Griffith School of Engineering

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6007ENG – Industry Affiliates Program

Comparison of Three Battery Storage Systems to Aid in Energy Efficiency Within Residential Buildings.

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Wattblock

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EXECUTIVE SUMMARY

In Semester 1, 2016 an industry based project was conducted at Wattblock as apart of Griffith Universities Industry Affiliates Program (IAP). Wattblock, is an energy efficiency company focusing on reducing residential building's common area energy bill. This is completed through various methods of energy optimisation, accompanied by proposing the implementation of renewable energies and other energy saving projects. Consequently, reducing the effect placed on the surrounding environment. The project undertaken at Wattblock will compare three battery storage systems and their viability within residential buildings. This will cover the comparison of the different storage systems by analysing the environmental, economic and social feasibility of the proposed project. The project will assist Wattblock with photovoltaic and battery storage calculations by producing an excel spreadsheet to complete calculations. The results produced by the model will provide the basis for comparing the environmental and economic feasibility of the storage systems. More specifically, the model produces values for the following;

- Cost of the project – Including cost of photovoltaic solar panels, battery storage system, inverter and installation.
- Return on investment (ROI).
- Long Term cost assessment – Analysing the cost of replacement, cleaning, maintenance and initial costs over a 40-year period.
- Environmental comparison – comparing values of kilograms of carbon dioxide equivalent ($kgCo_2e$-) between the proposed battery storage systems and the original energy acquisition from the electrical grid.

In regards to the comparison of social aspects this will become a qualitative analysis on factors such as;

- Accessibility and difficulty of finding an installer;
- Size and weight and;
- Replacement.

The comparison of the three battery storage systems needed to be conducted on relevant battery storage systems that are currently on the market and emerging technology. Therefore, the comparison was conducted on a zinc-bromide, lithium-ion, and a lead-acid battery, specifically, a RedFlow, Tesla Powerwall, and a Lifeline GPL-4DL, respectively. It was determined that all three battery storage systems are economically, environmentally and

socially feasible. The project identifies that economically the Tesla Powerwall is the greater choice with quickest return on investment and the higher savings. However, a long term analysis finds that the RedFlow battery storage systems produces a greater financial benefit over the 40-year period. The environmental and social feasibility assessment concluded with the Tesla Powerwall, yet again, being the superior battery. The storage system displayed a larger reduction in kilograms of carbon dioxide equivalent when compared against the original acquisition of energy. Following on, comparing the social aspects of the Tesla Powerwall against the other two batteries exemplified the superiority in the battery storage system. Therefore, by unanimous decision the Tesla Powerwall is the clear winner when compared to the RedFlow and the Lifeline GPL-4DL. In saying this, all three battery storage systems are economically, environmentally, and socially feasible. Thus, the Tesla Powerwall, RedFlow and Lifeline GPL-4DL are all viable battery storage systems to implement into residential buildings to aid in energy efficiency.

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1 INTRODUCTION

Energy efficiency is a hot topic amongst many, however, the knowledge and application is minimal throughout society. Queensland, currently last within Australia's states for renewable energy, has only provided six to seven percent of its total electricity from renewable energy (Climate Council Australia, 2014; Clean Energy Australia, 2014). With the ever depleting fossil fuel reserves (Doherty, 2012), society is looking for new ways to acquire energy, whilst doing minimal damage to the surrounding environment.

In Semester 1, 2016 an industry based project was conducted at Wattblock as apart of Griffith Universities Industry Affiliates Program (IAP). Wattblock, is an energy efficiency company focusing on reducing residential building's common area energy bill. This is completed through various methods of energy optimisation, accompanied by proposing the implementation of renewable energies and other energy saving projects. Consequently, reducing the effect placed on the surrounding environment.

Photovoltaic (PV) solar energy is one of the many ways to reduce energy consumption and the environmental effect placed on the surrounding environment. PV modules use an electrochemical reaction to transform heat energy into electrical energy, this is also referred to as the photovoltaic effect. This process is completed through adding impurities to a specific material, generally, silicon, to provide the necessary electrical characteristics displayed when light is incident on a surface (Knier, 2002; Anonymous, 2014). A PV solar system uses modules connected in series, parallel or a combination of both to produce the required characteristics of the system (Anonymous, 2014). Implementing this technology into residential buildings is an energy efficiency proposal that is often used. If the PV solar energy harnessed through a PV solar system exceeds the needs of the residential building, one of two scenarios can occur; it is redirected back into the electrical grid, or it is stored in a battery to be used later in a time need.

Therefore, using this excess energy and storing it into a battery storage system can be another effective method of reducing environmental effects and energy consumption. However, this raises the question of what battery storage system is the best? Firstly, a battery as defined by Linden and Reddy (2011) is an electrical device that uses reduction-oxidation reactions to convert stored chemical energy into electrical energy. Further on, batteries can be categorized by their rechargeable characteristics (Warner, 2015). For the purpose of implementing a battery storage system as an accessory to a PV solar system it is necessary to use a rechargeable battery. Therefore, narrowing down the possible battery storage technologies to select to implement alongside a PV solar system. However, the extensive range of possible candidates that could be implemented, a further refinement is essential. Consequently, choosing three specific battery storage systems that are currently upcoming technology and on the market. These being, a lead-acid, lithium-ion and a zinc-bromide battery. These three batteries are commonly seen in the market for PV solar storage systems and therefore, are suitable candidates for conducting a comparative analysis of their economic, social and environmental feasibility within residential buildings.

Although the amount of research papers that have been dedicated to PV solar energy and/or battery storage systems is plentiful. There is a research gap in the comparison of battery storage systems and their economic, environmental and social aspects. Therefore, this opens an opportunity to compare three battery storage systems based upon their economic, environmental and social aspects. Development of a model will compare the battery storage systems economically and environmentally. In contrast to the social comparison being conduced as a qualitative assessment.

The aim of the project is to compare three battery storage systems to aid in energy efficiency within residential buildings. As an outcome of this aim, it is intended to produce a simple, accurate and user-friendly model for Wattblock. The model is constructed using an excel spreadsheet to tailor results and retain the individuality of each client. The major objective of the project is to develop the model to compare three battery storage systems and their economic and environmental feasibility within residential buildings. As previously stated, the social feasibility will be a qualitative analysis of each battery storage system.

1.1 Objectives

The objective of the project is to model the economic, social and environmental viability of three battery storage systems. The model must calculate comparable values for the economic and environmental elements of analysis. The social comparison is completed externally to the model being produced. The objectives are to remain concise and measurable, they are then used to evaluate whether the aim of the project has been achieved. Specifically, the objectives are as follows;

- Develop a model that calculates the yearly savings, return on investment and economic feasibility of the three battery storage systems. Using these specific values to compare the economic aspects of the different battery storage systems.
- Develop a model that effectively compares the three battery storage systems environmentally. The environmental comparison should exemplify the reduction in emissions of using one of the proposed systems against the original source of electrical energy.
- Develop a qualitative analysis that will compare the social feasibility of the three battery storage systems. The comparison will have to use a set of criteria relevant to the social issues that would arise from implementation.

2 LITERATURE REVIEW

2.1 Photovoltaic Solar Energy

Photovoltaic (PV) solar energy is one of the many renewable energy sources. Harnessing the solar radiation and converting it into a form of electrical energy through various chemical processes (Knier, 2002; Häberlin, 2012). The factors affecting the amount of energy harnessed by a PV solar system can be limited to several components throughout the process of acquisition, conversion and distribution.

2.1.1 Solar Irradiance

The solar irradiance that passes through the atmosphere and reaches a PV solar system is categorized into one of the three categories, direct, reflected or diffuse irradiance. Deciphering between diffuse and direct irradiance is determined by the path of the solar beams. The calculation of the solar radiation is dependent on several factors; weather conditions and atmospheric phenomena (Labouret & Villoz, 2010; El Mghouchi, 2016). The direct irradiance consists of solar rays that travel parallel to each other. The rays travel in a straight line from the sun without atmospheric diffusion (Labouret & Villoz, 2010). The reflected irradiance is the scattered solar rays reflected off a surface, generally the ground. The value reflected is determined by a coefficient, albedo. For example, the albedo of snow is much greater than grass, as snow will reflect a greater quantity of the solar radiation (Stephens et al., 2015). The analysis of diffuse irradiance is more complicated as the factors involved are subsequently greater than those of direct irradiance (Kocifaj, 2016). Atmospheric diffusion is a phenomenon that scatters parallel beams in different directions. The scatter occurs once the originally direct radiation travels through elements of the atmosphere such as; clouds, air and aerosols, resulting in diffuse irradiance. Consequently, the total irradiance is the sum of the direct, reflected and diffuse irradiance (Labouret & Villoz, 2010; Kocifaj, 2016). The direct, reflected and diffuse irradiance can be observed in figure 1 which displays a schematic of the separation of solar radiation.

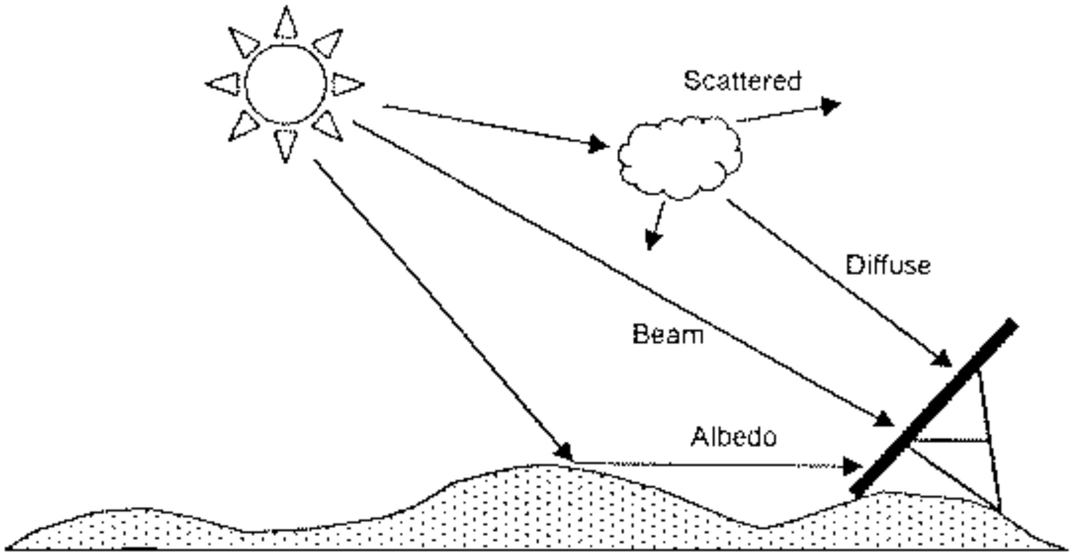

Figure 1. A diagram of the different categories of irradiance; direct, diffuse and reflected (Cuevas, 1998).

2.1.2 Photovoltaic Solar System

Photovoltaic solar systems are one of the two solar renewable energy sources. A PV system consists of many PV cells which form a module. Several modules are installed together to form an array (Knier, 2002; Anonymous, 2014). The process of harnessing solar radiation and converting the heat energy into electrical energy is known as the photoelectric effect (Knier, 2002). The photons that are incident on a surface transfer their energy to the outer electrons. If the photon carries sufficient energy the peripheral electrons can be released from the attraction of the nucleus (Labouret & Villoz, 2010; Häberlin, 2012). Figure 2 depicts the photoelectric effect as described previously.

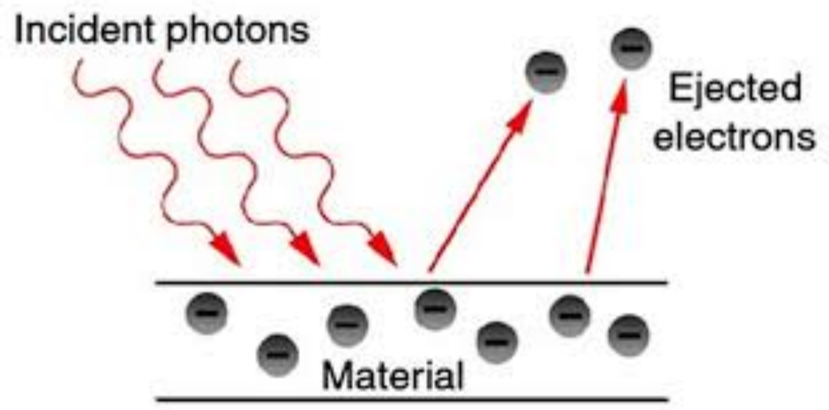

Figure 2. Photons containing sufficient energy liberating the peripheral electrons (America Pink, n.d.).

PV cells are constructed of semiconductor materials, commonly silicon (Anonymous, 2014). Within the semiconducting material the peripheral electrons are known as the valence electrons. When the valence electrons are liberated, they move from the valence band to the conduction band. Liberation of an electron therefore creates a gap or hole, this hole can be filled by electrons from a neighboring atom (Häberlin, 2012). The circulation of free electrons and holes within the semiconductor results in an electrical current (Labouret & Villoz, 2010). A PV cell is constructed using two semi-conductive layers, one positive and the other negative. The positive and negative layers are formed by adding impurities to the silicon. Adding phosphorous as an impurity creates a negative type semiconductor. Subsequently, adding Boron as an impurity will create a positive type semiconductor (Song et al., 2010). The two semi-conductive layers therefore form a positive-negative junction (p-n junction). The p-n junction establishes an electrical field where the electrons and holes, as previously discussed, are exchanged. As the photons are incident on the two semi-conductive layers the electrons are liberated and free to move. Electrons have the tendency to move to the n-type semi-conductor and the holes to the p-type semi-conductor (Mertens, 1963; Villalva et al., 2009). Figure 3 illustrates the process of photons landing on the p-n junction and the consequent actions of the electrons and their conduction of electricity.

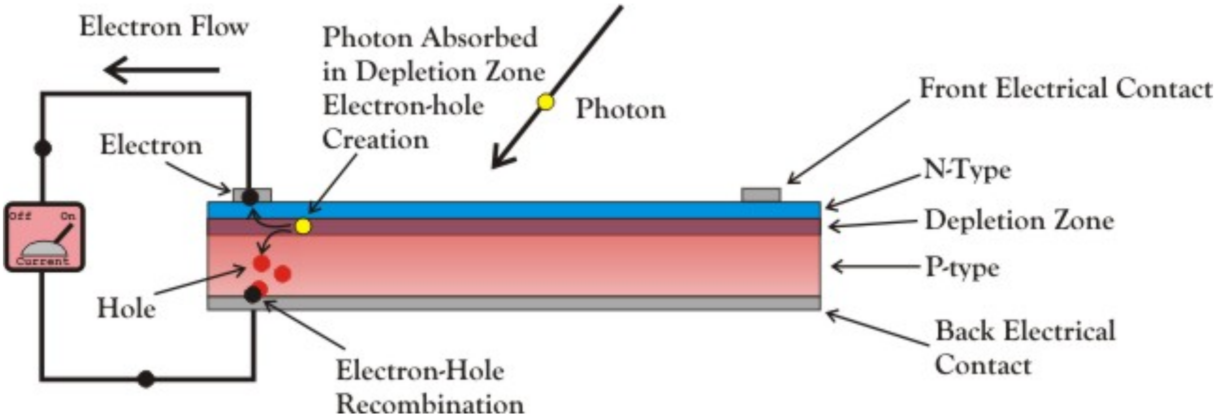

Figure 3. Diagram of a p-n junction and the electron flow (Images SI Inc., n.d.).

2.2 Battery Storage Systems

Batteries are categorized based on their rechargeable characteristics. The two types of batteries are primary and secondary, primary being non-rechargeable, commonly alkaline batteries, and secondary being rechargeable such as; lithium-ion or lead-acid batteries (Warner, 2015). A battery as defined by Linden and Reddy (2011) is a device that uses a reduction-oxidation (re-dox) reaction as a means of converting chemical energy into electrical energy.

A battery consists of cells appropriately arranged in series, parallel or a combination of both to provide the battery with the required voltage and capacity. Within each cell contains three major components (Divja & Østergaard, 2009; Hadjipaschalis et al., 2009; Linden & Reddy, 2011);

1) Anode;
   The anode is the oxidizing electrode throughout the re-dox reaction. It donates electrons to the external circuit and its characteristics of donating electrons is the reason it is also known as the negative electrode.

2) Cathode;
   The cathode is the other half of the equation. The positive electrode that accepts the electrons from the external circuit and is reduced during the re-dox reaction.

3) Electrolyte;
   The electrolyte is the medium between the electrodes, commonly a liquid which contains salts, alkalis or acids. This medium is used to transfer the charge between the anode and cathode.

Basic battery composition allows a deeper analysis of specific batteries and their key operations. Another key aspect of battery composition and application of a singular battery or battery system is depth of discharge. The depth of discharge is the amount the battery discharges, for example, 100% depth of discharge is releasing the entirety of the battery. Depth of discharges vary for different batteries; however it is the recommended amount to discharge in order to maximize the life of the battery. The section below will analyze the principles of operation, cost and specifications of three secondary batteries, specifically, a lithium-ion, lead-acid and a zinc-bromide battery.

2.2.1 Lithium-Ion Batteries

Lithium-Ion (Li-ion) battery systems are seen throughout society in varying technology. They are the most popular battery type due to their performance and ability to match the growing market as stated by Horiba (2014). Since the beginning of Li-ion batteries, in 1991, the battery technology has transformed phenomenally, from laptop and mobile phones to such extents as electric vehicles and storage systems for renewable energy sources (Väyrynen & Salminen, 2012). A Li-ion battery converts stored chemical energy into electrical energy, this is done through a process consisting of a cathode, an anode and an electrolyte. However, the construction of a Li-ion battery will also generally include the following; a battery management system (BMS), a voltage temperature monitor (VTM) board, and a thermal management system (Väyrynen & Salminen, 2012; Warner, 2015).

The principle operation of a Li-ion battery is like many of the other common battery types such as a lead-acid battery. The chemistry involves the anode (negatively charged electrode) and a cathode (positively charged electrode). These electrodes are generally lithium titanate or graphite and lithium metal oxide respectively (Väyrynen & Salminen, 2012). The electrolyte within a li-ion battery generally consists of lithium salts in an organic solvent. The charging phase initializes at the cathode when the electrochemical reaction releases the lithium atoms as lithium ions from the positive electrode. The ions are then processed through the electrolyte to the anode. The ions then combine with external electrons and deposit as lithium atoms in the carbon layers of the negative electrode. This process is then reversed as a load is required from the battery (Divya & Østergaard, 2009; Horiba, 2014). Figure 4 exemplifies the operating principle previously discussed for a lithium-ion battery.

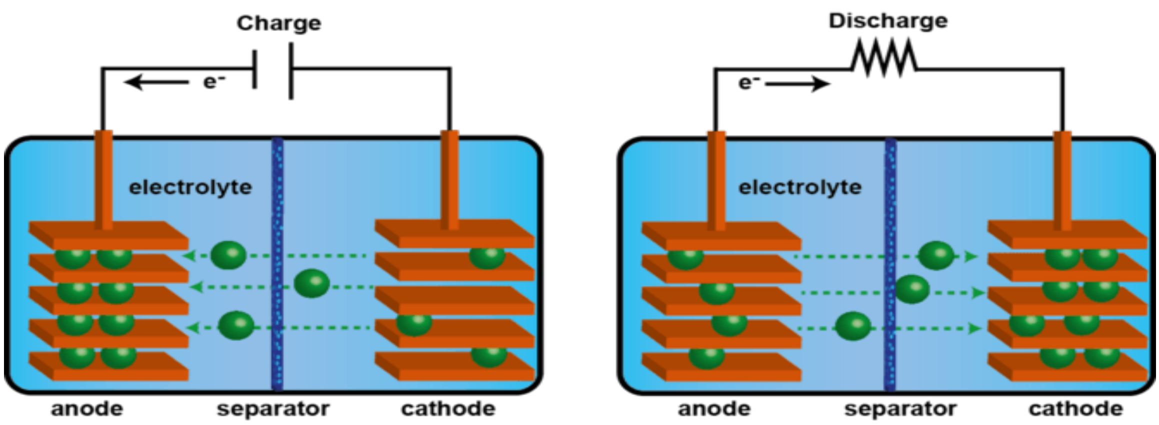

Figure 4. Schematic of the operating principle of a lithium-ion battery (Shearer, 2015).

For the purpose of assessing the Li-ion battery, a specific battery needs to be selected. Therefore, the Tesla Powerwall was selected, a Li-ion battery pack for home storage of solar energy or as a Time of Use (TOU) battery (Tesla, 2016). The Tesla Powerwall has various specifications that catch the eye of the viewer. A TOU battery refers to the battery system drawing energy from the electrical grid during off-peak periods for a cheaper cost. Consequently, using this energy during peak periods where prices are substantially higher. However, the battery as a stand alone TOU battery pack doesn't provide nearly as many benefits as advertised, this is exemplified in Conditt's (2016) report. The calculations in the report concluded that it'd take approximately 31 years for the Tesla Powerwall to pay for itself as a TOU battery alone. Therefore, the battery pack is to be used solely as an accessory to a PV solar system and provide electrical energy in times of need. The relevant specifications of the Tesla Powerwall are summarized in Table 1.

Table 1. Specifications of the Tesla Powerwall (Tesla, 2016).

Specification	
Model	10kWh
Depth of Discharge	100%
Warranty	10 Years
Price	$4,800* (Vorrath, 2016) *$3,500USD for battery alone, converted using 1USD = 0.73AUD.
Dimensions	1302mm x 862mm x 183mm
Weight	97kg
Efficiency	92.5% (Round Trip DC Efficiency)

2.2.2 Lead-Acid Batteries

The lead-acid battery is one of the oldest rechargeable batteries, it has existed for more than 130 years (Zhang et al., 2016). The battery itself has been used for various applications over its extensive lifespan. The initial invention of the lead-acid battery dates back to 1859 with Gaston Plante investigating the effects of various electrodes submerged in sulfuric acid. Noting the reverse current that flowed through the electrodes as an electric current was applied, lead was deemed the best option. Thus, leading to the invention of the lead-acid battery (Pavlov, 2011). The lead-acid battery consists of the same three components as majority of rechargeable batteries; an anode, cathode and an electrolyte. These being; lead, lead dioxide and sulfuric acid, respectively (Hadjipaschalis et al., 2009).

There are two main processes in a rechargeable battery, the charge and discharge cycles. The process that occurs during the charging process is similar to that of the discharge. However, the electrochemical process is done in reverse (Hadjipaschalis et al., 2009; Pavlov, 2011). To understand the charge and discharge processes in more depth they will be discussed individually and the steps that occur during each process.

Firstly, the discharge process begins with a fully charged lead-acid battery. As the battery is connected to a load the electrochemical reaction between the electrodes and electrolyte causes an electrical current to flow towards the load. This process can be described in more depth as the negatively charged sulfate ions within the sulfuric acid hands over their negative charge to the anode. The remaining sulfate then attaches itself to the anode to form lead sulfate. Following on, the electron flow begins with the excess of electrons being transported out the negative terminal of the battery, towards the load, and finally, back to the positive battery terminal. The cathode then accepts the electrons. Subsequently, the cathode then undergoes a chemical process where the oxygen in the cathode reacts with the positive ions (hydrogen) from the sulfuric acid to form water. This then results in the lead to react with the sulfate to consequently form lead sulfate on the cathode (Oltman, n.d.; Pavlov, 2011; Progressive Dynamics, 2015). Figure 5 displays a schematic of the discharging process within a lead-acid battery.

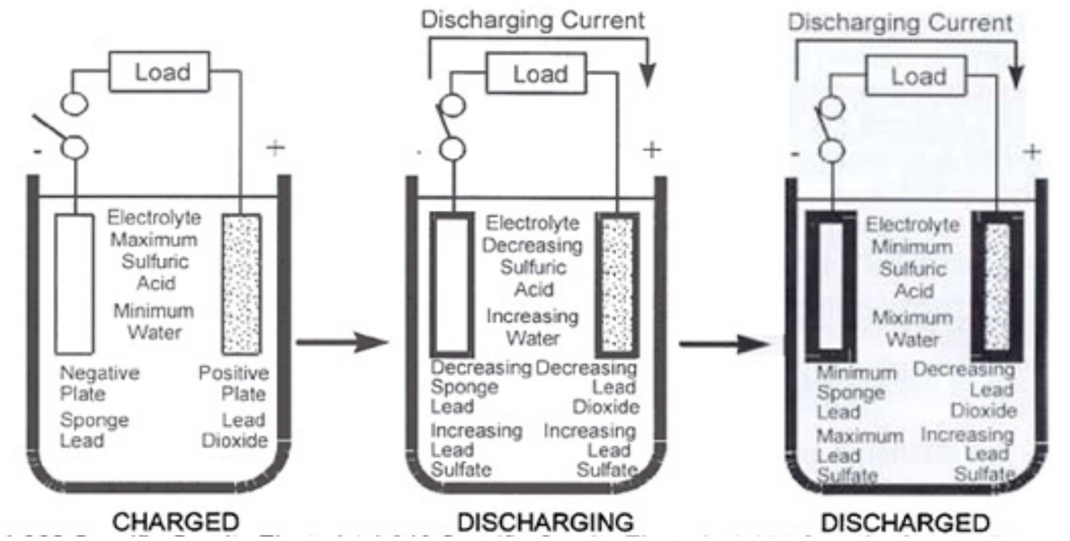

Figure 5. Schematic of the discharging process of a lead-acid battery (Long Way, 2008).

The later part of the process is the charging cycle. As stated earlier, this is the reverse of the discharge cycle. When an electrical charge is applied to the battery there is an excess in electrons. The hydrogen ions are attracted to these electrons, which chemically causes a reaction between the lead sulfate and the positive ions. This reaction causes the lead sulfate to form into lead and sulfuric acid as in the originally charged battery. On the positive side of the battery the original lead dioxide is formed when the oxygen in the water reacts with the lead sulfate on the cathode. At the end of the reactions hydrogen rises from the anode and oxygen rises from the cathode (Oltman, n.d.; Pavlov, 2011; Progressive Dynamics, 2015). Figure 6 exemplifies the process that occurs during the charging of a lead-acid battery.

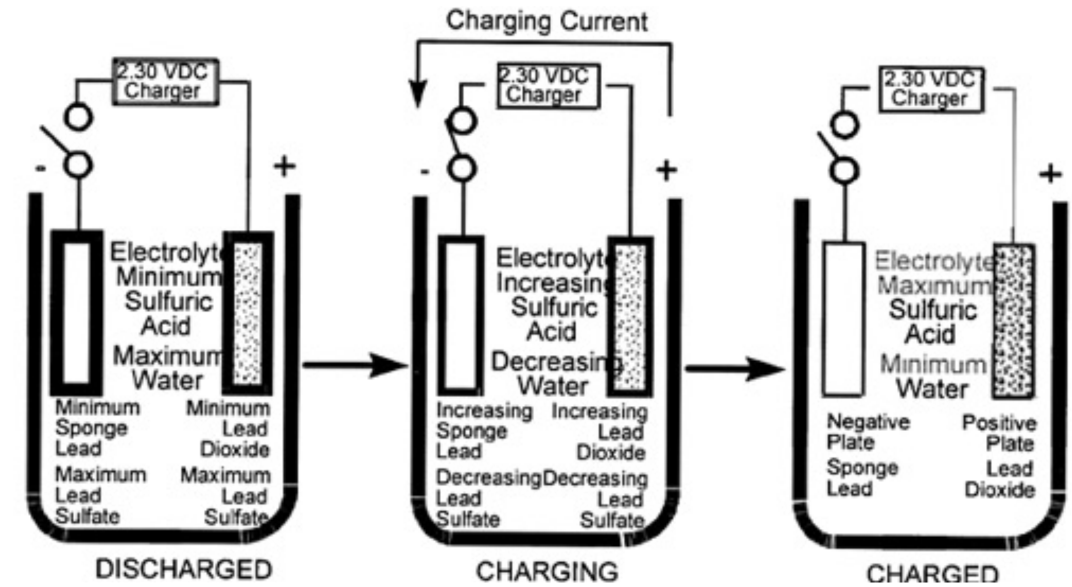

Figure 6. Schematic of the charging process of a lead-acid battery (Long Way, 2008).

Similar to the lithium-ion battery, a specific battery needs to be selected to complete the analysis. The lifeline GPL-4DL battery was chosen. The lifeline battery range has various batteries available, however, to meet the needs of the study the GPL-4DL has similar sizing and pricing as the other batteries. Therefore, based on the needs of the study the GPL-4DL was selected for the lead-acid battery. The required specifications are extracted from Batteries Direct (2016) and can be seen in table 2.

Table 2. Specifications for the selected lead-acid battery.

Specification	
Model	Lifeline GPL-4DL 12V, 210Ah AGM Battery
Depth of Discharge	50%
Warranty	5 Years
Price	$1,273 Per Battery
Dimensions	519mm x 217.5mm x 216mm
Weight	56.2kg (per battery)
Efficiency	Based on other lead-acid batteries (85% Round trip) (Díaz-González et al., 2012)

2.2.3 Zinc-Bromide Batteries

A zinc-bromide battery is another rechargeable battery; the only difference is that it is a hybrid redox flow battery. A standard redox flow battery uses a similar electrochemical redox reaction with an anode, cathode and an electrolyte. However, the major difference is that redox flow batteries are a two electrolyte system (Ibrahim et al., 2008). The electrolytes are then classified as anolyte and catholyte, negative and positive electrolytes, respectively. The anolyte and catholyte are stored in reservoirs and during usage they are pumped to their designated compartment. The anolyte is pumped to the anode and the catholyte to the cathode. An ion selective membrane is then incorporated to separate the anolyte and catholyte (Weber et al., 2011; Luo et al., 2015). The pumping of the electrolytes to their specific compartment is illustrated in figure 7.

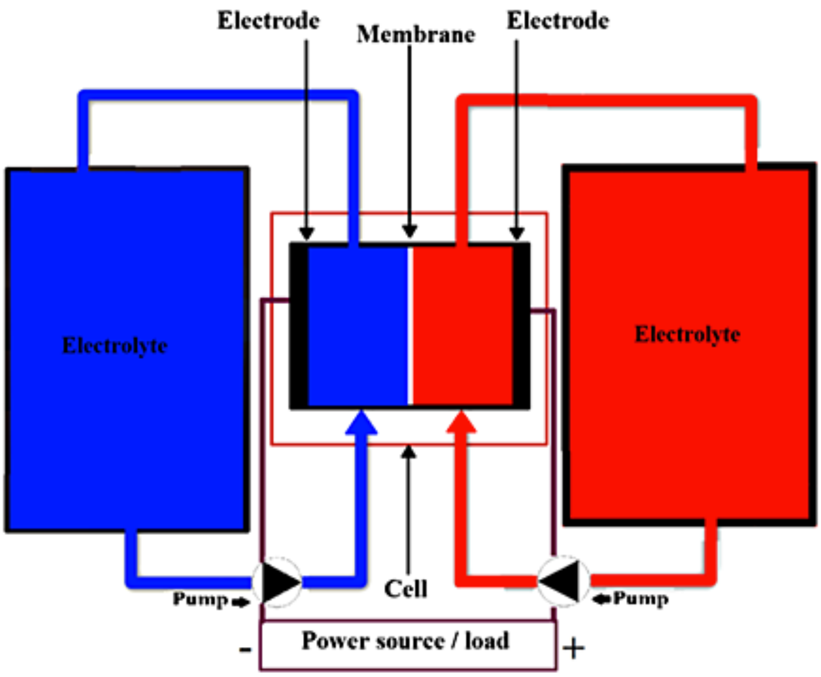

Figure 7. Illustration of a standard redox flow batteries operation (Cunha et al.,2015).

A hybrid redox flow battery is the middle ground between a redox flow battery and a conventional battery (lead-acid). During the charge and discharge cycles zinc is non-aqueous at the charged state and aqueous at the discharged state. In contrast to the bromide being aqueous in both states (Cunha et al.,2015).

The process that takes place within a hybrid redox flow battery, specifically a zinc-bromide battery, is as follows. During the charging phase the zinc electrolyte (anolyte) and bromine electrolyte (catholyte), are circulated through the battery cell. Addition of electricity to the process and the subsequent reactions occur (Lex, 1999);

Overall: $ZnBr_2 \rightarrow Zn + Br_2$ Eq (1)

Negative (Anode): $Zn^{2+} + 2e^{-} \rightarrow Zn$ Eq (2)

Positive (Cathode): $2Br^{-} \rightarrow Br_2 + 2e^{-}$ Eq (3)

The zinc is plated on the anode in solid form, simultaneously bromine and free electrons are produced at the cathode. Within the electrolyte a complexing agent (quaternary salts) cause the bromine to form into a polybromide complex. This polybromide liquid is removed from the battery via the flowing electrolyte. It is then deposited at the base of the cathode reservoir, thus, completing the charging cycle. A valve, or an additional pump, circulates the polybromide liquid back into the battery to commence the discharge cycle. The discharge cycle is the reverse of the charging cycle. At the anode the zinc is oxidized, while the bromine is reduced at the cathode. The subsequent reactions form zinc ions and bromide ions, respectively (Lex,1990; Byrne & MacArtain, 2015). Figure 8 demonstrates the operation principle of a zinc-bromide battery.

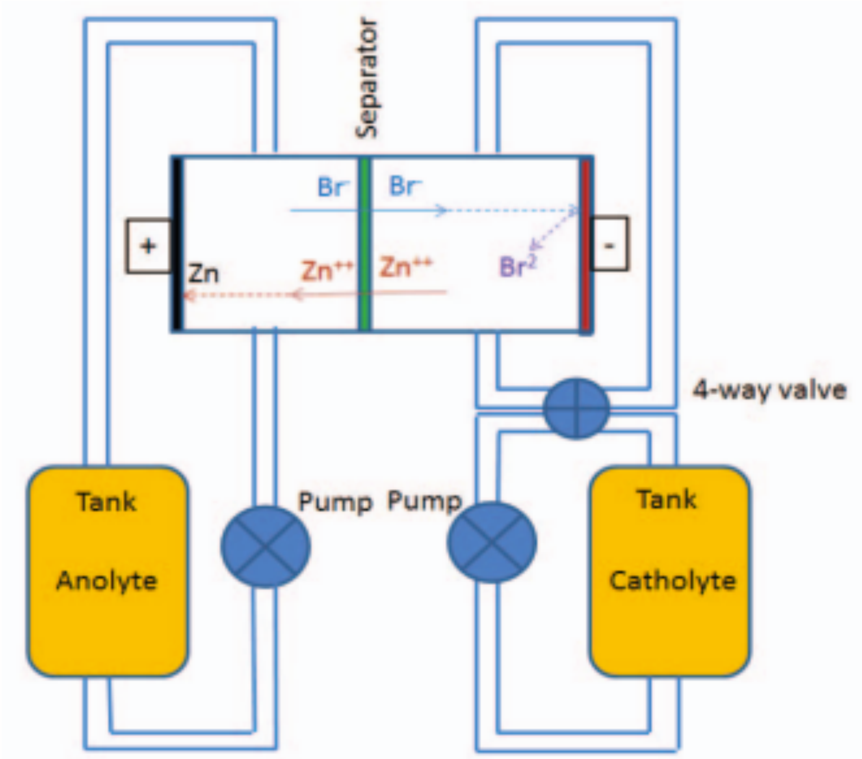

Figure 8. Schematic of a zinc-bromide battery and its operating principle (Byrne & MacArtain, 2015).

RedFlow is a company currently manufacturing the zinc-bromide combination of a hybrid redox flow battery. The RedFlow battery offers an alternate battery compared to the lead-acid and lithium-ion batteries for renewable energy storage. For the comparison of the batteries a specific battery from RedFlow has to be selected. Therefore, a similar battery in terms of size and price was selected. The RedFlow ZBM 2 is a 10kWh battery currently offered by RedFlow as a storage system for PV solar energy. The specifications of this battery are summarized in table 3 below (RedFlow, 2015; RedFlow, 2016).

Table 3. Summary of specifications for the RedFlow ZBM 2.

Specification	
Model	RedFlow ZBM 2 10kWh
Depth of Discharge	100%
Warranty	20,000,000 MWh or 10 Years (Which ever comes first)
Price	$11,000* (Vorrath, 2016) *$8,000USD for battery alone, converted using 1USD = 0.73AUD.
Dimensions	845mm x 823mm x 400mm
Weight	240kg with electrolyte 90kg without electrolyte
Efficiency	80% (Round Trip DC Efficiency)

3 METHODOLOGY

3.1 Model Construction

The construction of the model required the acquisition of data to be implemented as 'known data'. The 'known data' is assumed data based on averages and data acquired from researching relevant materials. This data would include details such as hourly solar irradiance, specifications for solar panels, batteries and other components in a residential PV solar and battery system. The section below describes the processes and sources used to acquire the data mentioned above. This will provide an in depth look into the construction, application and usage of the excel spreadsheet used for PV solar and battery storage calculations.

3.1.1 Model elements

The model is an intricate document that uses values as references across multiple sheets. To ensure a reduction in confusion and complexity, the spreadsheet uses minimal inputs, whilst maintaining accurate results. This section will entail each sheet within the spreadsheet and discuss its purpose and calculations used throughout. The model contains the following sheets where calculations are conducted; basic data, PV solar, load profile, battery calculations, pivot table, pricing and costs, and environmental analysis.

3.1.1.1 Basic Data

The first sheet is the 'basic data' sheet; this is to be the only section where values are inserted. In saying this, if an hourly load profile is known that will also be inserted, however, that will be discussed in detail below. The inputs can easily be identified by the highlighting of the cell within the spreadsheet being a bright yellow, view figure 9 as an example. The initial input is the monthly energy consumption; this data is easily accessed from the energy bills. It is important that the data that is entered is in the correct unit, for example; monthly energy consumption is to be in kilowatt hours (kWh). At the time of accessing the data for monthly energy consumption, the tariff in c/kWh, can be introduced into the model. The final two inputs are slightly more complicated and require the use of Google Maps (2016). Firstly, the address of the building requiring an assessment is to be entered on earth view, from here the roof can be seen. Google Maps provides a measurement tool; this is used to extract the roof size in m^2. Leaving the final input as a fitting coefficient, this factor multiplies the roof size by the value to produce a measurement of 'usable' roof space where PV solar panels can be installed. For example, a clear roof with no ventilation systems or other external fixtures would have a fitting coefficient of 0.9. Whereas, a roof that has half the roof unusable due to units installed on the roof would use a fitting coefficient of 0.5. This value is used under the judgment of the user and is only a factor of assumption. It is assumed that the coefficient will be used to identify the available space for installation of PV solar panels. The obtained data for roof size and fitting coefficient, alongside the sizing of a single panel, obtained from SolaHart's specifications of a 250W PV solar panel (SolaHart, 2013). This information then produces, the daily load, Eq (4), number of PV solar panels, Eq (5), the system size, Eq (6), and area that will be exposed to solar irradiance, Eq (7). The remaining elements of known data within the basic data sheet is the relevant specifications of the fundamentals within the system. Examining table 4 shows a summary of the remaining data in the basic data spreadsheet.

$$Daily\ Load = \frac{Monthly\ Load}{Days\ in\ the\ Month} \quad \text{Eq (4)}$$

$$Number\ of\ PV\ Solar\ Panles = \frac{Area\ of\ Roof * Fitting\ Coefficient}{Area\ of\ Singular\ PV\ Solar\ Panel} \quad \text{Eq (5)}$$

$$System\ Size\ (kWh) = \frac{Number\ of\ PV\ Solar\ Panels * Power\ output\ of\ a\ PV\ solar\ Panel}{1000} \quad \text{Eq (6)}$$

$$Area\ Exposed\ to\ Solar = Number\ of\ Solar\ Panels * Area\ of\ Singular\ Solar\ Panel \quad \text{Eq (7)}$$

	Monthly Energy Consumptio	
	January	February
Monthly Load	4947	4947
Number of Days	31	28
Daily Load	159.5806452	176.6785714
	Solar Panel Fitting Factor	Roof Size (m^2)
	0.9	200

Figure 9. Example of input data from the 'Basic Data' sheet within the model.

Table 4. Summary of values within 'Basic Data' sheet in excel model.

Specification	**Value**	**Source**
Solar Panel Efficiency	15.5%	(SolaHart, 2013).
Solar Panel Size	$1.616m^2$	(SolaHart, 2013).
Inverter Efficiency	95%	(Energy Matters, 2016).
System Losses	9%	(Green Rhino Energy, 2013).
Shading Coefficient	100%	The shading coefficient is an assumed value. It is assumed that the installation of PV solar panels will only be in regions of no shading.

Tesla Powerwall	Refer to Table 1.	Refer to Table 1.
RedFlow	Refer to Table 3.	Refer to Table 3.
Lead-Acid	Refer to Table 2.	Refer to Table 2.

3.1.1.2 Load Profile

The 'load profile' is a sheet within the model that produces a more accurate analysis of the daily load versus an averaged hourly load acquired from the monthly energy consumption. The sheet uses an example of a daily load, where over a 24-hour period the hourly load is entered. Following on, these values are summed and divided into a percentage for their respective hour, Eq (8). As previously mentioned, this would be the final input if the user has access to a daily load in hourly increments. If this data is unattainable an example is provided on assumed peak and off-peak consumption times. The final procedure in the 'Load Profile' sheet is to multiply the percentage of daily load to the respective daily increment of the monthly load, Eq (9). Figure 10 shows an example of a daily load profile in hourly increments and the corresponding percentage.

$$\%\ of\ Daily\ Load = \frac{Load_n}{\sum Load} \qquad \text{Eq (8)}$$

$$Hourly\ Load = \%\ of\ Daily\ Load * Daily\ Load \qquad \text{Eq (9)}$$

Example of Daily Load Profile			
Hour	Load (kWh)	% of Daily Load	
0	1.1	0.03133011	0.03133011
1	1.15	0.0327542	0.0327542
2	1.2	0.0341783	0.0341783
3	1.21	0.03446312	0.03446312
4	1.3	0.03702649	0.03702649
5	1.29	0.03674167	0.03674167
6	1.33	0.03788095	0.03788095
7	1.37	0.03902022	0.03902022
8	1.5	0.04272287	0.04272287
9	1.56	0.04443179	0.04443179
10	1.57	0.0447166	0.0447166
11	1.6	0.04557106	0.04557106
12	1.55	0.04414697	0.04414697
13	1.53	0.04357733	0.04357733
14	1.5	0.04272287	0.04272287
15	1.56	0.04443179	0.04443179
16	1.59	0.04528624	0.04528624
17	1.62	0.0461407	0.0461407
18	1.65	0.04699516	0.04699516
19	1.68	0.04784962	0.04784962
20	1.63	0.04642552	0.04642552
21	1.55	0.04414697	0.04414697
22	1.54	0.04386215	0.04386215
23	1.53	0.04357733	0.04357733
	35.11	1	

Figure 10. Example of Daily Load Profile in hourly increments, extracted from the model.

3.1.1.3 PV Solar

The third sheet ‘PV solar’ is used for majority of the photovoltaic solar calculations. It begins with hourly values of solar irradiance (direct, diffuse and plane of array irradiance), ambient temperature and wind speed which were obtained through the national renewable energy laboratory (NREL) PVWatts Calculator. NREL is apart of the U.S department of energy, specifically, the office of renewable energy and energy efficiency (NREL, 2016). These values in addition to values acquired in the ‘basic data’ sheet form the basis of the PV solar calculations. The model initially calculates the ‘solar collected’ (kWh) using the ‘plane of array irradiance’ (W/m^2) and ‘area exposed to solar’ (m^2), Eq (10). After conversions and multiplication of efficiencies (PV solar panel efficiency and system losses) we are left with the theoretical value for usable PV solar energy, Eq (11). Continuing from the load profile we can model how much solar energy can be used, Eq (12)*, how much is remaining to be stored in batteries, Eq (13)**, and how much electrical grid energy is required, Eq (14)***. The energy that is to be stored in batteries is converted to the ‘battery calculations’ sheet where charge and discharge cycles are analyzed. The resulting discharge is then returned to the ‘PV solar’ sheet. These discharge values are for when there is not enough PV solar energy and the battery supplies the necessary energy to meet the load. This procedure is discussed in more depth in the ‘battery calculations’ section. The final element within the ‘PV solar’ sheet is the energy that is still required from the electrical grid in these four circumstances; using only PV solar, and the remaining three are using PV solar accompanied by the three battery storage systems. This data is later used within the economic and environmental calculations.

$$PV\ Solar\ Collected = \frac{Plane\ of\ Array\ Irradiance * Area\ Exposed\ to\ Solar}{1000} \qquad \text{Eq (10)}$$

$$PV\ Solar\ including\ Losses = PV\ Solar\ Collected * \eta_{PV\ Solar\ Panels} * \eta_{Inverter} * Shading\ Coefficient \qquad \text{Eq (11)}$$

$$PV\ Solar\ Used = PV\ Solar\ including\ Losses\ (to\ a\ maximum\ of\ the\ Hourly\ Load) \qquad \text{Eq (12)}$$

$$Remaining\ PV\ Solar = PV\ Solar\ Used - Load \qquad \text{Eq (13)}$$

$$Electrical\ Grid\ Energy\ Required = Load - PV\ Solar\ Used \qquad \text{Eq (14)}$$

* This calculation is used if PV Solar Including Losses is greater than 0.

** This calculation is used if PV Solar Used is greater than or equal to the Load.

*** This calculation is used if the Load if greater than the PV Solar Used.

3.1.1.4 Battery Calculations

The ‘battery calculations’, as suggested by the name of the sheet, is the section of the model that calculates the charge and discharge cycles of the three battery storage systems. Initially, the charging cycles of the battery is calculated, Eq (15), this is completed by examining if there is either an excess of PV solar energy or previous charge within the battery. The process is more complicated than seeing if there is an excess. The criteria must meet at least one of the following in order for the battery to charge;

- The PV solar energy exceeds that of the load;
- The battery contains left over charge from the previous hour, whilst either providing energy in addition to the PV solar energy exceeding the load.

However, these conditions are also reliant on factors including; efficiencies of the battery and inverter, and the capacity of the battery system.

The next stage of the calculations with the charge and discharge cycles is whether or not the battery is charging or discharging. This process is much simpler and isn’t reliant on conditions or having to meet criteria like the charge cycle. The basic method used is a subtraction of the current hour from the previous hour of the battery charging cycle, Eq (16). If this produces a positive number, it can be said that the battery has charged over the past hour. In contrary, if the produced number is negative, it can be seen that the battery has lost charge, and therefore discharged. Finally, converting these values into accurate amounts of energy that is discharged by the battery. The negative numbers are consequently multiplied by negative one and the efficiency of the inverter and battery to produce an accurate discharge value, Eq (17)*.

$$Battery\ Charge = Left\ over\ PV\ Solar * \eta_{Inverter} * \eta_{Battery} \qquad \text{Eq (15)}$$

$$Battery\ Charge\ or\ Discharge_n = Battery\ Charge_n - Battery\ Charge_{n-1} \qquad \text{Eq (16)}$$

$$Battery\ Discharge_n = -Battery\ Charge\ or\ Discharge_n * \eta_{Inverter} * \eta_{Battery} \qquad \text{Eq (17)}$$

*Use this equation only if the corresponding charge/discharge value is negative.

3.1.1.5 Pivot Table

The pivot table is a tool used to summarize the data within the ‘PV solar’ sheet. The ideology of the pivot table is to provide an hourly average value for the following sections; discharge of each battery, PV solar energy used, electrical grid energy required after implementation of PV solar and each battery storage system as a counterpart. The pivot table is an analytical tool and provides values to transform from tabulated data into graphical form. To ensure the updated data in the model is inserted into the pivot table, it is essential to refresh the table.

3.1.1.6 Pricing and Costs

The 'pricing and costs' sheet is a large contributor to the economic analysis, it makes a model for savings, return on investment (ROI), and initial and ongoing costs. The beginning of the sheet calculates the total yearly spend on electricity, Eq (18). This is completed by multiplying the tariff inputted at the beginning of the model, by the required electrical grid energy after implementing PV solar, and PV solar accompanied with each battery system. Using this data calculations of savings can commence by subtracting the revised yearly expenditure on energy from the original yearly spend on energy, Eq (19). Subsequently, forming the basis for calculating the ROI. The ROI is calculated using the yearly savings and dividing the initial costs by the value, to give a yearly figure for how long the project will take to repay, Eq (20). The final element of the 'pricing and costs' sheet is a 40-year analysis; this is an on-going cost analysis, Eq (21). This is to include factors like; replacement, maintenance, and cleaning, refer to table 5 for details of the on-going costs. Beginning at 0 years, initial purchase of the system, jumping to 5 years and then increasing in yearly increments to 10 years. Finally, increasing in 5 year increments from 10 to 40 years. The time period between 5 and 10years shows the turnover of costs from financially outlaying money to receiving a positive financial benefit from installation.

$$Revised\ Total\ Yearly\ Spend = \sum Grid\ Energy\ Required_n * Tariff \quad \text{Eq (18)}$$

$$Yearly\ Savings = Total\ Yearly\ Spend - Revised\ Yearly\ Spend \quad \text{Eq (19)}$$

$$ROI = \frac{\sum initial\ costs}{Yearly\ Savings} \quad \text{Eq (20)}$$

$$Year\ of\ Analysis_n = (Yearly\ Savings * n) - (initial\ costs + (ongoing\ costs * n)) \quad \text{Eq (21)}$$

Table 5. Summary of the on-going costs involved with the three battery storage systems.

Battery Type	On-going Costs ($)		Replacement	
	Maintenance	Cleaning	Duration	Cost
Lithium-Ion	$1,000*	$500**	10 Years	$4,800
Lead-Acid	$1,000*	$500**	10 Years	$10,200
Zinc-Bromide	- *	$500**	7 Years***	$5,500****

* Assumed value of maintenance, RedFlow (2015) states the RedFlow battery requires no maintenance.
** Assumed cost for cleaning.
*** Refer to Table 3, this value is approximately how long it takes to reach 20MWh.
**** It is assumed that the replacement of the RedFlow battery is half the initial cost (RedFlow, 2015).

3.1.1.7 Environmental Analysis

The 'Environmental Analysis' sheet of the model, much like the 'Pricing and Costs' sheet forms the groundwork for comparing the three battery storage systems. However, this comparison is based on the kilograms of carbon dioxide equivalent. The sheet uses a coefficient (kilograms of carbon dioxide equivalent per kilowatt hour) for the three sources of energy; the electrical grid, PV solar panels, and battery storage systems. This coefficient is used for the basis of all environmental calculations within the model. It begins by multiplying the coefficient by the respective amount of kilowatt hours used per source of energy, Eq (22). For example; building A uses 6,000kWh a year from the electrical grid, and let's say the electrical grid has a coefficient of 0.66 kilograms of carbon dioxide equivalent per kilowatt hour. Therefore, building A would be emitting 3,960kg of carbon dioxide equivalent. The final stage of the model after acquiring the results is to translated the outcomes into graphical form.

$$kgC_{O_2}equivaent = \frac{kgC_{O_2}equivaent}{kWh} * kWh\,produced \qquad \text{Eq (22)}$$

3.2 Elements of Analysis

The spreadsheet does not only calculate the accessible solar energy to be stored or used for electrical energy. It will provide a comparison of three battery storage systems and their consequent economic and environmental analysis. The social analysis will be conducted outside of the calculator as a qualitative analysis of possible social issues that will become apparent to the users. The section below will provide a thorough description on how the economic, environmental and social analysis is conducted. This will include the values implemented in the excel spreadsheet and elements to be discussed and analyzed.

3.2.1 Economic Analysis

The economic analysis is a large factor in determining the superior battery storage system. The model produces graphical evidence of each battery systems savings and determines the ROI. To determine the feasibility of implementing a battery storage system into residential buildings to accompany a PV solar system, the economic analysis focuses on more than the savings and ROI. To conclude if the battery storage systems are economically viable a 40-year analysis was conducted. This included the initial costs outlaid for the project and the on-going costs. The ideology of including the on-going costs, such as; replacement, maintenance and cleaning, is to identify if the project will produce monetary savings for the clientele. In other words, the project can also be referred to as economically viable.

3.2.2 Environmental Analysis

The environmental analysis is the second quantitative comparison of the three battery storage systems. It segregates the areas of energy acquisition for each battery storage system into electrical grid, PV solar system, and the battery. These sections are each assigned a coefficient for kilograms of carbon dioxide equivalent per kilowatt-hour. The selected values for these coefficients can be studied in table 6. The respective quantity of energy provided by each area of acquisition is multiplied by its coefficient of $kgC_{O2}e$-/kWh. Finally, accumulating the results for each section of the system to conclude with an overall value for the amount of kilograms of carbon dioxide equivalent produced.

Table 6. Summary of coefficients of $kgC_{O2}e\text{-}kWh^{-1}$ used.

Section of Acquisition	**Coefficient of $kgC_{O2}e\text{-}kWh^{-1}$**	**Source**
Electrical Grid	0.79	(Department of the Environment, 2015)
PV Solar System	0.057	(Hsu et al., 2012)
Battery	0.059	(Dufo-López et al., 2011)

This analysis contains various limitations revolving around the battery storage systems. The major limitation is the lack of information surrounding carbon dioxide emissions specific to a lead-acid, lithium-ion and zinc-bromide battery. This results in researching relevant literature to discover a coefficient applicable to all three models of battery. The next limitation revolves around the emissions themselves and where they are produced. Due to batteries and PV solar panels producing almost zero emissions during the acquisition and use of solar energy. It is necessary to look beyond the acquisition and use, to the production and entirety of the PV solar panels and batteries life. This allows for a coefficient to be introduced into the model for both the PV solar panels and the battery storage systems.

3.2.3 Social Analysis

The social analysis is a qualitative analysis of the three battery storage systems. It will identify the social concerns relevant in each battery type. The comparison will evaluate the size and weight of each battery system, the availability, installation, and replacement. The social aspects that are used to conduct the social analysis will rank the three battery storage systems in the respective aspects by most feasible, feasible and least feasible. These results will then be accumulated to determine the most feasible battery in terms of their social aspects. However, the application of the battery storage and whether it is deemed socially viable in residential buildings is based on the circumstances of its user's scenario.

4 RESULTS AND DISCUSSION

The model created was used to compare three battery storage systems. To effectively create results and simulate the ideology of the model an example building was created. The buildings inputs were assumed to be;

- Monthly energy consumption – 4947kWh per month
- Tariff – 25.25c/kWh
- Roof size – 200m^2
- PV Solar panel fitting factor – 0.9

The results will be in correspondence to the objectives and identified as figures, graphs and tables within either the economic, environmental or social analysis. This will then lead into the comparison of the battery systems, this will in detail examine the results for their consequent area of analysis. Further on, discussing not only the feasibility, but, the distribution of energy and usage of the three battery systems. Therefore, the comparison will isolate the superior battery storage system based upon the presented information throughout the analysis.

4.1 Economic Analysis

The economic analysis, as previously discussed, consists of the yearly savings, ROI, and a 40-year analysis. The initial assessment is the yearly savings of all three batteries, the results can be summarized in table 7 and figure 11. The initial spend for the building is $14,989.41, implementing a PV solar system accompanied by either the lithium-ion, zinc-bromide or lead-acid battery provided copious savings. Moreover, the new yearly spend is $8,008.32 for the lithium-ion, $8,062.87 for the zinc-bromide, and $8,040.58 for the lead-acid. This translates to a 46.6%, 46.2%, and a 46.4% reduction, respectively, as exemplified in figure 12. Therefore, the yearly savings are $6,981.09, $6,926.54, and $6,948.83, respectively.

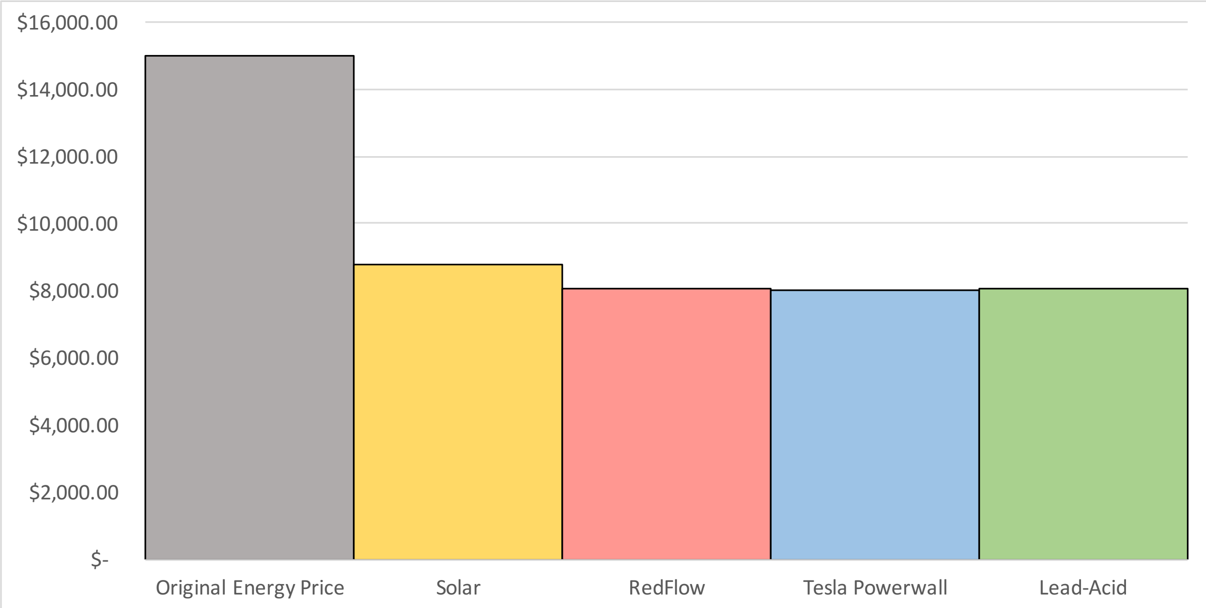

Figure 11. Energy cost comparison for electrical grid, PV solar, and PV solar accompanied by one of the three battery storage systems.

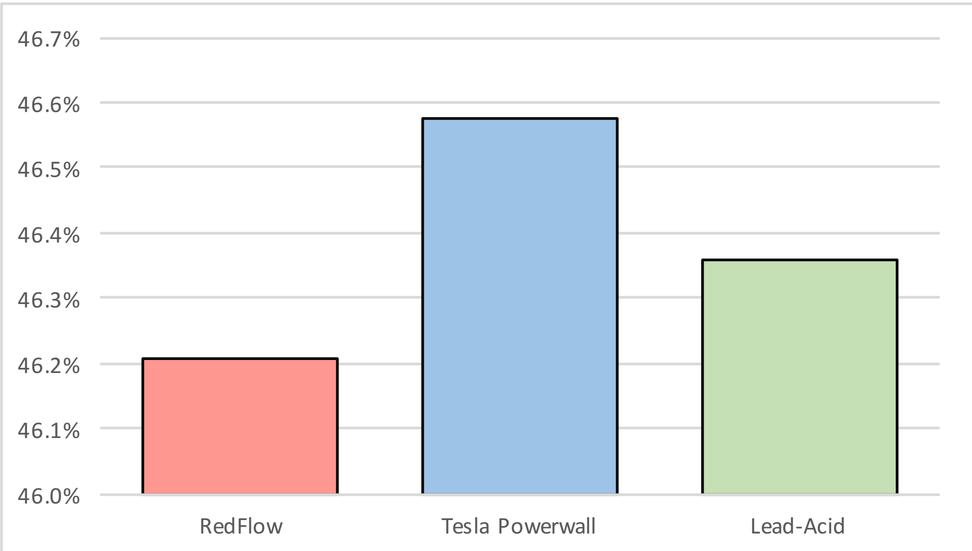

Figure 12. Graph comparing the three battery storage systems and their energy reduction if implemented with a PV solar system.

The yearly savings are then evaluated to calculate the ROI. This is completed by dividing the yearly savings by the initial costs of the systems. The initial costs include; the battery, installation, PV solar system, and the inverter. The costs for these can be seen in Table 7, it also displays the return on investment and the estimated payback period.

Table 7. Summary of the initial costs, yearly savings and return on investment for three battery storage systems.

Battery Type	Battery Cost	Installation	PV Solar Panel Costs	Inverter Costs	Yearly Savings	Return on Investment
Lithium-ion	$4,800	$2,000*	22,200**	$3,000***	$6,981.09	4.80 years
Lead-Acid	$10,200	$1,500*	22,200**	$3,000***	$6,948.83	5.53 years
Zinc-Bromide	$11,000	$4,000*	22,200**	$3,000***	$6,926.54	5.88 years
* Assumed values for installation based on complexity and rarity of system. ** Assumed price of PV solar panels to be $200 each. ***Information and prices extracted from Energy Matters (2016) for a 10kW three phase inverter.						

The final assessment method for the economic analysis is the 40-year cost analysis. This encompasses the initial costs and the on-going costs. Therefore, over the 40-years you can analyze the economic feasibility. It can be deemed economically feasible if the project has a positive monetary value after the 40-years. This can be illustrated in figure 13 where each line represents a battery system. The results of this are as follows; $168,043.55, $140,253,.23, and $189,361.63 for the lithium-ion, lead-acid, and zinc-bromide battery systems, respectively. Therefore, it is economically feasible to implement any of the three battery storage systems as an accessory to a PV solar system in residential buildings.

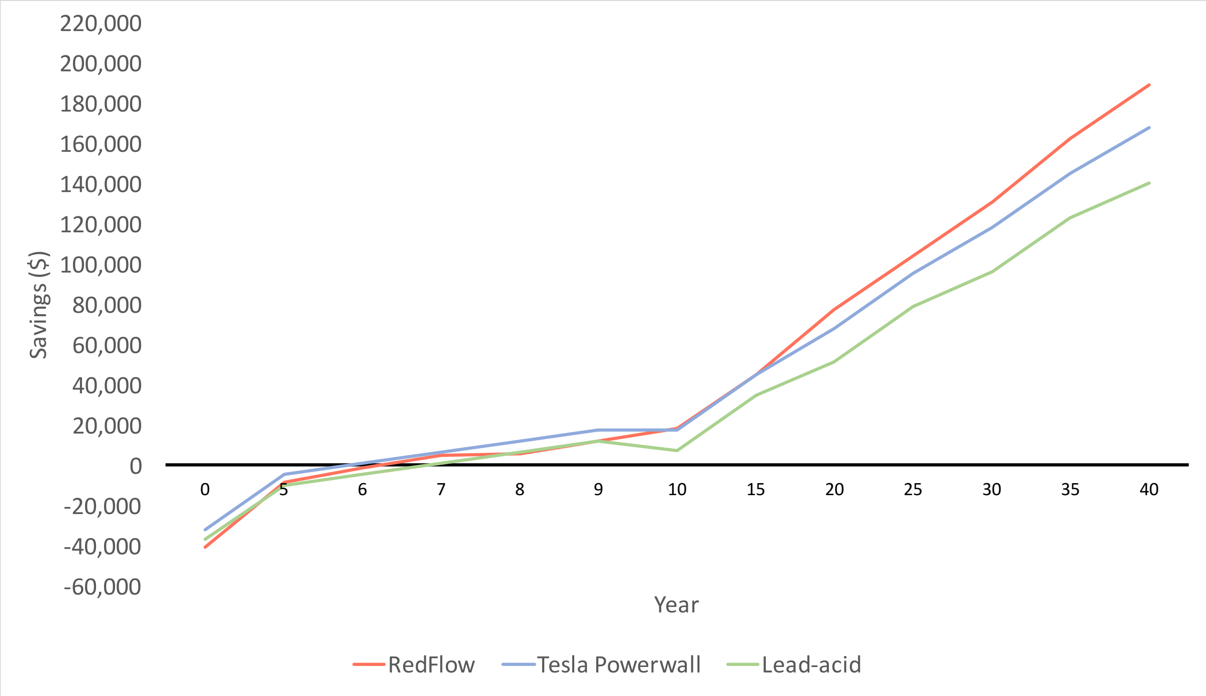

Figure 13. 40-year assessment of three battery storage systems to conclude if the project is economically feasible.

4.2 Environmental Analysis

The environmental analysis is a comparison of the three battery storage systems based upon their kilograms of carbon dioxide equivalent. This is conducted using a coefficient for three factors and their relevant distribution of energy. The analysis is then broken up into three sections; energy from batteries, energy from PV solar and energy from the electrical grid. Each section having a coefficient representing it, the respective values can be seen in table 6. Due to the all three battery storage systems using the same coefficient, the difference between them will be reliant on their efficiencies. This is due to the efficiencies being the key component fluctuating the discharge values. It can be seen that the lithium-ion battery has the lowest emissions, in comparison to the zinc-bromide and lead-acid batteries in figure 14. However, in the scheme of things, figure 15 exemplifies a similar reduction across all three batteries in comparison to the original energy source. The specific reduction in kilograms of carbon dioxide equivalent can be examined in figure 16.

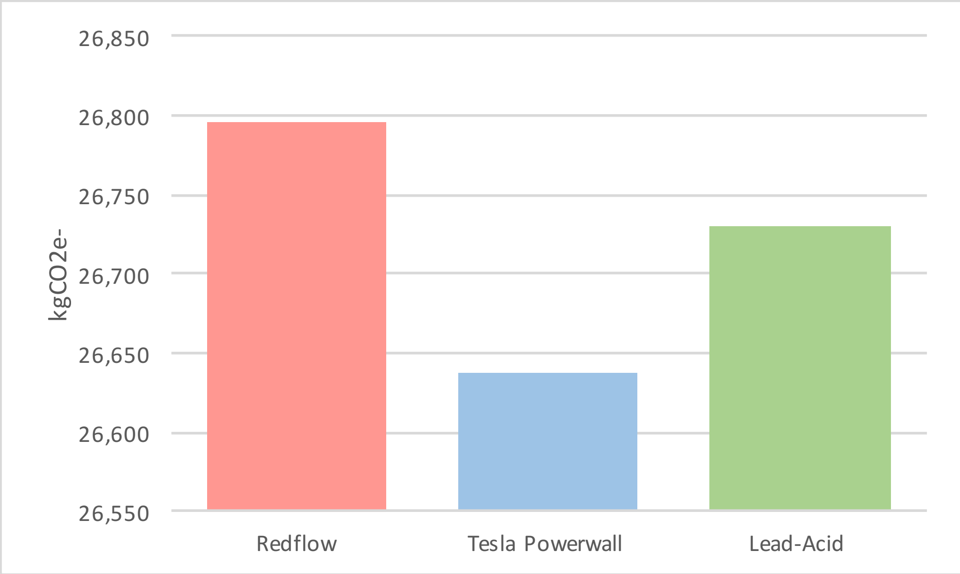

Figure 14. Comparison of the three battery storage systems and their respective $kgC_{O2}e$-.

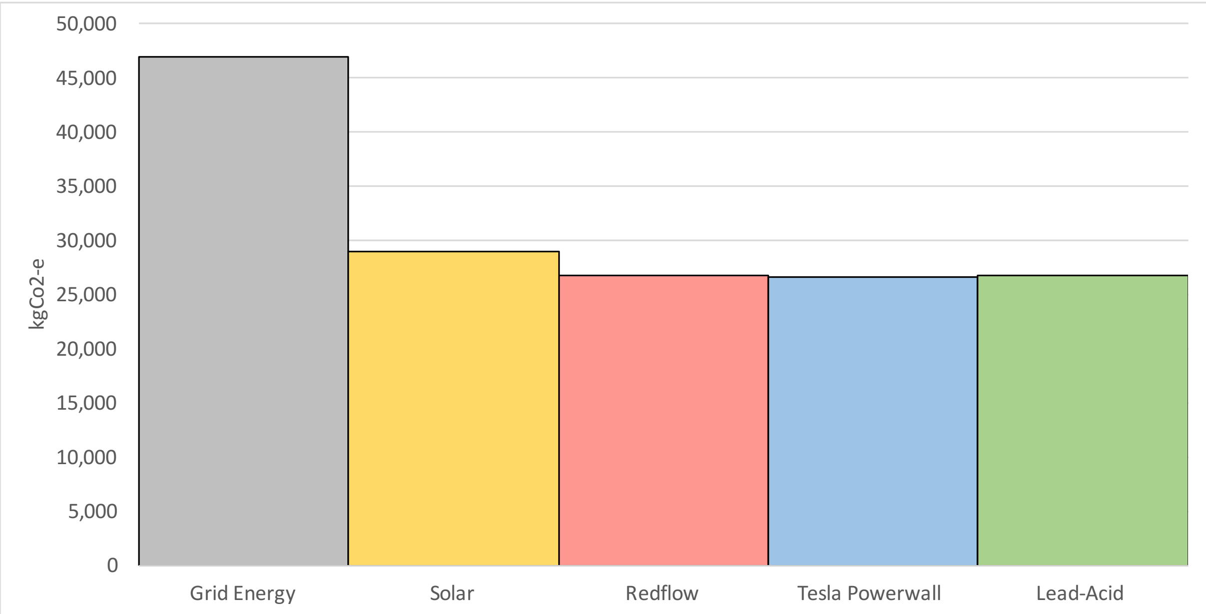

Figure 15. Comparison of the original acquisition of energy to the proposed projects and their respective $kgC_{O2}e$-.

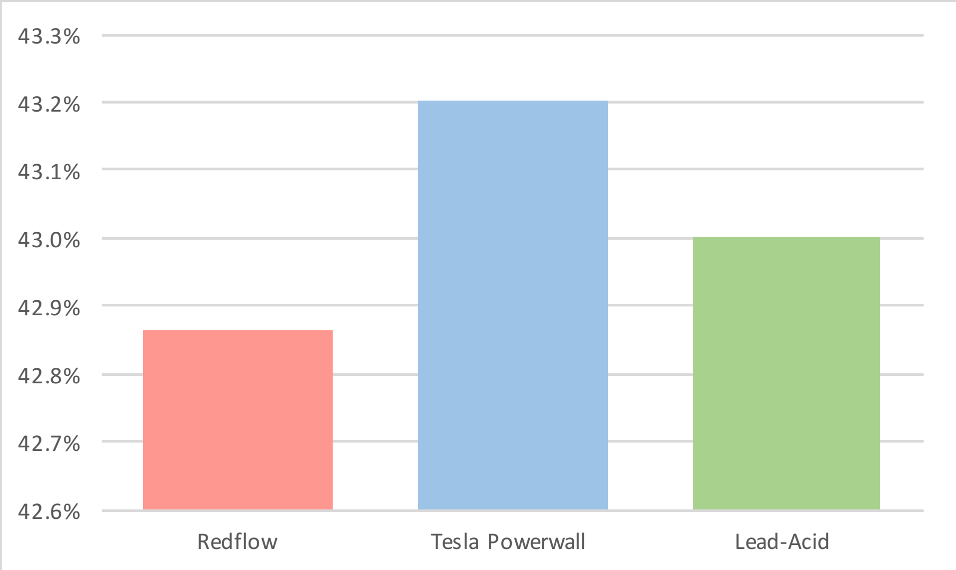

Figure 16. Bar graph displaying the percentile for reduction in $kgC_{O2}e$-.

The assessment examines the sources of the energy and their respective kilowatt-hour production. Specifically, for the exemplar building, the resulting production for each section can be observed in table 8. It can be seen that for the three battery storage systems the lithium-ion battery produced 181.00kg of carbon dioxide equivalent. The zinc-bromide and lead-acid battery produced 168.28 and 173.47 kg of carbon dioxide equivalent, respectively. Although, it seems the the zinc-bromide has produced the least emissions, this is contradicted by the remaining acquisition by the electrical grid. Due to the electrical grid having a severely higher coefficient of $kgC_{O2}e$-, the overall emissions emitted are greater than that of the lithium-ion or lead-acid battery systems. Therefore, it is essential to focus on not only the energy acquired from the battery itself, but, to view the system as a whole and examine the acquired energy in their respective forms.

Table 8. Breakdown of emissions based on acquisition of energy for three battery storage systems

	Lithium-Ion ($kgC_{O2}e$-)	**Lead-Acid** ($kgC_{O2}e$-)	**Zinc-Bromide** ($kgC_{O2}e$-)
Electrical Grid	25055.74	25156.66	25226.40
PV Solar	1400.87	1400.87	1400.87
Battery	181.00	173.47	168.28
Total	26637.61	26731.00	26795.55

4.3 Social Analysis

The social analysis of the three battery storage systems as previously mentioned is a qualitative analysis. This is completed because it is not possible to process social aspects through the created model. Due to social issues being a large consideration, it can't merely be dismissed. Therefore, the comparison will identify key factors that are deemed to provide social issues when implementing any of the battery storage systems.

The initial feasibility will incorporate the size and weight of the batteries. The Tesla Powerwall is the designated battery for the lithium-ion category, its specifications are visible in table 1. The weight of the battery is 97kg with the following dimensions 1302mm x 862mm x 183mm. The size of this battery is quite large, however the study is based around installing the battery storage system in residential buildings. Therefore, for the size and weight of this battery there is sufficient room, especially in common areas such as car parks. On the other hand, this factor is completely dependable on the area of the assessable building. The dimensions of the Tesla Powerwall are similar to that of the RedFlow, the designated battery for the zinc-bromide battery systems. The weight and dimensions of the RedFlow battery are as follows; 845mm x 823mm x 400mm with a weight of 90kg without electrolyte and 240kg with electrolyte. This weight difference is substantially larger than that of the Tesla Powerwall. The final battery storage system is the Lifeline GPL-4DL for the lead-acid batteries, this battery system requires eight batteries in a formation of two series of batteries connected in parallel with four batteries per series. Therefore, the sizing and weight is 8-fold that of a singular battery. The comparison of these batteries and their weight and dimensional factors can be analyzed in table 9.

Table 9. Summary of size and weight aspects of three battery storage systems.

	Lithium-Ion	**Lead-Acid**	**Zinc-Bromide**
Weight	97kg	56.2kg (each) 449.9kg (required amount of batteries)	90kg with electrolyte 240kg without electrolyte
Dimensions	1302mm x 862mm x 183mm	519mm x 217.5mm x 216mm (each) 2,076mm x 435mm x 216mm (in required formation)	845mm x 823mm x 400mm

The second section of the social analysis will focus on comparing the three battery storage systems and their availability, replacement and difficulty of installation. This section of the analysis will be based upon the age of the technology and how long it has been implemented. There is a direct correlation between the availability of the battery and its age. As the battery has been on the market for a substantial time, it's availability increases dramatically. The Lifeline GPL-4DL is the most available battery of the three. It can be purchased from a range of websites and stores. The Tesla Powerwall is the second most available battery, with the media hype of the battery, the knowledge and advertisement has increased substantially. Therefore, leaving the RedFlow battery to be the least available. The RedFlow battery system, although the tremendous specifications, doesn't have the extent of practical application as the Tesla Powerwall or Lifeline GPL-4DL or other lead-acid batteries.

The difficulty of finding an installer will produce identical results to the availability. The more available the battery, the higher the quantity of qualified installers. Consequently, difficulty of finding an installer will be ranked easiest to most difficult in the following order; Lifeline GPL-4DL, Tesla Powerwall and finally, the RedFlow.

The replacement of the battery systems is the final factor related to the second section of the social analysis. Although the previous sections have shown the order of feasibility to be Lifeline GPL-4DL, Tesla Powerwall, and then the RedFlow. The replacement of the system is on a similar view point as availability and finding an installer because these two factors are required to replace the system. However, based on the literature, although the RedFlow is the first applicable zinc-bromide battery for renewable energy, its proposed replacement characteristics, as stated by RedFlow (2015) is that the battery itself doesn't require full replacement. Therefore, the cost of replacement is approximately half that of the initial cost. In comparison to the Tesla Powerwall and the GPL-4DL which once the expiration of the batteries life has occurred they will require a full replacement. This consideration alongside the availability and finding an installer alters the hierarchy of the batteries feasibility.

The feasibility of the three battery storage systems in terms of their social aspects are summarized in table 10. The corresponding social aspect will have a resultant grading of each battery storage system as one of the following; most feasible, feasible and least feasible.

Table 10. Social feasibility for three battery storage systems

Social Aspect	Tesla Powerwall	GPL-4DL	RedFlow
Weight	Most Feasible	Least Feasible	Feasible
Dimensions	Feasible	Least Feasible	Most Feasible
Availability	Feasible	Most Feasible	Least Feasible
Finding an Installer	Feasible	Most Feasible	Least Feasible
Replacement	Feasible	Least Feasible	Most Feasible

4.4 Comparison of Battery Storage Systems

The Tesla Powerwall was nominated as the battery system to represent lithium-ion batteries. Analyzing the battery as a counterpart to a PV solar system it assessed well. Initially, the battery charge and discharge cycles were calculated. It then processed to summarize these yearly results into hourly averages. This data was then processed into graphical form to see the average daily load, PV solar and battery used, in hourly increments. This data is seen in figure 17, it is evident that PV solar is used and meets the majority of load between 9am and 4pm. The next period is from 4pm to 8pm we can see the contribution of the Tesla Powerwall. The specific values of discharge for the battery over the 24-hour period can be seen in table 11.

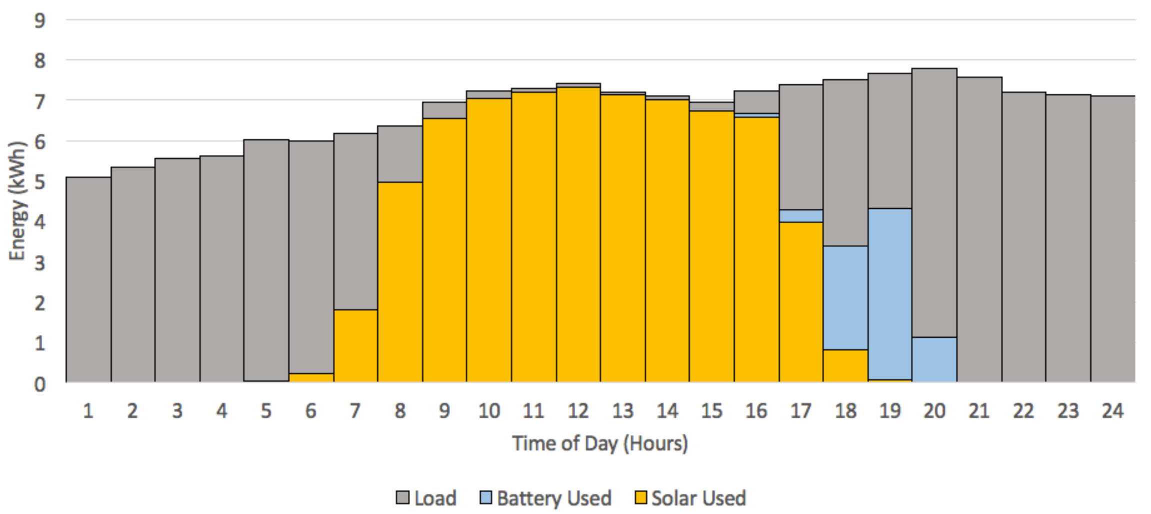

Figure 17. Bar graph displaying when the lithium-ion battery and PV solar system are being used.

The distribution of energy and their respective source is exemplified in figure 18. It can be seen that the largest source is still the electrical grid with 54% of the energy acquired here. Therefore, PV solar and the Tesla Powerwall contributing to the remaining 46%, this being made up of 5% from the battery and 41% from the PV solar system.

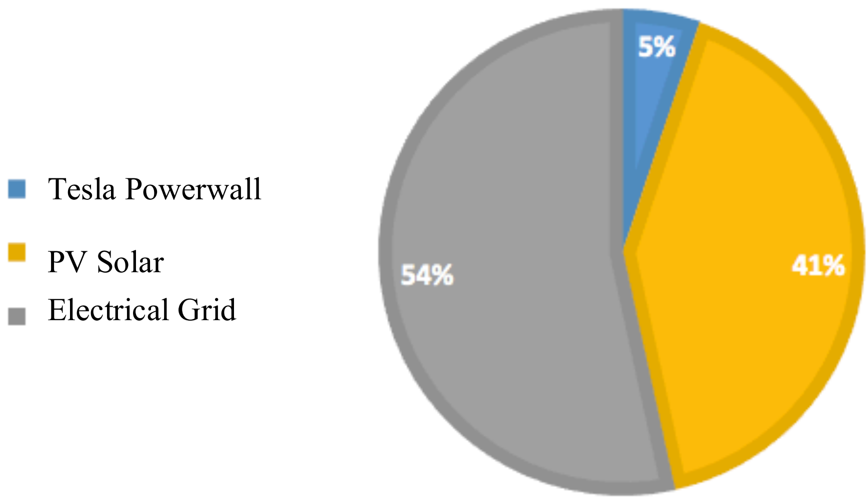

Figure 18. Pie graph displaying the distribution of energy from three sources for the lithium-ion battery system.

The lead-acid and zinc-bromide batteries possesses similar attributes to the lithium-ion battery system. It is evident that all three of these battery systems produce a similar result in terms of energy provided by the battery bank. Figure 19 and figure 20 have identical characteristics to figure 18 where only 5% of the energy is provided from the battery for all three batteries. This can be explained by the minimal difference in discharge between the batteries. The reasoning behind this is the difference in battery efficiency. Although, as seen in table 11 there is a minuet difference between the discharge across all batteries these small discharge differences are not substantial enough to alter the distribution of energy from the batteries. Figure 21 and figure 22 are nearly identical to figure 17, however the displayed discharges in table 11 are so close that graphically the difference can not be seen.

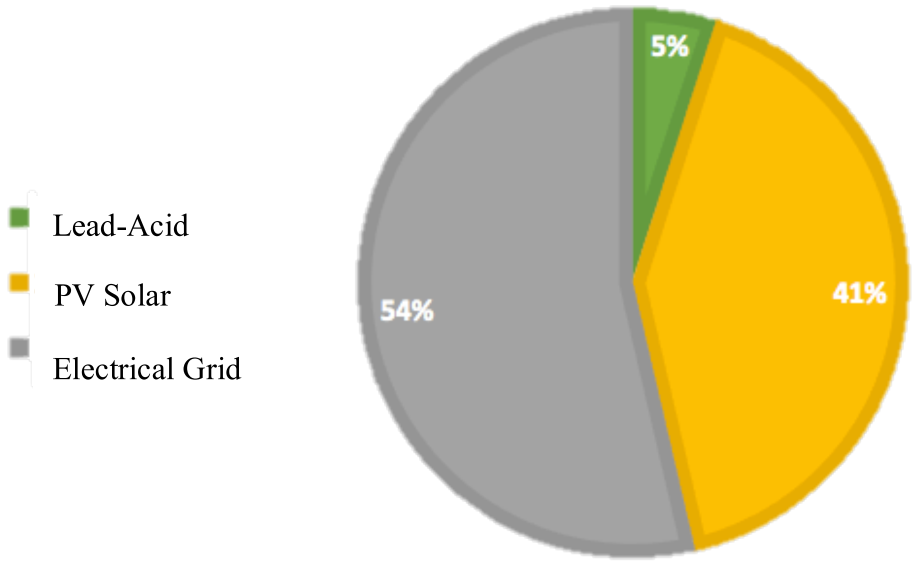

Figure 19. Pie graph displaying the distribution of energy from three sources for the lead-acid battery system.

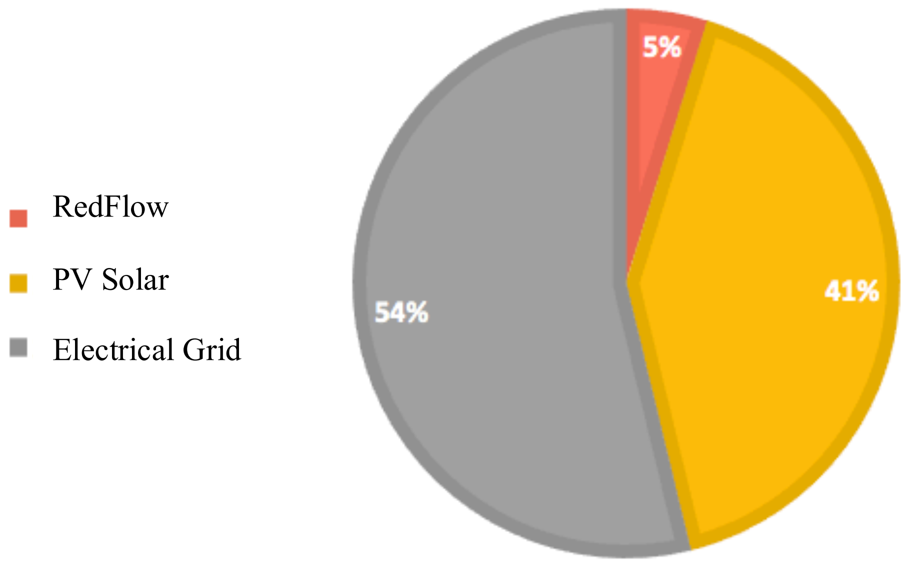

Figure 20. Pie graph displaying the distribution of energy from three sources for the zinc-bromide battery system.

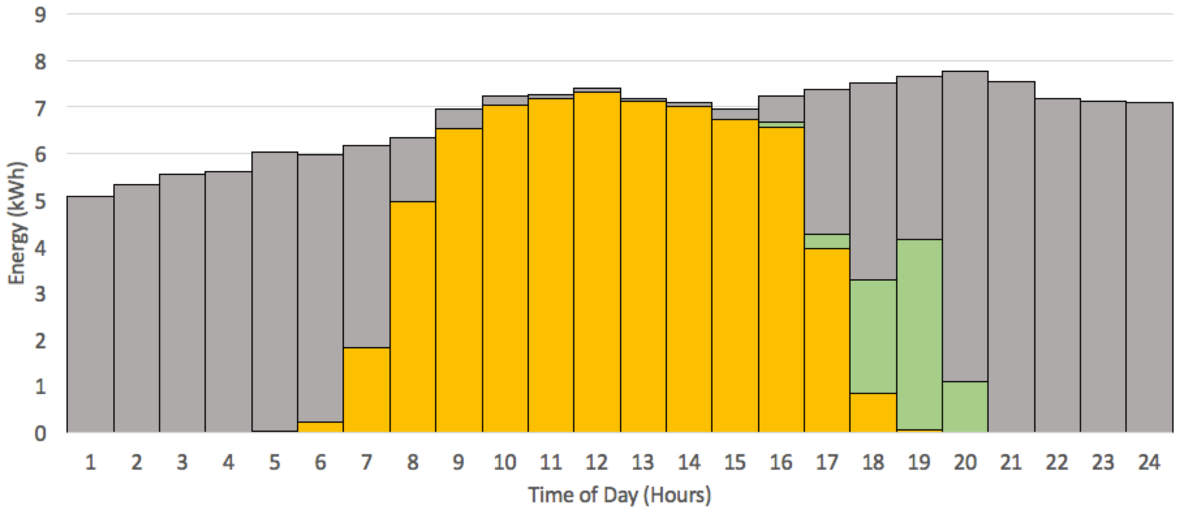

Figure 21. Bar graph displaying when the lead-acid battery and PV solar system are being used.

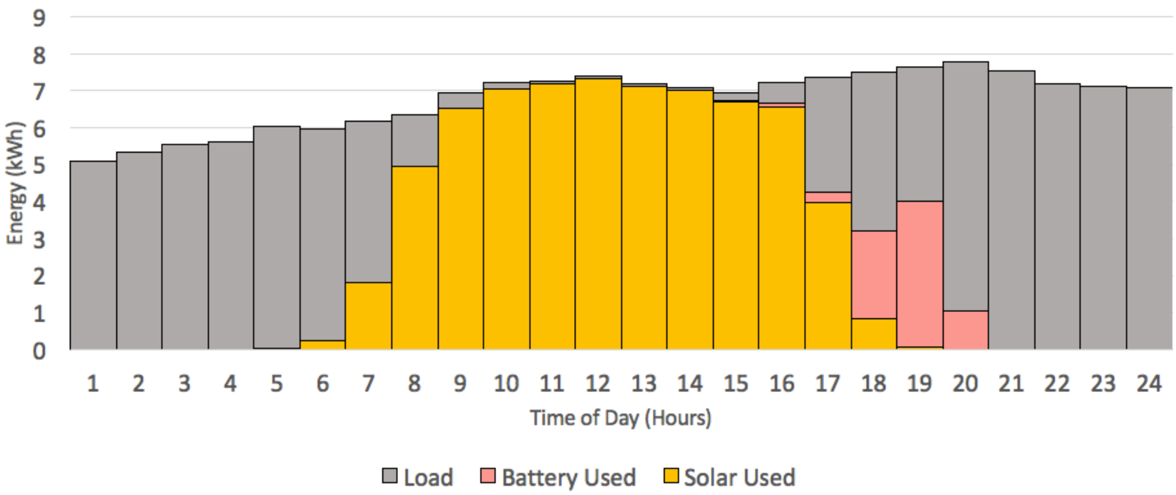

Figure 22. Bar graph displaying when the zinc-bromide battery and PV solar system are being used.

Table 11. Daily discharge for three battery storage systems in hourly increments.

Hour	Tesla Powerwall Discharge (kWh)	Lead-Acid Discharge (kWh)	RedFlow Discharge (kWh)
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	$2.12x10^{-4}$	$8.16x10^{-4}$	$1.44x10^{-3}$
7	$1.05x10^{-4}$	$1.45x10^{-4}$	$5.54x10^{-4}$
8	0	0	0
9	0	0	0
10	$8.26x10^{-4}$	$3.00x10^{-4}$	0
11	$4.74x10^{-3}$	$4.42x10^{-3}$	$4.20x10^{-4}$
12	$2.36x10^{-3}$	$1.83x10^{-3}$	$1.49x10^{-3}$
13	$1.39x10^{-2}$	$1.30x10^{-2}$	$1.25x10^{-2}$
14	0.10	$9.90x10^{-2}$	$9.54x10^{-2}$
15	0.32	0.31	0.30
16	2.57	2.46	2.39
17	4.25	4.08	3.96
18	1.13	1.09	1.05
19	0	0	0
20	0	0	0
21	0	0	0
22	0	0	0
23	0	0	0

4.5 Recommendations

The recommendations are incorporated to not only compare the feasibility of the three battery storage systems, but, to supply an optimal solution. The recommendation will be completed based on ranking the three battery systems for each section of analysis. The optimal battery will then be identified by comparing the ranking of each battery storage system.

Economically, all batteries were feasible as displayed in the 40-year analysis. However, for the purpose of comparing the batteries and providing a result that accurately ranks the batteries all aspects are to be considered. Firstly, the savings, the Tesla Powerwall provided the greatest savings, followed by the GPL-4DL and lastly, the RedFlow. Secondly, the ROI followed the same pattern as the savings with the Tesla Powerwall being the leader. However, in the long term, analyzing the 40-year assessment illustrates the RedFlow battery to come out on top, despite being the least likely from the previous two economic comparisons. Assessing all three methods of comparison for the economic analysis, it can be seen that the RedFlow battery is the most economically feasible battery, providing the largest monetary value over 40-years. On the other hand, as a short term investment the Tesla Powerwall would be the battery storage system of choice. This argument is supported by figure 13, it can be seen that the Tesla Powerwall has a greater economic value for the first 17 years. However, from this point onwards the RedFlow becomes the superior long term battery storage system.

Following on, the batteries were compared environmentally. All three of the battery storage systems can be deemed environmentally feasible. This decision is based on a severe reduction of the exemplar building's kilograms of carbon dioxide equivalent by approximately 43% across all battery systems. At first glance, the emissions of the batteries alone illustrated the RedFlow battery as the best choice. However, after a more detailed evaluation, it is apparent that the Tesla Powerwall provides the largest reduction in environmental impact. Consequently, basing the analysis entirely on environmental aspects, the Tesla Powerwall would be the recommendation, followed by the GPL-4DL, and lastly, the RedFlow.

The final criterion to compare and base recommendations on is, socially. The social analysis identified social issues that would become apparent when selecting the battery storage system. These included; availability of the battery, weight, size, replacement and finding an installer. Each aspect was individually assessed, ordering the batteries by most feasible, feasible, or least feasible. All three battery storage systems can be identified as socially viable to implement in residential buildings to aid in energy efficiency. Examination of these results recognizes that the Tesla Powerwall is the superior battery storage system in regards to the social analysis. This is followed by the RedFlow battery storage system, and lastly, the GPL-4DL lead-acid battery storage system.

A combination of these results can conclude with the optimal solution. Assessing the results across the economic, environmental and social analysis provides the final ranking of the battery storage systems. Environmentally and socially the best battery is the Tesla Powerwall, and economically it is the best battery when utilized as a short term battery system. Therefore, granting the Tesla Powerwall as the optimum solution to aid in energy efficiency within residential buildings. Followed closely by the RedFlow battery system that as a long term battery storage system provides greater economic feasibility. However, environmentally, the battery system merely isn't up to its competitors. On the other hand, the RedFlow battery fell between its two competitors in the social analysis. Finally, the lead-acid GPL-4DL, although, economically, environmentally and socially feasible, it doesn't provide the benefits or competition as the other two battery storage systems. Therefore, based on the economic, environmental and social analysis the recommended battery storage systems would be; Tesla Powerwall (lithium-ion), RedFlow (zinc-bromide), GPL-4DL (lead-acid).

5 CONCLUSIONS

An industry based project was conducted at Wattblock, as apart of Griffith University's IAP program. The project was to compare three battery storage systems to be implemented into residential buildings to aid in energy efficiency. The three chosen battery systems were lithium-ion, lead-acid and zinc-bromide. Specifically, a Tesla Powerwall, RedFlow, and a Lifeline GPL-4DL, respectively. These three batteries are commonly seen in the market for PV solar storage systems and therefore, are suitable candidates for conducting a comparative analysis of their economic, social and environmental feasibility within residential buildings.

Initially, the battery storage systems were discussed and analyzed within the literature review to grasp an understanding of their principle of operation, specifications and other key factors. It was then processed through the model to produce values for the economic and environmental analysis. These values are consequently used for the comparison of the three battery storage systems. It was identified that in terms of the economic analysis, the Tesla Powerwall provided the best results for savings and return on investment. However, over the 40-year assessment the RedFlow battery is the greatest candidate for a long term system. In contrast to this, the Tesla Powerwall did illustrate to be the more economically viable battery system up to approximately 17years. The environmental analysis illustrated that the Tesla Powerwall is environmentally the superior battery storage system. This is evident throughout the environmental analysis section where graphical results depict the previous statement. Finally, the social comparison exemplified the Tesla Powerwall, yet again, as the better battery storage system, leaving the other two competitors behind.

In conclusion, it is evident that the three battery storage systems are all economically, environmentally and socially viable to implement into residential buildings to aid in energy efficiency. However, although all three battery storage systems are feasible for residential buildings, the Tesla Powerwall is the greater battery storage system by a unanimous decision.

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APPENDIX A: BASIC DATA SHEET

	Monthly Energy Consumption (kWh)					
	January	February	March	April	May	June
Monthly Load	4947	4947	4947	4947	4947	4947
Number of Days	31	28	31	30	31	30
Daily Load	159.5806452	176.6785714	159.5806452	164.9	159.5806452	164.9

Solar Panel Fitting Factor	Roof Size (m^2)	Solar Panel Size (m^2)	Number of Solar Panels	Area exposed to solar (m^2)	System Size (kWh)
0.9	200	1.616	111	179.376	27.75

Battery Type	Battery Data				
	Efficiency	Voltage (V)	Capacity (kWh)	Capacity (Ah)	Depth of Discharge (DoD)
Tesla Powerwall	0.96	48V	10	210	1
RedFlow	0.89	48V	10	210	1
Lead-Acid*	0.92	48V	20	420	0.5

*Formation: 8 Batteries - 2 series in Parallel, 4 per series

12v & 210Ah

Appendix 1. Example of the basic data sheet, part 1.

July	August	September	October	November	December
4947	4947	4947	4947	4947	4947
31	31	30	31	30	31
159.5806452	159.5806452	164.9	159.5806452	164.9	159.580645

Tarrif (c/kWh)	Solar Panel Efficiency	Inverter Efficiency	System Losses	Shading Factor
25.25	0.155	0.95	0.91	1

Appendix 2. Example of the basic data sheet, part 2.

APPENDIX B: LOAD PROFILE SHEET

Month	Day	Hour	Load (kWh)	Time of Use percentage	Load Profile (kWh)	Percentage of Daily Load (%)
1.00	1.00	0.00	159.58	0.040162396	5.00	0.031330105
1.00	1.00	1.00	159.58	0.040948182	5.23	0.032754201
1.00	1.00	2.00	159.58	0.031082202	5.45	0.034178297
1.00	1.00	3.00	159.58	0.0255817	5.50	0.034463116
1.00	1.00	4.00	159.58	0.029554285	5.91	0.037026488
1.00	1.00	5.00	159.58	0.022831449	5.86	0.036741669
1.00	1.00	6.00	159.58	0.03352687	6.05	0.037880946
1.00	1.00	7.00	159.58	0.034574584	6.23	0.039020222
1.00	1.00	8.00	159.58	0.025014188	6.82	0.042722871
1.00	1.00	9.00	159.58	0.024795914	7.09	0.044431786
1.00	1.00	10.00	159.58	0.038459859	7.14	0.044716605
1.00	1.00	11.00	159.58	0.029772559	7.27	0.045571062
1.00	1.00	12.00	159.58	0.033003012	7.05	0.044146967
1.00	1.00	13.00	159.58	0.032260881	6.95	0.043577328
1.00	1.00	14.00	159.58	0.0392893	6.82	0.042722871
1.00	1.00	15.00	159.58	0.03435631	7.09	0.044431786
1.00	1.00	16.00	159.58	0.042781682	7.23	0.045286243
1.00	1.00	17.00	159.58	0.054961366	7.36	0.046140701
1.00	1.00	18.00	159.58	0.071375562	7.50	0.046995158
1.00	1.00	19.00	159.58	0.06495831	7.64	0.047849615
1.00	1.00	20.00	159.58	0.068494347	7.41	0.04642552
1.00	1.00	21.00	159.58	0.062077094	7.05	0.044146967
1.00	1.00	22.00	159.58	0.059457808	7.00	0.043862148
1.00	1.00	23.00	159.58	0.060680141	6.95	0.043577328
1.00	2.00	0.00	159.58	0.040162396	5.00	0.031330105
1.00	2.00	1.00	159.58	0.040948182	5.23	0.032754201

Appendix 3. An example of the daily load profile, part 1.

Example of Daily Load Profile			
Hour	Load (kWh)	% of Daily Load	
0	1.1	0.03133011	0.03133011
1	1.15	0.0327542	0.0327542
2	1.2	0.0341783	0.0341783
3	1.21	0.03446312	0.03446312
4	1.3	0.03702649	0.03702649
5	1.29	0.03674167	0.03674167
6	1.33	0.03788095	0.03788095
7	1.37	0.03902022	0.03902022
8	1.5	0.04272287	0.04272287
9	1.56	0.04443179	0.04443179
10	1.57	0.0447166	0.0447166
11	1.6	0.04557106	0.04557106
12	1.55	0.04414697	0.04414697
13	1.53	0.04357733	0.04357733
14	1.5	0.04272287	0.04272287
15	1.56	0.04443179	0.04443179
16	1.59	0.04528624	0.04528624
17	1.62	0.0461407	0.0461407
18	1.65	0.04699516	0.04699516
19	1.68	0.04784962	0.04784962
20	1.63	0.04642552	0.04642552
21	1.55	0.04414697	0.04414697
22	1.54	0.04386215	0.04386215
23	1.53	0.04357733	0.04357733
	35.11	1	

Appendix 4. An example of the daily load profile, part 2.

APPENDIX C: PV SOLAR SHEET

Month	Day	Hour	Beam Irradiance (W/m^2)	Diffuse Irradiance (W/m^2)	Ambient Temperature (C)	Wind Speed (m/s)
1.00	1.00	0.00	0.00	0.00	21.20	2.50
1.00	1.00	1.00	0.00	0.00	21.10	2.30
1.00	1.00	2.00	0.00	0.00	21.00	2.10
1.00	1.00	3.00	0.00	0.00	21.00	2.70
1.00	1.00	4.00	0.00	0.00	20.90	2.50
1.00	1.00	5.00	0.00	11.00	20.80	2.50
1.00	1.00	6.00	0.00	69.00	22.10	3.40
1.00	1.00	7.00	0.00	142.00	23.60	4.20
1.00	1.00	8.00	3.00	209.00	23.60	4.30
1.00	1.00	9.00	92.00	396.00	24.00	4.60
1.00	1.00	10.00	91.00	456.00	24.00	3.60
1.00	1.00	11.00	16.00	309.00	23.80	4.10
1.00	1.00	12.00	113.00	458.00	23.00	4.60
1.00	1.00	13.00	14.00	284.00	21.00	5.70
1.00	1.00	14.00	6.00	247.00	21.70	2.10
1.00	1.00	15.00	2.00	189.00	22.00	2.10
1.00	1.00	16.00	0.00	119.00	21.00	3.60
1.00	1.00	17.00	0.00	48.00	21.10	3.10
1.00	1.00	18.00	0.00	5.00	21.00	3.10
1.00	1.00	19.00	0.00	0.00	21.00	3.10
1.00	1.00	20.00	0.00	0.00	20.70	3.60
1.00	1.00	21.00	0.00	0.00	21.00	2.60
1.00	1.00	22.00	0.00	0.00	21.00	3.10
1.00	1.00	23.00	0.00	0.00	20.50	3.10
1.00	2.00	0.00	0.00	0.00	20.00	2.60
1.00	2.00	1.00	0.00	0.00	21.00	2.60

Appendix 5. An example of PV solar calculations, part 1.

Month	Day	Hour	Plane of Array Irradiance (W/m^2)	Solar Collected (kWh)	Load (kWh)	Solar including losses (kWh)
1.00	1.00	0.00	0.00	0.00	5.00	0.00
1.00	1.00	1.00	0.00	0.00	5.23	0.00
1.00	1.00	2.00	0.00	0.00	5.45	0.00
1.00	1.00	3.00	0.00	0.00	5.50	0.00
1.00	1.00	4.00	0.00	0.00	5.91	0.00
1.00	1.00	5.00	10.26	1.84	5.86	0.26
1.00	1.00	6.00	64.51	11.57	6.05	1.63
1.00	1.00	7.00	132.48	23.76	6.23	3.35
1.00	1.00	8.00	197.71	35.46	6.82	5.00
1.00	1.00	9.00	448.72	80.49	7.09	11.35
1.00	1.00	10.00	518.70	93.04	7.14	13.12
1.00	1.00	11.00	307.99	55.25	7.27	7.79
1.00	1.00	12.00	551.60	98.94	7.05	13.96
1.00	1.00	13.00	280.25	50.27	6.95	7.09
1.00	1.00	14.00	236.65	42.45	6.82	5.99
1.00	1.00	15.00	177.98	31.93	7.09	4.50
1.00	1.00	16.00	110.95	19.90	7.23	2.81
1.00	1.00	17.00	44.93	8.06	7.36	1.14
1.00	1.00	18.00	4.66	0.84	7.50	0.12
1.00	1.00	19.00	0.00	0.00	7.64	0.00
1.00	1.00	20.00	0.00	0.00	7.41	0.00
1.00	1.00	21.00	0.00	0.00	7.05	0.00
1.00	1.00	22.00	0.00	0.00	7.00	0.00
1.00	1.00	23.00	0.00	0.00	6.95	0.00
1.00	2.00	0.00	0.00	0.00	5.00	0.00
1.00	2.00	1.00	0.00	0.00	5.23	0.00

Appendix 6. An example of PV solar calculations, part 2.

Month	Day	Hour	Solar used (kWh)	Solar Used + Battery - Redflow (kWh)	Solar Used + Battery - Tesla Powerwall (kWh)	Solar Used + Battery - Lead-Acid (kWh)
1.00	1.00	0.00	0.00	0.00	0.00	0.00
1.00	1.00	1.00	0.00	0.00	0.00	0.00
1.00	1.00	2.00	0.00	0.00	0.00	0.00
1.00	1.00	3.00	0.00	0.00	0.00	0.00
1.00	1.00	4.00	0.00	0.00	0.00	0.00
1.00	1.00	5.00	0.26	0.26	0.26	0.26
1.00	1.00	6.00	1.63	1.63	1.63	1.63
1.00	1.00	7.00	3.35	3.35	3.35	3.35
1.00	1.00	8.00	5.00	5.00	5.00	5.00
1.00	1.00	9.00	7.09	7.09	7.09	7.09
1.00	1.00	10.00	7.14	7.14	7.14	7.14
1.00	1.00	11.00	7.27	7.27	7.27	7.27
1.00	1.00	12.00	7.05	7.05	7.05	7.05
1.00	1.00	13.00	6.95	6.95	6.95	6.95
1.00	1.00	14.00	5.99	5.99	5.99	5.99
1.00	1.00	15.00	4.50	5.21	5.26	5.23
1.00	1.00	16.00	2.81	5.01	5.17	5.07
1.00	1.00	17.00	1.14	4.89	5.17	5.01
1.00	1.00	18.00	0.12	1.96	2.09	2.01
1.00	1.00	19.00	0.00	0.00	0.00	0.00
1.00	1.00	20.00	0.00	0.00	0.00	0.00
1.00	1.00	21.00	0.00	0.00	0.00	0.00
1.00	1.00	22.00	0.00	0.00	0.00	0.00
1.00	1.00	23.00	0.00	0.00	0.00	0.00
1.00	2.00	0.00	0.00	0.00	0.00	0.00
1.00	2.00	1.00	0.00	0.00	0.00	0.00

Appendix 7. An example of PV solar calculations, part 3.

Month	Day	Hour	Left over Solar (kWh)	Grid power required after solar (kWh)	Grid Power Required after Solar + Battery (kWh) - Redflow
1.00	1.00	0.00	0.00	5.00	5.00
1.00	1.00	1.00	0.00	5.23	5.23
1.00	1.00	2.00	0.00	5.45	5.45
1.00	1.00	3.00	0.00	5.50	5.50
1.00	1.00	4.00	0.00	5.91	5.91
1.00	1.00	5.00	0.00	5.60	5.60
1.00	1.00	6.00	0.00	4.41	4.41
1.00	1.00	7.00	0.00	2.88	2.88
1.00	1.00	8.00	0.00	1.82	1.82
1.00	1.00	9.00	4.05	0.00	0.00
1.00	1.00	10.00	5.69	0.00	0.00
1.00	1.00	11.00	0.49	0.00	0.00
1.00	1.00	12.00	6.57	0.00	0.00
1.00	1.00	13.00	0.13	0.00	0.00
1.00	1.00	14.00	0.00	0.83	0.83
1.00	1.00	15.00	0.00	2.59	1.88
1.00	1.00	16.00	0.00	4.42	2.22
1.00	1.00	17.00	0.00	6.23	2.47
1.00	1.00	18.00	0.00	7.38	5.54
1.00	1.00	19.00	0.00	7.64	7.64
1.00	1.00	20.00	0.00	7.41	7.41
1.00	1.00	21.00	0.00	7.05	7.05
1.00	1.00	22.00	0.00	7.00	7.00
1.00	1.00	23.00	0.00	6.95	6.95
1.00	2.00	0.00	0.00	5.00	5.00
1.00	2.00	1.00	0.00	5.23	5.23

Appendix 8. An example of PV solar calculations, part 4.

Month	Day	Hour	Grid Power Required after Solar + Battery (kWh) - Tesla Powerwall	Grid Power Required after Solar + Battery (kWh) - Lead-Acid	Redflow Discharge	Tesla Powerwall Discharge	Lead-acid Discharge
1.00	1.00	0.00	5.00	5.00	0.00	0.00	0.00
1.00	1.00	1.00	5.23	5.23	0.00	0.00	0.00
1.00	1.00	2.00	5.45	5.45	0.00	0.00	0.00
1.00	1.00	3.00	5.50	5.50	0.00	0.00	0.00
1.00	1.00	4.00	5.91	5.91	0.00	0.00	0.00
1.00	1.00	5.00	5.60	5.60	0.00	0.00	0.00
1.00	1.00	6.00	4.41	4.41	0.00	0.00	0.00
1.00	1.00	7.00	2.88	2.88	0.00	0.00	0.00
1.00	1.00	8.00	1.82	1.82	0.00	0.00	0.00
1.00	1.00	9.00	0.00	0.00	0.00	0.00	0.00
1.00	1.00	10.00	0.00	0.00	0.00	0.00	0.00
1.00	1.00	11.00	0.00	0.00	0.00	0.00	0.00
1.00	1.00	12.00	0.00	0.00	0.00	0.00	0.00
1.00	1.00	13.00	0.00	0.00	0.00	0.00	0.00
1.00	1.00	14.00	0.83	0.83	0.71	0.76	0.73
1.00	1.00	15.00	1.83	1.86	2.20	2.36	2.27
1.00	1.00	16.00	2.06	2.15	3.76	4.04	3.87
1.00	1.00	17.00	2.19	2.36	1.84	1.98	1.89
1.00	1.00	18.00	5.41	5.49	0.00	0.00	0.00
1.00	1.00	19.00	7.64	7.64	0.00	0.00	0.00
1.00	1.00	20.00	7.41	7.41	0.00	0.00	0.00
1.00	1.00	21.00	7.05	7.05	0.00	0.00	0.00
1.00	1.00	22.00	7.00	7.00	0.00	0.00	0.00
1.00	1.00	23.00	6.95	6.95	0.00	0.00	0.00
1.00	2.00	0.00	5.00	5.00	0.00	0.00	0.00
1.00	2.00	1.00	5.23	5.23	0.00	0.00	0.00

Appendix 9. An example of PV solar calculations, part 3.

APPENDIX D: BATTERY CALCULATIONS SHEET

Month	Day	Hour	Tesla Powerwall		
			Battery Charge (kWh)	Battery Charge/Discharge (kWh)	Battery Discharge (kWh)
1.00	1.00	0.00	0.00	0.00	0.00
1.00	1.00	1.00	0.00	0.00	0.00
1.00	1.00	2.00	0.00	0.00	0.00
1.00	1.00	3.00	0.00	0.00	0.00
1.00	1.00	4.00	0.00	0.00	0.00
1.00	1.00	5.00	0.00	0.00	0.00
1.00	1.00	6.00	0.00	0.00	0.00
1.00	1.00	7.00	0.00	0.00	0.00
1.00	1.00	8.00	2.08	2.08	0.00
1.00	1.00	9.00	7.28	5.20	0.00
1.00	1.00	10.00	7.37	0.09	0.00
1.00	1.00	11.00	10.00	2.63	0.00
1.00	1.00	12.00	10.00	0.00	0.00
1.00	1.00	13.00	10.00	0.00	0.00
1.00	1.00	14.00	9.17	-0.83	0.76
1.00	1.00	15.00	6.58	-2.59	2.36
1.00	1.00	16.00	2.16	-4.42	4.04
1.00	1.00	17.00	0.00	-2.16	1.98
1.00	1.00	18.00	0.00	0.00	0.00
1.00	1.00	19.00	0.00	0.00	0.00
1.00	1.00	20.00	0.00	0.00	0.00
1.00	1.00	21.00	0.00	0.00	0.00
1.00	1.00	22.00	0.00	0.00	0.00
1.00	1.00	23.00	0.00	0.00	0.00
1.00	2.00	0.00	0.00	0.00	0.00
1.00	2.00	1.00	0.00	0.00	0.00

Appendix 10. Example of charge and discharge cycles of the Tesla Powerwall battery system.

Month	Day	Hour	Lead-Acid		
			Battery Charge (kWh)	Battery Charge/Discharge (kWh)	Battery Discharge (kWh)
1.00	1.00	0.00	0.00	0.00	0.00
1.00	1.00	1.00	0.00	0.00	0.00
1.00	1.00	2.00	0.00	0.00	0.00
1.00	1.00	3.00	0.00	0.00	0.00
1.00	1.00	4.00	0.00	0.00	0.00
1.00	1.00	5.00	0.00	0.00	0.00
1.00	1.00	6.00	0.00	0.00	0.00
1.00	1.00	7.00	0.00	0.00	0.00
1.00	1.00	8.00	1.92	1.92	0.00
1.00	1.00	9.00	7.05	5.13	0.00
1.00	1.00	10.00	7.35	0.30	0.00
1.00	1.00	11.00	10.00	2.65	0.00
1.00	1.00	12.00	10.00	0.00	0.00
1.00	1.00	13.00	10.00	0.00	0.00
1.00	1.00	14.00	9.17	-0.83	0.73
1.00	1.00	15.00	6.58	-2.59	2.27
1.00	1.00	16.00	2.16	-4.42	3.87
1.00	1.00	17.00	0.00	-2.16	1.89
1.00	1.00	18.00	0.00	0.00	0.00
1.00	1.00	19.00	0.00	0.00	0.00
1.00	1.00	20.00	0.00	0.00	0.00
1.00	1.00	21.00	0.00	0.00	0.00
1.00	1.00	22.00	0.00	0.00	0.00
1.00	1.00	23.00	0.00	0.00	0.00
1.00	2.00	0.00	0.00	0.00	0.00
1.00	2.00	1.00	0.00	0.00	0.00

Appendix 11. Example of charge and discharge cycles of for the lead-acid battery system.

Month	Day	Hour	Redflow		
			Battery Charge (kWh)	Battery Charge/Discharge (kWh)	Battery Discharge (kWh)
1.00	1.00	0.00	0.00	0.00	0.00
1.00	1.00	1.00	0.00	0.00	0.00
1.00	1.00	2.00	0.00	0.00	0.00
1.00	1.00	3.00	0.00	0.00	0.00
1.00	1.00	4.00	0.00	0.00	0.00
1.00	1.00	5.00	0.00	0.00	0.00
1.00	1.00	6.00	0.00	0.00	0.00
1.00	1.00	7.00	0.00	0.00	0.00
1.00	1.00	8.00	1.81	1.81	0.00
1.00	1.00	9.00	6.89	5.09	0.00
1.00	1.00	10.00	7.34	0.44	0.00
1.00	1.00	11.00	10.00	2.66	0.00
1.00	1.00	12.00	10.00	0.00	0.00
1.00	1.00	13.00	10.00	0.00	0.00
1.00	1.00	14.00	9.17	-0.83	0.71
1.00	1.00	15.00	6.58	-2.59	2.20
1.00	1.00	16.00	2.16	-4.42	3.76
1.00	1.00	17.00	0.00	-2.16	1.84
1.00	1.00	18.00	0.00	0.00	0.00
1.00	1.00	19.00	0.00	0.00	0.00
1.00	1.00	20.00	0.00	0.00	0.00
1.00	1.00	21.00	0.00	0.00	0.00
1.00	1.00	22.00	0.00	0.00	0.00
1.00	1.00	23.00	0.00	0.00	0.00
1.00	2.00	0.00	0.00	0.00	0.00
1.00	2.00	1.00	0.00	0.00	0.00

Appendix 12. Example of charge and discharge cycles for the RedFlow battery system.

APPENDIX E: PIVOT TABLE SHEET

Row Labels	Average of Load (kWh)	Average of Redflow Discharge	Average of Tesla Powerwall Discharge	Average of Lead-acid Discharge	Average of Solar used (kWh)
0.00	5.082067553	0	0	0	0
1.00	5.327179159	0	0	0	0
2.00	5.558795644	0	0	0	0
3.00	5.605118941	0	0	0	0
4.00	6.022028615	0	0	0	0.001533725
5.00	5.975705318	0	0	0	0.225592522
6.00	6.160998506	0.001439373	0.000211783	0.000816197	1.812119195
7.00	6.346291694	0.000554259	0.000105376	0.000145392	4.956104281
8.00	6.948494555	0	0	0	6.528425593
9.00	7.226434337	0	0	0	7.049114339
10.00	7.272757635	0	0.000826057	0.00030026	7.181113263
11.00	7.411727526	0.004204314	0.004741068	0.004419996	7.313946013
12.00	7.18011104	0.001490141	0.00235616	0.001831385	7.12617954
13.00	7.087464446	0.012451849	0.013893436	0.013032593	7.011698951
14.00	6.948494555	0.095363631	0.104306938	0.09898953	6.717292878
15.00	7.226434337	0.298763185	0.321477895	0.308044496	6.57057866
16.00	7.365404229	2.388502495	2.568334421	2.462012019	3.961868299
17.00	7.50437412	3.956477418	4.254363208	4.078243575	0.821812586
18.00	7.643344011	1.05499512	1.134426397	1.087464078	0.055802674
19.00	7.782313902	0	0	0	0
20.00	7.550697417	0	0	0	0
21.00	7.18011104	0	0	0	0
22.00	7.133787743	0	0	0	0
23.00	7.087464446	0	0	0	0
Grand Total	6.776150032	0.325593408	0.350210114	0.33563748	2.805549272

Appendix 13. Example of the pivot table, part 1.

Row Labels	Average of Load (kWh)	Average of Solar Used + Battery - Redflow (kWh)	Average of Solar Used + Battery - Tesla Powerwall (kWh)	Average of Solar Used + Battery - Lead-Acid (kWh)
0.00	5.082067553	0	0	0
1.00	5.327179159	0	0	0
2.00	5.558795644	0	0	0
3.00	5.605118941	0	0	0
4.00	6.022028615	0.001533725	0.001533725	0.001533725
5.00	5.975705318	0.225592522	0.225592522	0.225592522
6.00	6.160998506	1.812119195	1.812119195	1.812119195
7.00	6.346291694	4.956104281	4.956104281	4.956104281
8.00	6.948494555	6.528425593	6.528530969	6.528425593
9.00	7.226434337	7.049114339	7.049114339	7.049114339
10.00	7.272757635	7.181113263	7.181113263	7.181113263
11.00	7.411727526	7.313946013	7.31440934	7.314156449
12.00	7.18011104	7.127673596	7.127893804	7.127759883
13.00	7.087464446	7.012712558	7.013542698	7.013039136
14.00	6.948494555	6.729744727	6.731186314	6.730325471
15.00	7.226434337	6.665942292	6.674885598	6.66956819
16.00	7.365404229	4.260631485	4.283346194	4.269912796
17.00	7.50437412	3.210315081	3.390147007	3.283824605
18.00	7.643344011	4.012280092	4.310165881	4.134046249
19.00	7.782313902	1.05499512	1.134426397	1.087464078
20.00	7.550697417	0	0	0
21.00	7.18011104	0	0	0
22.00	7.133787743	0	0	0
23.00	7.087464446	0	0	0
Grand Total	6.776150032	3.130926828	3.15558798	3.141004157

Appendix 14. Example of the pivot table, part 2.

Row Labels	Average of Load (kWh)	Average of Grid Power Required after Solar + Battery (kWh) - Redflow	Average of Grid Power Required after Solar + Battery (kWh) - Tesla Powerwal	Average of Grid Power Required after Solar + Battery (kWh) - Lead-Acid
0.00	5.082067553	5.082067553	5.082067553	5.082067553
1.00	5.327179159	5.327179159	5.327179159	5.327179159
2.00	5.558795644	5.558795644	5.558795644	5.558795644
3.00	5.605118941	5.605118941	5.605118941	5.605118941
4.00	6.022028615	6.02049489	6.02049489	6.02049489
5.00	5.975705318	5.750112795	5.750112795	5.750112795
6.00	6.160998506	4.348879311	4.348879311	4.348879311
7.00	6.346291694	1.390187413	1.390187413	1.390187413
8.00	6.948494555	0.420068962	0.419963586	0.420068962
9.00	7.226434337	0.177319998	0.177319998	0.177319998
10.00	7.272757635	0.091644371	0.091644371	0.091644371
11.00	7.411727526	0.097781513	0.097318186	0.097571076
12.00	7.18011104	0.052437445	0.052217236	0.052351157
13.00	7.087464446	0.074751889	0.073921749	0.07442531
14.00	6.948494555	0.218749828	0.217308242	0.218169084
15.00	7.226434337	0.560492046	0.551548739	0.556866148
16.00	7.365404229	3.104772744	3.082058035	3.095491433
17.00	7.50437412	4.294059038	4.114227113	4.220549515
18.00	7.643344011	3.631063919	3.33317813	3.509297762
19.00	7.782313902	6.727318782	6.647887505	6.694849823
20.00	7.550697417	7.550697417	7.550697417	7.550697417
21.00	7.18011104	7.18011104	7.18011104	7.18011104
22.00	7.133787743	7.133787743	7.133787743	7.133787743
23.00	7.087464446	7.087464446	7.087464446	7.087464446
Grand Total	6.776150032	3.645223204	3.620562052	3.635145875

Appendix 15. Example of the pivot table, part 3.

APPENDIX F: PRICING AND COSTS SHEET

			Total yearly spend	Total yearly spend	Total yearly spend	Total yearly spend
			8782.571822	8062.869204	8008.321202	8040.57916
Month	Day	Hour	Grid Energy required after solar ($)	Grid Energy required after solar + battery ($) - Redflow	Grid Energy required after solar + battery ($) - Tesla Powerwall	Grid Energy required after solar + battery ($) - Lead-Acid Battery
1.00	1.00	0.00	1.262418804	1.262418804	1.262418804	1.262418804
1.00	1.00	1.00	1.319801476	1.319801476	1.319801476	1.319801476
1.00	1.00	2.00	1.377184149	1.377184149	1.377184149	1.377184149
1.00	1.00	3.00	1.388660684	1.388660684	1.388660684	1.388660684
1.00	1.00	4.00	1.491949495	1.491949495	1.491949495	1.491949495
1.00	1.00	5.00	1.414914187	1.414914187	1.414914187	1.414914187
1.00	1.00	6.00	1.114282604	1.114282604	1.114282604	1.114282604
1.00	1.00	7.00	0.725962488	0.725962488	0.725962488	0.725962488
1.00	1.00	8.00	0.458397339	0.458397339	0.458397339	0.458397339
1.00	1.00	9.00	0	0	0	0
1.00	1.00	10.00	0	0	0	0
1.00	1.00	11.00	0	0	0	0
1.00	1.00	12.00	0	0	0	0
1.00	1.00	13.00	0	0	0	0
1.00	1.00	14.00	0.209622813	0.209622813	0.209622813	0.209622813
1.00	1.00	15.00	0.653314402	0.475196676	0.461786075	0.469714852
1.00	1.00	16.00	1.115977848	0.560852791	0.51905706	0.543768037
1.00	1.00	17.00	1.572176134	0.623923248	0.552528664	0.594739432
1.00	1.00	18.00	1.86386419	1.399852635	1.3649169	1.385572027
1.00	1.00	19.00	1.928057809	1.928057809	1.928057809	1.928057809
1.00	1.00	20.00	1.870675136	1.870675136	1.870675136	1.870675136
1.00	1.00	21.00	1.77886286	1.77886286	1.77886286	1.77886286
1.00	1.00	22.00	1.767386325	1.767386325	1.767386325	1.767386325
1.00	1.00	23.00	1.75590979	1.75590979	1.75590979	1.75590979
1.00	2.00	0.00	1.262418804	1.262418804	1.262418804	1.262418804

Appendix 16. Example of economic analysis in the pricing and costs sheet of the model.

		Solar + Battery		
Original Energy Price	Solar	RedFlow	Tesla Powerwall	Lead-Acid
$ 14,989.41	$ 8,782.57	$ 8,062.87	$ 8,008.32	$ 8,040.58
Reduction in costs	41%	46.2%	46.6%	46.4%

Appendix 17. Summary of results for the total spend and reduction in costs.

Battery Type	Intial costs	Installation	Solar panel costs ($)	Inverter Costs ($)
RedFlow	$ 11,000.00	$ 4,000.00	$ 22,200.00	$ 3,000.00
Tesla Powerwall	$ 4,800.00	$ 2,000.00	$ 22,200.00	$ 3,000.00
Lead-acid	$ 10,200.00	$ 1,500.00	$ 22,200.00	$ 3,000.00

Appendix 18. Summary of the initial costs within the economic model.

On-going costs ($)		Replacement		Yearly savings ($)	Payback period (years)
Maintenance	Cleaning	Cost ($)	Duration (years)		
$ -	$ 500.00	$ 5,500.00	7	$ 6,926.54	5.88
$ 1,000.00	$ 500.00	$ 4,800.00	10	$ 6,981.09	4.80
$ 1,000.00	$ 500.00	$ 10,200.00	10	$ 6,948.83	5.53

Appendix 19. Summary of the on-going costs, savings and payback in the economic model.

0	5	6	7	8
-40200.00	-8067.30	-1640.76	4785.79	5712.33
-32000.00	-4594.56	886.53	6367.62	11848.71
-36900.00	-9655.85	-4207.01	1241.82	6690.65

Appendix 20. Summary of the 40-year analysis, part 1.

Long term assessment							
9	10	15	20	25	30	35	40
12138.87	18565.41	$ 45,198.11	$ 77,330.82	$ 103,963.52	$ 130,596.22	$ 162,728.93	$ 189,361.63
17329.80	18010.89	$ 45,416.33	$ 68,021.78	$ 95,427.22	$ 118,032.66	$ 145,438.11	$ 168,043.55
12139.48	7388.31	$ 34,632.46	$ 51,676.62	$ 78,920.77	$ 95,964.93	$ 123,209.08	$ 140,253.23

Appendix 21. Summary of the 40-year analysis, part 2.

APPENDIX G: ENVIRONMENTAL ANALYSIS SHEET

Grid Energy CO2 Emissions	
kg Co2-e	tonnes of Co2-e
46897.56	46.90

	Emission Coeffecients (kgCO2e-/kWh)
Grid Energy	0.79
Solar Panels	0.057
Battery	0.059

Solar Panel CO2 Emissions	
	Solar Panel CO2 Value (kgCO2e-)
Solar Panels	1400.87
Grid Left Over	27478.15
Total	28879.01

Solar + Battery CO2 Emissions (kgCO2e-)			
	Battery Types		
	RedFlow	Tesla Powerwall	Lead-Acid
Grid Required after solar + Battery	25226.40	25055.74	25156.66
Solar Panels	1400.87	1400.87	1400.87
Battery Emisions	168.28	181.00	173.47
Total	26795.55	26637.61	26731.00

Total CO2 Emissions				
Grid Energy (kgCO2e-)	Solar (kgCO2e-)	Redflow (kgCO2e-)	Tesla Powerwall (kgCO2e-)	Lead-Acid (kgCO2e-)
46897.56	28879.01	26795.55	26637.61	26731.00
	Reductions in Emissions	42.9%	43.2%	43.0%

Appendix 22. Example of the Environmental Analysis.