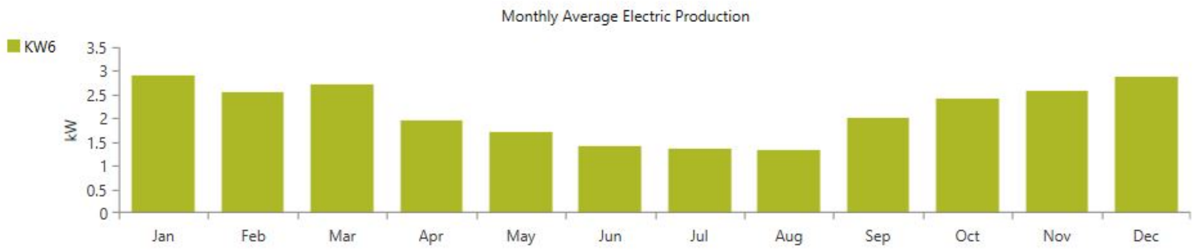


Figure 61 – Electricity Production for Trojan IND17-6V with Wind (stand-alone) System in Aberdeen

TROJAN IND29-4V

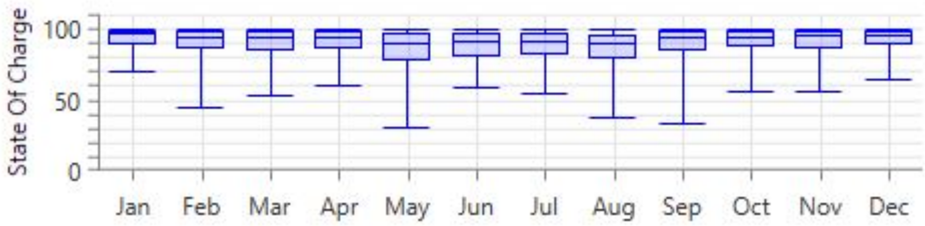


Figure 62 – Trojan IND29-4V SOC for Wind (stand-alone) System in Aberdeen

LG Chem

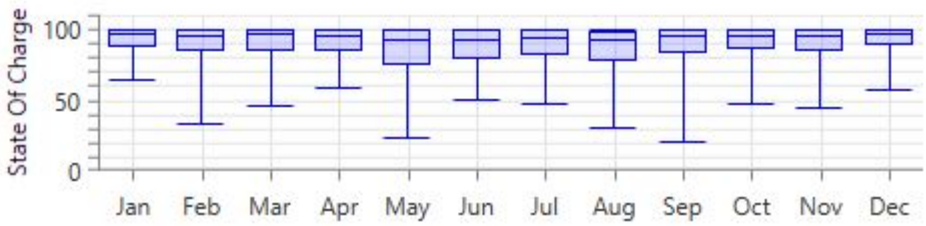


Figure 63 – LG Chem SOC for Wind (stand-alone) System in Aberdeen

Juicebox Energy

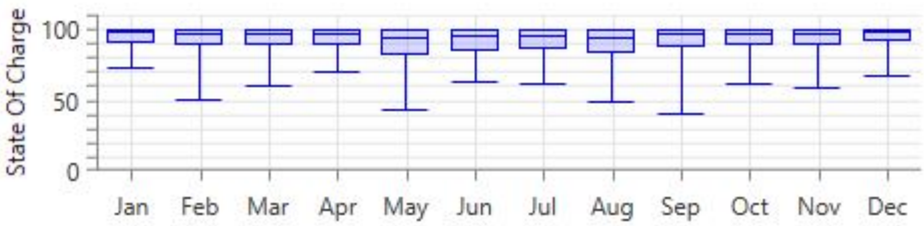


Figure 64 – Juicebox SOC for Wind (stand-alone) System in Aberdeen

Arguably, the most noteworthy results were obtained in the case of a stand-alone residential wind system in Aberdeen. This model resulted in four of the six types of batteries not requiring any electricity to be generated by the generator, leading to no fuel costs or emissions. Each of these used a cycle charging type of dispatch in order to generate the best results. The simulation also results in high net present costs, with high amounts of excess electricity. As much as it is good that the load is fully met by renewable sources, without the wasted electricity being utilised, the net present cost and therefore initial capital cost, cannot be balanced out. However, with the use of feed-in-tariffs and, perhaps, more dwellings using this excess electricity, this problem could be easily resolved. Each type of battery shown in this case, is being charged to 100% and then discharged when required, meaning that, for the most part, the battery system will be sitting at full capacity. This would be particularly beneficial in the event of problems arising with the wind turbine, for example when maintenance procedures are carried out, or during an irregular period of low wind, as the battery could still be used to cover the load required.

Comparing both Aberdeen stand-alone systems, it is clear that a lot of electricity is wasted, which could otherwise have been exported to the grid or used for another dwelling. This is particularly the case for the wind turbine system, since exporting the electricity to the grid, as demonstrated in earlier simulations, could generate a great deal of revenue. There is no doubt from these results that the wind resource is the much more fruitful avenue for power generation for a typical dwelling in Aberdeen and, with the incentives in place in the UK such as feed-in-tariffs, a substantial amount of revenue could be generated, which would comfortably overcome the net present cost, given that a generation of 18,819kWh from the wind turbine would bring in an income of over £2700, based on the generation tariff of 14.5p/kWh. (Energy Saving Trust, 2015b) With this kind of revenue, this could become a hopeful path for domestic power generation. However, one of the key factors in any wind turbine system is its associated environmental issues and concerns, which would still always need to be taken into account before a system could be installed. The best type of battery systems for the Aberdeen stand-alone system are the Trojan IND17-6V and IND29-4V batteries, as they result in lower excess electricity in the case of solar PV and the lowest operating costs in the case of wind power.

7. Conclusions

7.1. Review of the Thesis

The main purpose of this thesis was to study the feasibility of small-scale battery systems for domestic application. In order to do this, the topic had to be thoroughly researched, in order to ensure a full understanding of the way in which energy storage systems operate. It became evident very quickly that there is great potential for storage technology, such as batteries, to overcome the erratic nature of both wind and solar resources, facilitating, as a result, the improved harnessing of the renewable energy they provide, in order to reduce the strain on conventional methods of power generation, and, thereby, their negative environmental impacts.

There are many types of renewable energy systems that are utilised in dwellings across the world, and there is therefore a great deal of space for energy storage to be implemented to moderate the fluctuating power outputs of renewable power generation at the domestic level. With the benefits of load-shifting capabilities, the enhanced self-consumption of renewables and a means of back-up power, it is clear that the use of energy storage systems could provide a reliable and stable electricity supply to consumers at the domestic level. In order to develop this hypothesis further, one of the areas that had to be thoroughly researched was the way in which energy is consumed at the domestic level, with aspects such as appliance use and behavioural patterns highlighted as areas of great importance.

In order to fully understand the ability of small-scale battery systems to overcome the sporadic power outputs of renewable technology, typical renewable systems were simulated with different batteries, so as to develop an understanding of how batteries can be used in conjunction with these technologies. The chosen renewable technologies were a typical solar PV system of 4kWp, and a wind turbine aimed for residential applications, manufactured by Kingspan Wind, with a power output of 6.1kWp. Two types of batteries were assessed in this thesis: lithium-ion and lead-acid. The lithium-ion batteries were SAFT Intensium Home, LG Chem and Juicebox Energy, the lead-acid batteries were the tubular gel Discover 6VRE-2400TG battery, and the flooded lead-acid batteries Trojan IND17-6V and Trojan IND29-4V. Various characteristics for each technology, as well as other important components such as inverters, generator, grid costs, project lifetime and many more, were inputted into HOMER, in order to study the feasibility of different domestic renewable energy systems with storage, as detailed in Chapter 5.

The simulations for the PV system and the wind system in a domestic application for the two locations, both grid-connected and stand-alone, resulted in a number of conclusions. Firstly, comparing the grid-connected home renewable systems in San Francisco and Aberdeen, it is clear just how important the level of load required to be met by the supply is. With the dwelling having a much higher load in San Francisco than in Aberdeen, more interaction with the grid is required, in order to match the higher demand. This is even the case despite the high levels of PV power generation in San Francisco annually. It is clear that, in both locations, the most suitable batteries in terms of functionality are the lithium-ion SAFT Intensium Home and the LG Chem batteries. However, the net present cost of these technologies is higher, based on the cost assumptions made for this project, and, if lithium-ion costs were lower, then this technology would be just as economically feasible as lead-acid. This being the case, in all grid-connected cases, it appears to be more economically feasible to make use of the export revenue and interact with the grid, than to utilise battery systems, as is illustrated in the state of charge graphs for the grid-connected systems, which display a lack of use of the batteries. The results from the grid-connected simulations of the thesis are not exhaustive, and there are many other aspects that should be considered before using this as a basis for whether or not to employ battery systems. For example, UK feed-in-tariffs and USA renewable incentives, such as Renewable Portfolio Standards (RPS) would have to be economically assessed based on the results in this thesis.

Referring to the stand-alone results in both locations, in general, it is clear that both lithium-ion and lead-acid batteries are used more frequently in these cases than in the grid-connected systems, as can arguably be expected. It would be more expensive to use the generator found within HOMER rather than to import electricity, and, therefore, it is better economically to store electricity generated from renewable sources to use later on, when the renewable source is not generating enough electricity. In each of the stand-alone simulations for both locations, other than the Aberdeen wind system, the generator is used frequently. However, different types of batteries vary its use. For example, in the case of the stand-alone PV system in San Francisco, the Juicebox Energy battery is more capable than the other types of batteries of decreasing the use of the generator and increasing the use of PV production, which, in turn, increases the renewable fraction of the system. It is clear, in most of the stand-alone simulations, that the lithium-ion batteries will be used more frequently than the lead-acid batteries, making them the more technically feasible option. However, all of the cases would have to be further assessed, taking into account financial incentives, in order to fully understand the true economic feasibility of each battery type. Without such a process it would not be appropriate to pass any decisive comment on the economic feasibility of each system.

All in all, it is evident from the results that, despite the higher capital costs of lithium-ion batteries over lead-acid, technically, in most of the simulations, lithium-ion were the more widely used batteries, operating at a largely varying state of charge (SOC) in all months. The lead-acid batteries, primarily in the grid-connected simulations, were operated at either a 100% state of charge or an extremely low state of charge, meaning that the battery is not being allowed to be fully charged and fully discharged. As previously mentioned in section 2.2.2., if the daily depth of discharge is limited, then the lifetime will be improved, as is the case in some of the simulations conducted herein, since, by limiting the lifetime throughput, a replacement cost would not be required over the project lifetime of 15 years, meaning that the net present cost would be lower for lead-acid batteries than for lithium-ion. It is clear, however, that, technically, due to the lower operating costs brought about by reducing imported electricity, in many cases, lithium-ion batteries are more suitable.

7.2. Further study

The many conclusions that can be drawn from this study indicate the requirement for further work, in order to achieve a greater understanding of residential energy storage systems in the UK and the USA. Firstly, a more in-depth cost analysis would allow for a better economic perspective to be created. Another important aspect that has been illustrated in the previous section is the nature of energy consumption. Not only the climates differ, leading to variations in renewable technology output, but also the energy consumption. Different countries have different load profiles, meaning that the requirement for energy storage varies greatly from country to country, which is evident in the results of this project. For this reason it would be suitable for further study to involve assessing small-scale battery systems as a means of residential energy storage in other countries where consumption differs to the UK and the USA. Another potential area of further study would be to look at not only the consumption as whole, but also at load profiles for individual appliances, in order to improve the understanding of how batteries could match the demand of certain appliances. The program championed by Yao and Steemers is a good example of this. (2005) With this in mind, looking at electrical consumption at a residential level in the USA, a substantial amount of the consumption is from air conditioning, whereas the UK we does not have this requirement and is more dependent on heating, which, in many cases, does not consume electricity. If this were to be used in conjunction with modelling, for example in HOMER, then the comprehension of the discharging batteries to meet certain loads could be improved.

Another appropriate avenue proceeding from this discussion would be the application of electric vehicles as a form of residential energy storage. As mentioned in the Introduction of this thesis, Tesla, an electric vehicle manufacturer, has recently unveiled its new product, Tesla 'Powerwall', the introduction of which into the home will allow Tesla to move into the home energy field as well as the transportation sector. This lithium-ion energy storage device was made available to order in April 2015, and has since sold out in the USA until the middle of 2016, receiving upwards of 30,000 reservations. (Randall, 2015) The device is retailed at $3000 and $3500, for a 7kWh unit and a 10kWh unit, respectively. With the incredibly high demand for this product, and due to its availability for purchase at a low cost, this represents a clear step in the right direction towards the more widespread use of residential battery storage. Given that the daily energy consumption is lower in the UK than the USA, and that the renewable resources here are of great abundance, the results obtained for the purposes of this thesis could therefore allow this exercise to be treated as a preparatory study for researching the implementation of TESLA in the UK. As demonstrated herein, lithium-ion based small-scale battery systems for residential use have been modelled, resulting in good use of the batteries, with the one of the only problems centring on cost. This implies that, with the help of feed-in-tariffs for renewable technology investments, the feasibility of such systems could be greatly improved. This assertion finds support throughout the literature. For example, Swierczynski et al. write that, “in projects with long payback times, there is always an additional risk,” (2015, p. 491) while assurance is provided by Delfanti et al., who claim that, incentives in storage could be of great use in improving the feasibility of the technology. (2015, p. 72)

In addition to economic feasibility, further potential areas for development must also be considered, as highlighted by Harsha and Dahleh. Principal areas of concern for future study, they claim, include “the incorporation of battery degradation and lifecycle effects into the analysis, and the use of robust optimisation methods for storage management that would be adaptive to limited forecast information available about renewable energy.” (2015, p. 1177) The requirement for energy storage management has been particularly evident throughout the development of this thesis. As demonstrated in the grid-connected results, if an energy management strategy were to be simulated along with the residential energy systems modelled, then the battery systems could be better utilised to meet demand, thereby reducing the consumer’s dependency on the grid.

As established throughout the course of this thesis, home energy storage systems are a highly viable avenue for the mitigation of problems currently arising from depleting conventional energy generation methods, together with the sporadic nature of their renewable counterparts. To be sure, a number of criticisms and drawbacks of energy storage by means of batteries have been highlighted herein. However, as detailed above, in this final section, there is indeed scope to overcome and improve upon these, through further study of this complex topic. From the conclusions reached during this study, it is hoped that considerable positive developments, both academic and practical, towards a bright and secure future for home energy storage might gradually follow, in order to facilitate the effective harnessing of the valuable energy provided by the renewable resources currently available to us.

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Programs

HOMER Pro

Merit, University of Strathclyde

9. Appendix - Specification Sheets of Components Used in HOMER

SAFT Intensium Home

Intensium® Home
48 Volts Indoor

Based on Synerion® 24M modules, the Intensium® Home is a 48 V energy storage system for residential applications offering compactness, outstanding efficiency and high reliability over thousands of cycles

Applications
- PV self-consumption increase
- Load peak shaving
- Backup in case of grid outage
- Local voltage control

Features
- Field-proven Li-ion technology (15 years experience)
- Operation at any state of charge with 100% useable capacity
- Full recharge in 1 hour
- Compact 12U cabinet integrating two Synerion® 24M modules and a Battery Management Module (BMM)
- Power connectors and cabling included for easy installation with inverters
- Advanced industrial design offering highest reliability and robustness based on Saft's system development experience in high tech markets
- BMM integrating specific management functions required in residential applications
- Best energy efficiency of all electrochemical technologies (better than 95%)
- Outstanding calendar and cycle life

Benefits
- Flexibility to provide both energy and power functions. It can provide more power per kWh than competition to handle complex load profiles
- Maximized self-consumption and energy throughput over lifetime
- Easily compatible with 48 V inverters for residential market
- Compactness
- Low maintenance
- Effective troubleshooting with user-friendly diagnostic tool

Nominal characteristics at + 25°C	
Voltage (V)	48
Capacity (C/5) (Ah) at + 25°C	84
Rated energy (C/5) (Wh)	4000
Mechanical characteristics	
Width (mm)	535
Height (mm)	700
Depth (mm)	520
Weight (kg)	85
Electrical characteristics at + 25°C	
Voltage (V)	42 to 56
Maximum continuous discharge current (A)	160
Maximum continuous discharge power (W) at 50% SOC	7600
Peak discharge power in 3 s (W) at 50% SOC	15100
Maximum continuous recharge current (A)	82
Maximum continuous recharge power (W) at 50% SOC	4100
Peak recharge power in 5 s (W) at 50% SOC	12100
Operating conditions	
Operating temperature	0 to 40°C
Cycle efficiency DC roundtrip	>96%
Standby consumption	10 W
Self-discharge	<5% per month
Calendar lifetime at + 25°C	>20 years
Cycling lifetime at 60% DOD	>7000 cycles
Cooling	Natural convection

http://www.saftbatteries.com/battery-search/intensium®-home

LG Chem

Technical Specification

Item		Description	
		Main Pack	Expansion Pack
Nominal Energy		6.4 kWh	3.2 kWh
Nominal Capacity (CC/CV Mode, Cut-off : 0.05C)		126 Ah	63 Ah
Dimension (Width x Height x Depth)		406 x 664 x 165 ㎜	230 x 664 x 165 ㎜
Weight		60 kg	30 kg
Max Discharge Current		110 A	
Nominal Voltage (DC)		51.8 V	
Voltage Range (DC)		45.2 V – 58.1 V	
Nominal Discharge Current		0.3C	
Nominal Charge Current		0.3C	
Peak Power (25℃/77℉)		5 kW	
Faradic Charge Efficiency (25℃/77℉)		99 %	
Battery Roundtrip Efficiency (C/3, 25℃/77℉)		95 %	
Expected Lifetime (25℃/+77℉)		> 10 years	
Cycle life (90% DOD, 25℃/+77℉)		> 6,000 cycle	
Available Operating Temperature		0 – 40℃	
Optimal Operating Temperature		15 – 30℃	
Storage Temperature		-30 – 50℃	
Cooling		Natural Convection	
Interface		CAN, CANopen Communication	
Certification	Cell Safety	IEC 62133	
	Pack Safety	IEC 62619	
	United Nation Class	UN 3480	
	Hazard Classification	Class 9	
	Transportation Regulation Compliance	UN 38.3	
	Protection Class	IP 21	

LG Chem

Energy Solution Company
ESS Business Division

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Dealer Information

http://www.solarjuice.com.au/storage

Juicebox

JUICEBOX ENERGY 8.6 KWH

Energy Storage System Specifications

PHYSICAL	Dimensions	43"x22"x17"
	Module weight (qty 4)	47 lbs
	Enclosure weight	87 lbs
	Total installed weight	275 lbs
	Color	White or Black
	Enclosure material	Aluminum
	Enclosure rating	NEMA 3R
	Maintenance	None
	Operating temperature	-10ºC to 50ºC
	Installation	Wall-mounted
	Modular assembly - no special equipment	
	LED State of Charge gauge	
	LCD for battery and system metrics	
ELECTRICAL	Nominal voltage	50V
	Capacity	172Ah
	Rated energy	8.6kWh
	Rated power	4.3kW
	Battery life	10 years minimum
	Max discharge rate	140A
	Max charge rate	80A
	Round trip efficiency battery charge/discharge cycle	98%

http://www.juiceboxsolar.com/home/

Discover 6VRE-2400TG

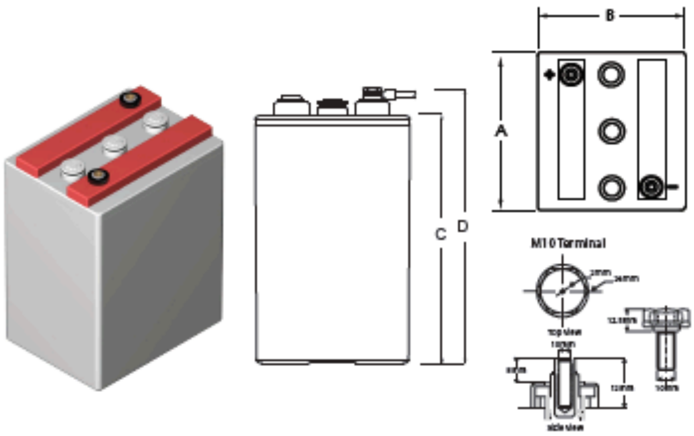
6VRE-2400TG

DATA SHEET

Tubular Gel OPzV Battery Block

Discover® Tubular Gel RE Batteries provide superior deep cycling performance and reliability for demanding commercial, industrial and residential applications. Discover® Tubular Gel RE Batteries utilize Advanced Tubular Plate Technology to deliver long service life with maintenance-free requirements. Gel RE Batteries provide reliable energy storage for Stationary Backup and Telecom Networks, Road Surface, and Rail Traffic Signaling Systems, Solar, Wind, and Hybrid Off-grid and Grid-Tie renewable energy applications. Discover® Tubular Gel RE Batteries provide maximum efficiency per discharge-charge cycle, and proven reliability in remote, high temperature, or unstable power network installations.

Mechanical Drawings



Mechanical Specifications

Industry Reference	6V Tubular Gel OPzV	
Length (A)	15.0 in	380 mm
Width (B)	8.1 in	205 mm
Height (C)	13.1 in	332 mm
Total Height (D)	14.6 in	371 mm
Weight (Wet)	82 lbs	37 kgs
Terminal	M10 Insert	
Poles	2	
Cell(s)	3	
Container	ABS	

Electrical Specifications

Reference LVD (I10 at 20°C | 68°F)	20% DOD	6.1V
	50% DOD	5.9V
	80% DOD	5.7V
Cycle Life	20% DOD	6000
	50% DOD	2500
	80% DOD	1700
RINT		1.89 mΩ
Short Circuit (20°C | 68°F)		3220 A
Self Discharge (20°C | 68°F)		2-3% per month
Maximum Operating Temperature		-20°C | -4°F - 45°C | 113°F
Electrolyte (20°C | 68°F)		1.26 S.G.

Electrical Specifications

1.85 VPC at 20°C | 68°F				1.75 VPC at 27°C | 80°F			1.75 VPC at 20°C | 68°F			
240 HR	120 HR	120 HR	100 HR	20 HR	10 HR	8 HR	5 HR	3 HR	1 HR	1 HR
404 AH	2.41 KWH	402 AH	398 AH	340 AH	309 AH	-	285 AH	253 AH	1.0 KWH	173 AH

Constant Power Reference in Watts / Cell to 1.92VPC at 20°C | 68°F										
240 HR	168 HR	120 HR	100 HR	72 HR	50 HR	48 HR	24 HR	20 HR	12 HR	10 HR
2.9	4.0	5.5	6.4	8.6	11.8	12.3	22.0	25.6	38.4	44.2

Benefits & Features

Unparalleled Performance
- Engineered to deliver 80% of rated capacity above 5.7 volts.

Long Cycle Life
- Tubular positive plates and proprietary alloy compositions to provide a 50% Depth of Discharge cycle life of up to 2500 cycles @ 20°C | 68°F.

Low Total Cost of Ownership
- Low cost per cycle. Lifetime value maximized especially in hybrid systems where using batteries can dramatically reduce generator run times delivering lower maintenance and fuel costs and less CO2 emissions.

Maintenance-Free
- Sealed technology, Gel electrolyte and safety pressure relief valve with integral flame arrestor.

Complete Battery Solution
- Complete and ready to install systems with all necessary installation accessories. Flame retardant (UL 94-V0) containers available upon request.

Safe
- Tested and verified for compliance to applicable International Safety Standards.

IEC 61427 Compliant
- Tested for compliance with the International Electrical Commission requirements for battery performance and life in PV applications.

Certified Quality

Discover Energy Corp. and its facilities and products are certified to multiple standards and compliance:

- IEC 60896-21: Requirements for Photovoltaic Energy
- IEC 60896-22: Requirements for Valve-Regulated lead-acid batteries
- DIN 40742: Specifications for Tubular Gel RE Cells
- DIN 40744: Specifications for Tubular Gel RE Blocks
- EN 50272-2: Safety Requirements for stationary batteries
- ISO 9001, ISO 14001, BS OHSAS 18001: Manufacturing and Production facilities.
- ETTS Germany

Contact Us

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http://discover-energy.com/product-search/view/6VRE-2400TG

Trojan IND29-4V

Trojan BATTERY COMPANY

IND29-4V DATA SHEET

for Renewable Energy / Hybrid Systems / Backup Power Applications

INDUSTRIAL LINE

MODEL: IND29-4V

DIMENSIONS: inches (mm)

BATTERY: Flooded/wet lead-acid battery

COLOR: Maroon (case/cover)

MATERIAL: Polypropylene (internal cell container)
Polyethylene (outer container)

Now Available With SMART CARBON

SMART CARBON™

Deep-cycle batteries used in off-grid and unstable grid applications are heavily cycled at partial state of charge (PSOC). Operating at PSOC on a regular basis can quickly diminish the overall life of a battery, which results in frequent and costly battery replacements.

To address the impact of PSOC on deep-cycle batteries in renewable energy (RE), inverter backup and telecom applications, Trojan Battery has now included Smart Carbon™ as a standard feature in its Industrial and Premium flooded battery lines.

PRODUCT SPECIFICATIONS

BCI GROUP SIZE	TYPE	CAPACITY A Amp-Hours (AH)							ENERGY (kWh)	VOLTAGE	TERMINAL Type D	DIMENSIONS B Inches (mm)			WEIGHT lbs. (kg)
		5-Hr Rate	10-Hr Rate	20-Hr Rate	48-Hr Rate	72-Hr Rate	100-Hr Rate	240-Hr Rate	100-Hr Rate			Length	Width	Height C	
INDUSTRIAL LINE - DEEP-CYCLE FLOODED BATTERIES															
N/A	IND29-4V	1274	1448	1618	1899	2022	2105	2111	8.42	4 VOLT	14	27.10 (688)	10.35 (263)	23.81 (605)	465 (211)

CAPACITY AMP-HOURS (AH)

Cutoff Voltage	5-Hr	10-Hr	20-Hr	48-Hr	72-Hr	100-Hr	240-Hr
1.75 vpc	1274	1448	1618	1899	2022	2105	2111
1.80 vpc	1148	1361	1553	1849	1973	2050	2055
1.85 vpc	1041	1232	1426	1652	1800	1932	1936
1.90 vpc	764	995	1195	1382	1529	1716	1719

CHARGING INSTRUCTIONS

CHARGER VOLTAGE SETTINGS (AT 77°F/25°C)	
	Voltage per cell
Absorption charge	2.35-2.45
Float charge	2.20
Equalize charge	2.58

Do not install or charge batteries in a sealed or non-ventilated compartment. Constant under or overcharging will damage the battery and shorten its life as with any battery.

OPERATIONAL DATA

Operating Temperature	Specific Gravity
-4°F to 113°F (-20°C to +45°C). At temperatures below 32°F (0°C) maintain a state of charge greater than 70%.	The specific gravity at 100% state-of-charge is 1.260

CHARGING TEMPERATURE COMPENSATION

To the Voltage Reading -- Subtract 0.005 volt per cell (VPC) for every 1°C above 25°C or add 0.005 volt per cell for every 1°C below 25°C.

http://www.trojanbattery.com/product/ind29-4v/

Trojan IND17-6V

Trojan BATTERY COMPANY

IND17-6V DATA SHEET

for Renewable Energy / Hybrid Systems / Backup Power Applications

INDUSTRIAL LINE

MODEL: IND17-6V

DIMENSIONS: inches (mm)

BATTERY: Flooded/wet lead-acid battery

COLOR: Maroon (case/cover)

MATERIAL: Polypropylene (internal cell container)
Polyethylene (outer container)

Now Available With SMART CARBON™

SMART CARBON™

Deep-cycle batteries used in off-grid and unstable grid applications are heavily cycled at partial state of charge (PSOC). Operating at PSOC on a regular basis can quickly diminish the overall life of a battery, which results in frequent and costly battery replacements.

To address the impact of PSOC on deep-cycle batteries in renewable energy (RE), inverter backup and telecom applications, Trojan Battery has now included Smart Carbon™ as a standard feature in its Industrial and Premium flooded battery lines.

PRODUCT SPECIFICATIONS

BCI GROUP SIZE	TYPE	CAPACITY [B] Amp-Hours (AH)							ENERGY (kWh)	VOLTAGE	TERMINAL Type [B]	DIMENSIONS [B] Inches (mm)			WEIGHT lbs. (kg)
		5-Hr Rate	10-Hr Rate	20-Hr Rate	48-Hr Rate	72-Hr Rate	100-Hr Rate	240-Hr Rate	100-Hr Rate			Length	Width	Height [C]	
INDUSTRIAL LINE - DEEP-CYCLE FLOODED BATTERIES															
N/A	IND17-6V	727	820	925	1085	1156	1202	1205	7.21	6 VOLT	14	27.21 (691)	10.38 (264)	23.73 (603)	415 (188)

CAPACITY AMP-HOURS (AH)

Cutoff Voltage	5-Hr	10-Hr	20-Hr	48-Hr	72-Hr	100-Hr	240-Hr
1.75 vpc	727	820	925	1085	1156	1202	1205
1.80 vpc	655	771	888	1057	1128	1172	1175
1.85 vpc	594	700	816	945	1029	1104	1106
1.90 vpc	434	561	680	790	874	981	983

CHARGING INSTRUCTIONS

CHARGER VOLTAGE SETTINGS (AT 77°F/25°C)	
	Voltage per cell
Absorption charge	2.35-2.45
Float charge	2.20
Equalize charge	2.58

Do not install or charge batteries in a sealed or non-ventilated compartment. Constant under or overcharging will damage the battery and shorten its life as with any battery.

OPERATIONAL DATA

Operating Temperature	Specific Gravity
-4°F to 113°F (-20°C to +45°C). At temperatures below 32°F (0°C) maintain a state of charge greater than 70%.	The specific gravity at 100% state-of-charge is 1.260

CHARGING TEMPERATURE COMPENSATION

To the Voltage Reading -- Subtract 0.005 volt per cell (VPC) for every 1°C above 25°C or add 0.005 volt per cell for every 1°C below 25°C.

http://www.trojanbattery.com/product/ind17-6v/

SMA Sunny Boy Inverter 2.5kW

Technical Data	Sunny Boy 1.5	Sunny Boy 2.5
Input (DC)		
Max. DC power (@cos φ = 1)	1,600 W	2,650 W
Max. input voltage	600 V	600 V
MPP voltage range	160 V to 500 V	260 V to 500 V
Rated input voltage	360 V	360 V
Min. input voltage / initial input voltage	50 V / 80 V	50 V / 80 V
Max. input current	10 A	10 A
Max. input current per string	10 A	10 A
Number of independent MPP inputs / strings per MPP input	1 / 1	1 / 1
Output (AC)		
Rated power (at 230 V, 50 Hz)	1,500 W	2,500 W
Max. apparent AC power	1,500 VA	2,500 VA
Nominal AC voltage	220 V / 230 V / 240 V	220 V / 230 V / 240 V
Nominal AC voltage range	180 V to 280 V	180 V to 280 V
AC power frequency/range	50 Hz, 60 Hz / -5 Hz to +5 Hz	50 Hz, 60 Hz / -5 Hz to +5 Hz
Rated power frequency/rated grid voltage	50 Hz / 230 V	50 Hz / 230 V
Max. output current	7 A	11 A
Power factor at rated power	1	1
Adjustable displacement power factor	0.8 overexcited to 0.8 underexcited	
Feed-in phases/connection phases	1 / 1	1 / 1
Efficiency		
Max. efficiency / European weighted efficiency	97.2 % / 96.1 %	97.2 % / 96.7 %

http://www.windandsun.co.uk/products/Inverters/SMA-Inverters/Sunny-Boy-Inverters#10150

SMA Sunny Boy Inverter 3.3kW

Technical data	Sunny Island 3.0M	Sunny Island 4.4M
AC output (loads / stand-alone grid)		
Rated grid voltage / AC voltage range	230 V / 202 V ... 253 V	230 V / 202 V ... 253 V
Rated frequency / frequency range (adjustable)	50 Hz / 45 Hz ... 65 Hz	50 Hz / 45 Hz ... 65 Hz
Rated power (for Unom / fnom / 25 °C / cos φ = 1)	2200 W	3300 W
AC power at 25 °C for 30 min / 5 min / 3 sec	3 000 W / 3 700 W / 5 500 W	4 400 W / 4 600 W / 5 500 W
AC power at 45 °C	2 000 W	3 000 W
Rated current /short-circuit current (peak)	9,6 A / 60 A	14,5 A / 60 A
THD output voltage / power factor with rated power	< 4 % / -1 ... +1	< 4 % / -1 ... +1
AC input (PV array, grid or diesel generator)		
Rated input voltage / AC input voltage range	230 V / 172.5 V ... 264.5 V	230 V / 172.5 V ... 264.5 V
Rated input frequency / allowable input frequency range	50 Hz / 40 Hz ... 70 Hz	50 Hz / 40 Hz ... 70 Hz
Maximum AC input current	50 A	50 A
Maximum AC input power	11 500 W	11 500 W
Battery DC input		
Rated input voltage / DC voltage range	48 V / 41 V ... 63 V	48 V / 41 V ... 63 V
Maximum battery charging current / Rated DC charging current / DC discharging current	49 A / 43 A / 49 A	75 A / 63 A / 75 A
Battery type / battery capacity (range)	FLA, VRLA, Li-Ion* / 100 Ah ... 10 000 Ah	FLA, VRLA, Li-Ion* / 100 Ah ... 10 000 Ah
Charge control	IUoU charge procedure with automatic full charge and equalization charge	IUoU charge procedure with automatic full charge and equalization charge
Efficiency / self-consumption		
Maximum efficiency	95 %	95 %
Self-consumption without load / standby	18.8 W / 7.6 W	18.8 W / 7.6 W

http://www.windandsun.co.uk/products/Inverters/SMA-Inverters/SMA-Sunny-Island-Off-Grid-Inverters#.VejPSLRxtKM