University of Southern Queensland
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INVESTIGATION INTO THE ECONOMIC FEASIBILITY OF GRID-TIED PHOTOVOLTAIC PANEL AND STORAGE SYSTEMS

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ABSTRACT

Renewable Energy is a subject of great interest but the widespread implementation of renewable energy does have its limitations. One of the most notable, and the driving notion behind this work, is the abundance of solar energy available during daylight hours but the inability to maintain generation during hours with sunlight.

The aim of this work is to identify a means of energy storage to be used in conjunction with a domestic grid-tied photovoltaic panel and to discover the point at which the use of storage might provide economic benefit. It also aims to investigate the potential for automatic switching of a domestic load, such that reliance on grid-supplied energy is reduced thus also reducing the reliance on 'dirty' energy sources.

To complete this investigation, various storage technologies have been reviewed allowing for modelling using measured load and solar data gathered from a domestic residence. The results suggest that installation of energy storage is currently not feasible in a domestic application but future installation is possible if capital costs continue to decrease by a minimum of 16.67% and tariff schemes such as the Victorian Time-of-Use tariff becomes widespread. Viability could be increased by implementing automatic switching of domestic loads to reduce grid usage during peak hours.

There is great potential for expansion on the results presented due to expected emergence of new, less hazardous technologies and continual improvement of existing technologies. While it has been concluded that storage is not currently economically feasible, future feasibility does appear likely.

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NOMENCALTURE AND ACRONYMS (OR ABBREVIATIONS)

DoD – Depth of discharge is a means of describing how deeply a battery has been discharged. If a battery is fully charged, it is said to have a DoD of 0%. Similarly if a battery is charged to only 70%, its DoD is 30%.

FLA – Valve-regulated lead-acid battery with liquid electrolyte.

HOMER – Refers to the software application utilized in the modelling phase of this research. HOMER is a tool that provides optimization of microgrids allowing input of various different technologies and variables surrounding these technologies.

LCOE – Levelized cost of energy (COE) is the average cost per kWh of useful electrical energy produced by a system. To calculate the COE, divide the annualized cost of producing electricity (the total annualized cost minus the cost of serving the thermal load) by the total useful electric energy production.

NPC – The total net present cost of a system is the present value of all the costs that it incurs over its lifetime, minus the present value of all the revenue that it earns over its lifetime. Costs include capital costs, replacement costs, O&M costs, fuel costs, emissions penalties, and the costs of buying power from the grid. Revenues include salvage value and grid sales revenue.

PV – Photovoltaic – refers to a method of converting solar radiation into electrical energy using semiconducting materials that exhibit the photovoltaic effect.

ToU – Time of Use – refers to a tariff strategy employed by Victorian electricity retailers where customers pay more for electricity usage in peak hours than in shoulder and off-peak hours. Peak hours in this case are between 3pm and 9pm weekdays, shoulder hours are between 7am and 3pm and 9 and 10pm weekdays and 7am to 10pm on weekends. Off-peak hours are all other hours.

VRLA – Valve-regulated Lead-acid battery with immobilized electrolyte in gel or glass mat.

1 CHAPTER 1

INTRODUCTION

1.1 OUTLINE OF THE STUDY

With a growing general awareness and increasing acceptance throughout the world of environmental concerns such as greenhouse emissions and global warming, sustainable and renewable energy sources have become a topic of great discussion and increased research. In line with the increased research and development of renewable energy sources comes a question of energy storage, specifically, how the energy generated by these 'clean' energy sources might best be stored for use during hours when generation has diminished. This describes the motivation for the work presented in this report.

The purpose and scope of this study is identified in 1.4 Research Objectives. The need for this study was identified from research into photovoltaic and energy storage technologies and limitations as well as changing domestic and Feed-in-tariffs. The study intends to explore the various technologies and their limitations with the ultimate aim being to provide a carefully considered recommendation for an appropriate storage technology to be used in a domestic storage application.

1.2 INTRODUCTION

Photovoltaic panels have been described as one of the cleanest energy sources available currently (Kumar Sahu, 2015). A photovoltaic panel takes the sun's energy and converts it to direct current (DC) voltage. The DC voltage is then applied to a converter (in this case an inverter) resulting in an alternating current (AC) voltage that can then be utilized on-site or delivered to the grid.

Photovoltaic cell technologies are under continuous development with regards to improving efficiency and cost of supply /install as described by Chen et al. (2009); Cho, Jeong and Kim (2015); Fthenakis and Kim (2011); Tsalikis and Martinopoulos (2015); Zakeri and Syri (2015). These two factors have now been approved under stringent power quality guidelines by Energex and Ergon to allow commission large-scale Photovoltaic Power Plants up to 100 kW, and even in special cases up to 1 MW, though many of these systems will be zero reverse power systems.

In terms of storage systems, currently there are a variety of storage systems available (Chen et al, 2009). Some of these technologies include:

- Compressed air energy storage;
- Pumped hydroelectric storage;
- Flywheel storage;
- Thermal energy storage and;
- Electrochemical or battery storage.

The focus of this study will be on battery storage and its ability to be used in a domestic installation with intended financial gain to the customer.

Instead of forcing the Australian domestic public to pay for photovoltaic power plants through taxes and tariff price increases (AEMC (2014)), the public could be encouraged/motivated to pursue domestic renewable energy solutions themselves through competitive pricing that should ideally result in obvious financial gain/benefit to the public, but not at the expense of the distributor or retailer.

By combining research into the many battery technologies and research into current and future domestic and feed-in-tariffs it is hoped that a solution to the question of domestic energy storage might be identified. This solution is hoped to have considered the many environmental, health and socio-economic concerns surrounding each technology.

1.3 THE PROBLEM

Despite the assumed environmental benefits that storage of renewable energy appears to have, the research objectives identified have found several limitations of current photovoltaic and energy storage technologies as well as potential environmental hazards that are likely to occur due to the growing use of energy storage technologies.

An obvious limitation of the photovoltaic panel is its reliance on the availability of the sun. Without the sun, or more specifically its solar radiation, a panel's ability to deliver continuous energy is severely limited. The lack of available energy during peak hours results in a customer paying high prices for electricity that they might not need to pay for if they were to utilize storage.

To further argue the need for energy storage, one need only consider Australia's strong reliance on non-renewable, specifically coal, power plants especially for non-daylight hours (Kumar Sahu (2015)). The reliance will remain until the energy storage issue for sustainable energy sources is resolved. Renewable penetration beyond 20% is difficult until appropriately costed energy storage is implemented.

In addition to the implied need for storage solutions is the gradual decrease in offered feed-in-tariffs across Australian states. In Queensland alone, the last few years have seen the feed-in-tariff drop from up to $0.52 to $0.06 (CEC, 2014). Unfortunately, with the decreases in feed-in-tariffs, it is also expected that electricity purchasing prices will increase gradually across some states of Australia.

In terms of battery storage, there are a variety of technologies currently available with many more under research and development (Cho, Jeong and Kim, 2015). The lead-acid battery is the oldest battery technology being used in storage capacities across the world however it is reported to have a limited lifetime and cycle life, which could suggest that it might not necessarily be the best choice for storage in the future.

Some of the limitations of other battery technologies reviewed are:

- Lithium-ion (used more in portable and electric vehicle applications);
- Nickel-Cadmium (high operating temperatures and cost);
- Sodium-sulfur (again high operating temperatures and cost) and;
- Vanadium redox flow battery (low energy density).

Finally, the research has identified a variety of potential safety risks/hazards that might eventuate or be associated with domestic battery installations. Battery short circuit currents often are in the thousands of Amps and pose an obvious immediate health risk to the general public. Toxic material release during battery breach or fires will also need assessment as well as disposal or recycling costs of some battery types. Ultimately, careful consideration towards appropriate storage and maintenance will also be required to ensure injury or death is as near to impossible as can be.

Each of the problems/issues/limitations mentioned above will be reviewed and addressed in the literature review and commented on in the deliverance of results and conclusions.

1.4 RESEARCH OBJECTIVES

The research involved a review of available literature surrounding battery, photovoltaic and inverter technologies, investigation into current tariffs and projected future electricity price trends. Most of the information discussed in this review has been discovered during perusal of existing peer-reviewed research.

Research methodology is divided into several major categories including grid-tied photovoltaic systems with energy storage, battery technologies, inverter technologies, limitations of these technologies, maintenance requirements and social and environmental concerns surrounding these technologies. An overview of the researched system is provided in **Error! Reference source not found.**

The research intends to identify the various factors that may influence the choice of a particular technology. It also intends to identify appropriate economic considerations for use in an analysis of the various battery technologies.

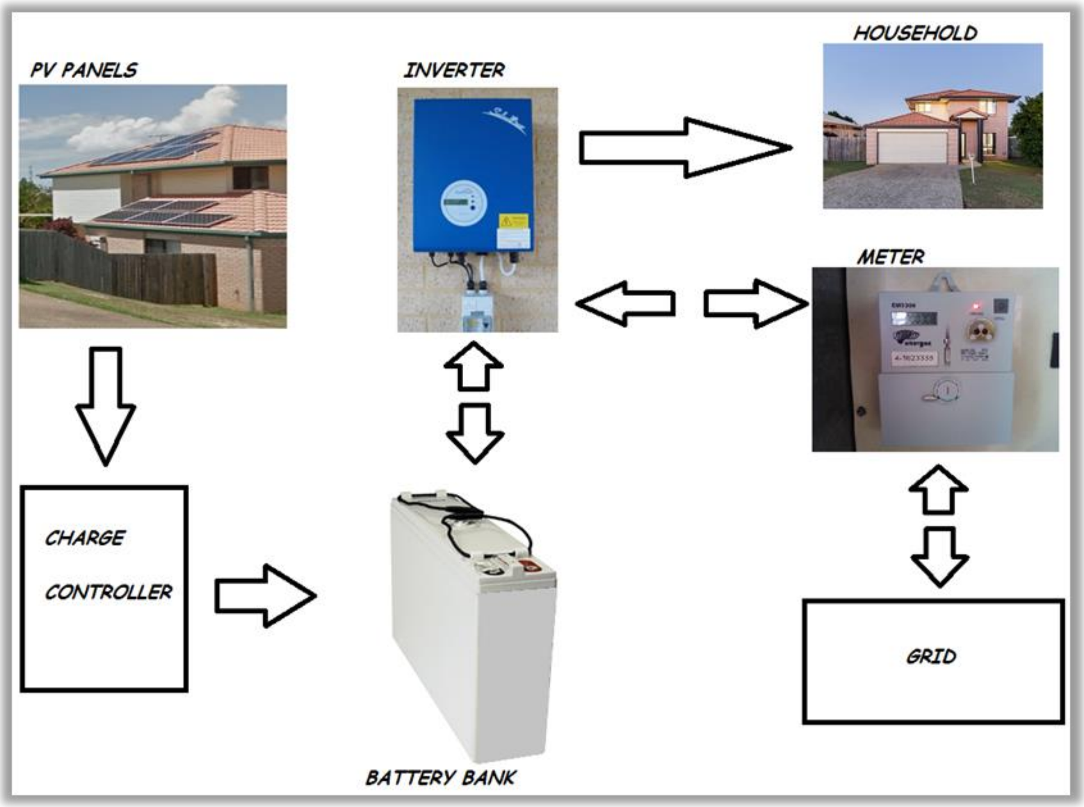

Figure 1-1 - System Overview

1.5 CONCLUSIONS

This project aims to identify a scenario within which domestic customers could install a storage system in conjunction with a photo-voltaic installation resulting in reduced reliance on grid supplied energy and potential financial benefits for the customer. Specifically it aims to answer the following three questions:

Q1. Can and at what point will domestic electrical energy storage, specifically battery storage, become financially viable/feasible?
Q2. Can switching of domestic loads improve the feasibility of domestic electrical energy storage or will the technology required to achieve domestic load switching negatively impact the feasibility of domestic electrical energy storage?
Q3. Is storage of electrical energy in battery technologies the ideal approach to domestic electrical energy storage or are there alternative technologies better suited to a domestic application?

The following chapters describe the research, methodology and analysis employed in an effort to answer the above three questions.

2 CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

In order to fully investigate the potential for a grid-tied photovoltaic (PV) array with battery bank storage system's ability to become economically feasible, research into a variety of subject areas is necessary.

The subject areas include technologies such as batteries, photovoltaic panels, grid-tied installations and inverters. Each of these categories will be further investigated to include research into maintenance and installation requirements and factors that impact the technology's life cycle and performance as this will have a significant impact on the suitability of a technology for increased economic performance.

In addition to these technologies, an investigation into alternative storage technologies is intended to identify how battery storage systems compare with other technologies Investigation into alternative technologies might identify a technology that should be further investigated in future research papers.

Along with technology, research into current Australian and global tariffs and future expectations is also required. In order to identify the point at which grid-tied solar and battery installations become economical various tariff situations will need to be addressed.

Finally, research into the ethical, environmental and sustainability issues surrounding these technologies is also required in order to identify current and future social motivations, if there is a need for these technologies and how these technologies will assist in reducing the impact on the environment, infrastructure and social expectations of the engineering industry.

The research will allow the identification of appropriate variables and technologies to be considered during modelling. Modelling will be carried out with largely only an economic consideration in mind. To support the economic analysis, the researched social impact of these technologies and their impacts on the environment will also be commented upon to allow for a more holistic approach in the delivery of results.

2.2 ENERGY STORAGE

Chen et al. (2009) describe pumped hydroelectric storage (PHS), compressed air energy storage, battery (CAES), flow battery, fuel cell, solar fuel, superconducting magnetic energy storage system, flywheel, capacitor and supercapacitor and thermal energy storage systems as the various Electrical Energy Storage (EES) systems under development and currently available today.

Poullikkas (2013) describes the major disadvantage of pumped hydro energy storage and compressed air energy storage systems as the need for special site requirements. In terms of domestic application, the need for additional fuel sources and hydro energy storage systems deem these types of technologies less suitable for use than BESSs.

In terms of renewable energy supply systems, Chen et al. (2009) write that intermittency and non-controllability are disadvantages to the renewable energy industry and then suggest that an appropriate EES will provide the storage required for surplus energy generated during times when generation exceeds the demand and allowing use of stored energy during times where generation is not possible.

Cho, Jeong and Kim (2015) agree with this sentiment, suggesting that limitations of renewable energy sources include output fluctuations, unavailability and unpredictability. They infer that EES systems can be used to improve reliability of power systems through provision of services such as frequency regulation, spinning reserve and improved power quality.

In terms of Battery Energy Storage Systems (BESS) Cho, Jeong and Kim (2015) state that new battery technologies with higher energy density, increased lifetime, lower costs, increased safety and improved environmental compatibility are required for increased use in energy storage applications. Currently there does not seem to be a single battery technology that meets each of these demands but the research does suggest that possibilities in the future are there.

Considering the information provided in the literature and given the limitations described in the research for CAES and PHS, these technologies will not be considered during modelling as installation of these technologies on a domestic residence appears impractical. Similarly, flywheel technologies will also be precluded based on the need for appropriate installation area.

The need for additional fuel sources that are often carbon-based reduces the desirability of fuel cells as then intention is to reduce the reliance on carbon-based fuel sources. The lack of available technical specifications and retail information for a domestic application of capacitors supercapacitor, superconducting magnetic energy storage system or a thermal storage system also make modelling of these technologies difficult as HOMER requires at least some sort of capital cost and technical specification input to complete optimization.

For the reasons stated above, it seems likely that any potential economic benefit for a customer choosing to install a means of storage in the near future will likely be at the hands of the electrochemical battery, though flow batteries will also be investigated. Future work could incorporate the consideration of supercapacitors or other storage systems in a domestic installation assuming detailed technical retail information becomes available.

2.3 GRID-TIED PV SYSTEM WITH BATTERY BACK-UP

Raugei, Fullana-i-Palmer and Fthenakis (2012) use the energy returned on investment (EROI) ratio to suggest that PV is a gradually improving and viable power generation option. EROI is the ratio of the usable energy the plant returns during its lifetime to all the invested energy needed to make this energy usable. It allows industry personnel a quantifiable metric for comparison to existing fossil fueled power generation systems.

Raugei, Fullana-i-Palmer and Fthenakis (2012) reported that the EROI of oil and natural gas fueled power generation systems has fallen significantly since the 1930s until now with a predicted continued fall due to the nearing exhaustion of available resources. Coal has appeared to remain stable however its uses are limited when compared to oil, gas and PV resources and environmental impacts are reportedly higher.

Conversely, Weißbach et al (Weißbach et al. 2013) suggest that while renewable energy generating systems all produce more energy than they consume, the economic benefit of using these generation systems in conjunction with the various available storage systems results in a poorer economic performance than technologies such as coal or nuclear.

This statement was made in conjunction with acknowledgment that EROIs for fossil fuels do change as stockpiles become more difficult to access. Similarly land consumption and the impact on the environment should also be considered though this research was outside of the intended subject area.

At an industry level, PV generation systems with storage are still highly debated as an economic means of power generation. In terms of domestic installations Parra, Walker and Gillott (2014) suggest that energy storage at a domestic level can introoduce technical benefits to the network.

It is proposed by Parra, Walker and Gillott (2014) that the introduction of storage of surplus energy could relieve the electricity generation system during hours of peak usage, resulting in reduced reliance of fossil fuel powered generation systems. Zakeri and Syri (2015) agree, citing EES as an opportunity to store power in low demand time for use in later peak hours reducing the need for increasing grid power capacity using fossil fuel generation technologies.

In their research, Zakeri and Syri (2015) compare the various energy storage technologies currently available by means of total capital cost (TCC) and life cycle costs (LCC). TCC includes the purchase, installation, delivery, power conversion system, energy storage and balance of power costs. LCC considers the number of cycles per year, the price of power and interest rates, the DoD (Depth of Discharge) and replacement time of batteries.

Of the available battery technologies, NiCd, Fe-Cr, Li-ion and Zn-Br are the high performers while ZEBRA (Sodium Nickel Chloride), VRFB, NaS and Lead-acid batteries are the low performers when TCC is compared. In terms of LCC, Fe-Cr and NaS are the high performers with Lead-Acid, VRFB and NiCd found to be low performers in terms of use as energy storage. Li-ion, ZEBRA and ZnBr performance was not reported.

Ultimately, Zakeri and Syri (2015) report that NaS is the optimal battery choice for energy storage however they do suggest uncertainties exist surrounding the costs of batteries. In addition to this, the presented quantitative evidence for the analysed batteries appears to be limited as the LCCs presented do not appear to consider cycle number or depth of discharge.

A final criticism is the lack of detail regarding Li-ion use in energy storage. Diouf and Pode (2015) suggest that Li-ion batteries could eventually be used more in an electric grid application than in electric vehicles (a market where Li-ion batteries have already enjoyed much success). Use is largely dependent on material cost and future research.

The potential benefits of using energy storage systems in a domestic grid-tied PV installation do not appear to be limited to the customer only. The reduction of surplus energy applied to the grid during peak PV conversion hours and the potential reduction of grid-supplied energy during peak usage hours provides a social and environmental aspect that will be further investigated within this work. The concept of reducing reliance on grid-supplied energy during peak hours can be used in both modelling and investigation into the logic required to carry out smart switching of a domestic load.

Ultimately, the research suggests that BESS systems are gradually becoming very suitable for use in domestic grid-tied PV installations. The most obvious factor limiting their suitability is the cost, however cost is expected to reduce with further research into materials and production. With a generalized expectation of decreasing capital costs in the future, it appears reasonable to include consideration of decreasing storage capital costs in the modelling phase of this work.

2.4 BATTERY TECHNOLOGIES

There are various battery technologies currently available to the domestic market. Cho, Jeong and Kim (2015) have researched several different types of battery technologies naming Lead-acid, Sodium-sulfur (Na-S), Lithium Ion (Li-ion) and Redox flow battery (all-vanadium) as the current battery technologies applicable to EES applications.

They have also identified Metal-air battery (Zinc-air), advanced redox flow batteries, aqueous lithium flow batteries and waste-lithium-liquid flow batteries as technologies undergoing research progress in EES applications.

Zakeri and Syri (2015) and Poullikkas (2013) have also investigated appropriate electro-chemical battery technologies for EES applications. Their research identified many of the same technologies with a few variations. The identified technologies and their variations have been listed in Table 2-1 - Battery technologies and variations
. For further technical characteristics, see Appendix 3 - Energy Storage Characteristics

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Battery Type	**Variations**
Lead-acid	Valve Regulated (VRLA)
Lead-acid	Deep Cycle (DCLA)
Lithium-ion (Li-ion)	Cobalt
Lithium-ion	Manganese
Lithium-ion	Phosphate
Nickel-Cadmium (Ni-Cd)	Sealed
Nickel-Cadmium	Vented
Sodium-sulfur (Na-S)	Beta double-prima alumina
Sodium-sulfur	Metal-Chloride/Nickel-Chloride ($NaNiCl_2$) or ZEBRA (Zeolite Battery Research Africa)
Flow Battery	Vanadium redox
Flow Battery	Zinc-bromine (Zi-Br)
Flow Battery	Aqueous lithium
Flow Battery	Waste-lithium-liquid
Advanced redox flow battery	Organic-inorganic aqueous system
Metal-air	Zinc-air

Table 2-1 - Battery technologies and variations

The technologies presented in the table are not necessarily the only technologies available. These technologies are those that are found most regularly described in research as appropriate technologies for use in EES applications and most regularly reviewed in terms of life cycle and total capital costs. These technologies and applicable research are to be reviewed separately in an attempt to identify appropriate technologies for modelling in HOMER.

2.4.1 LEAD-ACID

Zakeri and Syri (2015), Cho, Jeong and Kim (2015) and Poullikkas (2013) all describe the lead-acid battery as the oldest rechargeable battery technology currently used in EES applications. While a lot of the research presented is quite similar there are several differences in opinion.

Poullikkas (2013) suggests that lead-acid battery manufacturing costs are low but that batteries are slow to charge, have high DoD and are limited in charge/discharge cycles. Of the lead-acid batteries reviewed, deep cycle lead-acid batteries are most suited to grid-tied PV systems.

Zakeri and Syri (2015) also describe the limited life cycle, short discharge times and low energy densities expected of this technology. They are again described as low cost, however when suggesting these batteries are low cost they also note that battery costs are directly influenced by lead prices and that battery costs vary widely dependent on configuration, duty cycles and lifetime.

The limited cycle-life of the lead-acid battery is again discussed by Cho, Jeong and Kim (2015). They further explain that a lead sulfate layer can form during periods of high discharge on the negative electrode's surface that cannot be completely reversed during recharging. This results in a reduction of electrode area for subsequent discharge cycles. Additionally, charging of lead-acid batteries at high rates can induce generation of hydrogen reducing lifetime and creating an explosion hazard.

Finally, Cho, Jeong and Kim (2015) indicate that lead-acid batteries can be recycled at a rate up to 97%. However, Poullikkas (2013) describes the lead and sulfuric acid used in these batteries as highly toxic and suggests that they can create environmental hazards. Zakeri and Syri (2015) does not appear to comment on the potential environmental impacts of the lead-acid battery.

In terms of economic analysis, the modelling should provide an indication of how deeply the duty cycles and lifetime of this technology affect its usefulness and desirability as a potential storage system in a domestic application. The use of a heavier metal in its construction as well as sulfuric acid severely reduces its desirability in terms of a social/environmental consideration.

2.4.2 LITHIUM-ION

Poullikkas (2013) suggests that the lithium-ion technology is new to the grid storage application but with improvements these batteries will likely become utilized more often in grid storage. Current concerns surrounding Li-ion are high maintenance and operating costs, lower efficiencies and control of large battery banks.

Zakeri and Syri (2015) also describes Li-ion as a new storage technology initially intended for portable applications but having also been employed in grid-scale storage applications. It is again suggested that a future in energy storage is expected for Li-ion technologies as prices are decreasing, lifetime is increasing and safety parameters are improving.

Cho, Jeong and Kim (2015) offers information regarding the more endearing characteristics of the Li-ion battery. Li-ion batteries offer the highest energy density, cycle stability and energy efficiency of all technologies. In line with the other research the technology currently suffers from high costs and thermal instability reducing the ability for the technology to be used in large battery bank applications, though this is on the MW scale which is likely outside the concern of this investigation.

In the presented research there is very little discussion regarding the impact of DoD on the technology's life cycle making its robustness difficult to compare with other technologies. The only means of comparison is total life cycle with no reference to DoD.

However, the research does seem to suggest that Li-ion battery technologies, while still relatively new, are likely to become highly desired technologies for use in EES applications. Cost again appears to be the greatest limiting factor but with increasing demand and continued research it is likely to achieve a competitive edge against other technologies in the not too distant future.

2.4.3 NICKEL-CADMIUM

Ni-Cd batteries are described by Zakeri and Syri (2015) as another older technology used in storage applications. Maintenance requirements are reportedly low and life cycle can be as high as 50,000 cycles with a DoD of 10%.

Unfortunately, these higher life cycles do come at a high capital cost. In addition to cost, this technology is reportedly susceptible to the memory effect, overcharging and low efficiency. The heavy metals are also a point of concern in terms of disposal and handling due to their toxic nature.

Poullikkas (2013) does not discuss much in relation to cost, DoD or life cycles but does state that this technology has become a popular choice as storage for solar installations due to its' ability to withstand high temperatures.

Luo et al. (2015) agrees with Zakeri and Syri (2015) regarding the heavy metal toxicity being of great concern and that Ni-Cd are a low maintenance technology. It is also agreed that Ni-Cd suffers from the memory effect and further describes the negative impact this has on battery bank capacity.

Luo et al. (2015) disagrees with Poullikkas (2013) suggesting that Ni-Cd storage is unlikely to be used in any large-scale EES projects. Very little is mentioned regarding the technology's ability in domestic storage applications.

Very similar sentiments are again repeated by Akinyele and Rayudu (2014) again. However this time Ni-Cd batteries are reported to have low cycling capacities at 2000 to 2500 cycles. No DoD is mentioned so at what DoD this cycling capacity was achieved is not readily apparent.

The research does not seem to present the Ni-Cd battery as a suitable option for EES applications though there is some conflicting information and the research presented generally refers to large-scale installations. The low maintenance requirement, high cycle life and very high potential for deep discharge seem to present this battery as a very desirable technology regardless of capital costs.

A concern for the modelling of this technology is that HOMER Legacy does not appear to have the ability to consider memory effect which is a potential downfall of this battery type. This should also be considered when comparing results of the modelled technologies.

2.4.4 NICKEL IRON

As specified by (Changhong 2014), the NiFe Battery is likely to achieve a long cycle life (20 years or more if operated within manufacturer's specifications), is environmentally friendly due to no lead, cadmium or acid and is also highly recyclable. They are supposed to provide increased safety due to a reduced possibility of burning or thermal runaway, a wide operating temperature range and are considered low maintenance.

The long battery cycle life is also reported by(TheNickelIronBatteryAssociation 2012), suggesting that it can be continuously charged for over 40 years and due to the low solubility of the reactants in the electrolyte, the battery is able to survive frequent cycling. An additional advantage is the ability to improve the battery's performance by employing different standard concentrations of electrolyte for use in different temperature ranges.

The maintenance regime required for these battery types is largely dependent on the float voltage. The exact float voltage is not important and is a trade-off between topping-up of distilled water and the regularity of charging cycles the battery is likely to experience. If the battery is likely to experience many charging cycles then the float voltage should be increased. An increased float voltage will result in the need for more distilled water maintenance.

Zappworks (ZappWorks) suggests that the changing of electrolyte every 20 years will return battery capacity to 100%. This is also mentioned by (IronCoreBatteries) and is considered one of its greatest advantages over lead acid batteries. The replacement of electrolyte only every 20 years should significantly reduce replacement costs. It would also likely result in increased environmental benefits.

In addition to the environmental advantages provided by changing only the electrolyte every 20 years, the batteries are again cited by (TheNickelIronBatteryAssociation 2012) as having a lack of lead, cadmium or other toxic heavy metals found in other battery types. They are also regularly described as being entirely recyclable and extremely strong and durable.

A potential disadvantage is the lack of charge efficiency. There appears to be a lot of discussion and conflict surrounding the 65% charge and 85% discharge efficiency. It is, in some cases, still considered an advantage over the Lead Acid battery being that it's efficiency at 20 years of age will be no worse than a lead acid's efficiency at 5 years of age but, this is purely speculation with limited quantitative evidence of this comparison available.

Fortunately HOMER does provide the capacity for inclusion of roundtrip efficiency which allows for greater accuracy during modelling of this battery type.

2.4.5 SODIUM SULFUR

Cho, Jeong and Kim (2015), Zakeri and Syri (2015), Poullikkas (2013) and Luo et al. (2015) all describe Na-S batteries as a promising technology for high power EES use. They all appear to agree on the various desirable features and limitations of the technology.

The desirable features include high energy densities, nearly zero daily self-discharge, higher capacities, higher power capability and non-toxic material construction resulting in higher recyclability. The limitations of this technology are cites as high operating costs and the need for an additional system to ensure battery operating temperature.

Poullikkas (2013) has included reference to two variations of the Na-S battery. Both the beta double-prime alumina and sodium/metal chloride (ZEBRA) cells have higher operating temperatures. The ZEBRA cells are reported to achieve higher voltages, wider operating temperature range, less corrosive and reaction products are reportedly safer.

Another possible limitation could also be that utility-scale Na-S batteries are only manufactured by one company. This fact is reported by both Poullikkas (2013) and Zakeri and Syri (2015). However, it could be assumed that this is unlikely to impact domestic applications as capacity requirements are significantly smaller.

Luo et al. (2015) reports that future research on this technology appears to be tailored towards decreasing the high temperature operating constraints of the battery. Cho, Jeong and Kim (2015) also report on research into operating temperatures offering the use of polymers or organic solvents as catholytes.

Overall the research seems to support Na-S as a well-established means of EES. Continued research into operating temperature seems to be a high priority as this is the most discussed limitation of this technology.

2.4.6 FLOW BATTERIES

Zakeri and Syri (2015), Cho, Jeong and Kim (2015), Poullikkas (2013) and Luo et al. (2015) all report on the benefits flow batteries will provide to large-scale energy storage systems assuming manufacturing costs can be reduced. They all describe an obvious benefit of flow batteries as the independence of power from the storage capacity.

Cho, Jeong and Kim (2015) describe the redox flow battery as useful in large-scale EES systems of power 10kW – 10MW which is, in most circumstances, outside the needs of domestic applications. However, Zakeri and Syri (2015) state that relatively low energy density, limited operating temperature range and high capital costs reduce the desirability of this technology for large-scale applications.

Akhil et al. (2013) present data applicable to residential applications for the Zn-Br, Fe-Cr and Vanadium flow batteries. The data agrees with the above statements, suggesting flow batteries do have high capital costs in comparison to other technologies as well as high O&M costs.

Further research is expected across the various types of flow batteries as this technology promises increased lifetime, increased DoD with little or no life cycle effects, reduced environmental impacts and a high degree of installation flexibility. Currently cost is a major limiting factor but as has been discussed before, further research and development should reduce technology capital costs.

2.4.7 METAL-AIR BATTERIES

Cho, Jeong and Kim (2015) describe the metal-air batteries, specifically Zinc-air, as an emerging technology for storage applications. Cho, Jeong and Kim (2015) comprehensively describe the technology and identify its advantages as having an abundance of resources, low cost and environmental compatibility of Zinc.

Mahlia et al. (2014) also describe metal-air batteries as low cost, going as far as suggesting they are the cheapest battery available in the market. They state that Zinc-air batteries use inexpensive material and are environmentally safer than the Lithium-air battery. The main disadvantage is the low efficiency of the battery due to inefficient recharging. They also mention that this battery is best suited to very small applications such as energy storage in hearing aids.

Akhil et al. (2013) describe Zn-air batteries as a far more stable and less dangerous battery than other. It is described as having a superior energy density than Li-ion and again its environmental advantages are quoted. It is again described as an emerging technology and is expected to have low capital costs as well as O&M costs. Due to its moderately recent emergence, available technical specifications and retail information seem to be limited. For this reason it is unlikely that any modelling will be carried out in this research however this technology is worth consideration after the expected future development.

2.5 BATTERY LIMITATIONS

2.5.1 COST

The various reported costs are expressed in Table 2-2 - Battery costs - Akhil et al. (2013); Cho, Jeong and Kim (2015); Luo et al. (2015); Poullikkas (2013); Zakeri and Syri (2015)for quick comparison of the research. This table is a very quick summary of the presented research and does not include all battery technologies as technologies such as Zn-Br flow and Zn-air batteries are often not discussed.

Battery	**Research Paper**	**Capital Cost – Power (US$/kW)**	**Capital Cost – Energy (US$/kWh)**	**O & M (US$/kW/year)**
Lead-acid	(Luo et al.)	200 – 600	50 – 100	50
	(Cho, Jeong & Kim)	300 – 600	200 – 400	Not specified
	(Zakeri & Syri)	1526 – 3577	315 – 792	Fixed 3.74 Variable 0.41/MWh
	(Poullikkas)	Not specified	50 – 310	Not specified
	(Akhil et al.)	1407 – 1994	275 – 1766	Fixed 37.2 Variable 0.0027/kWh
Li-ion	(Luo et al.)	900 – 1590	600 – 3800	Not specified
	(Cho, Jeong & Kim)	175 – 4000	500 – 2500	Not specified
	(Zakeri & Syri)	2318 – 3018	504 – 616	Fixed 7.58 Variable 2.31/MWh
	(Poullikkas)	Not specified	Not specified	Not specified
	(Akhil et al.)	1231 - 1047	542 - 1581	Fixed 26.8 Variable 0.0027/kWh
Ni-Cd	(Luo et al.)	500 – 2500	400 – 2400	20
	(Cho, Jeong & Kim)	Not specified	Not specified	Not specified
	(Zakeri & Syri)	2505 – 4597	655 – 888	Fixed 12.09 Variable Not specified
	(Poullikkas)	Not specified	400 – 2400	Not specified
	(Akhil et al.)	Not specified	Not specified	Not specified
Na-S	(Luo et al.)	350 – 3000	300 – 500	80
	(Cho, Jeong & Kim)	1000 – 3000	300 – 500	Not specified
	(Zakeri & Syri)	2048 – 2595	361 – 437	Fixed 3.96 Variable 1.98/MWh
	(Poullikkas)	Not specified	180 – 500	Not specified
	(Akhil et al.)	474 – 757	372 – 426	Fixed 4.5 – 9.2

				Variable 0.0004 – 0.0008/kWh
Flow - Vanadium	(Luo et al.) (Cho, Jeong & Kim) (Zakeri & Syri) (Poullikkas) (Akhil et al.)	600 – 1500 600 – 1500 1404 – 1813 Not specified 635 - 2133	150 – 1000 150 – 1000 282 – 476 175 – 1000 620 – 880	70 Not specified Fixed 9.34 Variable 0.99/MWh Not specified Fixed 4.5 – 16.5 Variable 0.0005 – 0.0016/kWh

Table 2-2 - Battery costs - Akhil et al. (2013); Cho, Jeong and Kim (2015); Luo et al. (2015); Poullikkas (2013); Zakeri and Syri (2015)

The research presents very similar figures in terms of power and energy capital costs for most battery types. Unfortunately there does seem to be a lack of available research regarding operation and maintenance costs of these technologies. What research is available is somewhat conflicting.

Luo et al. (2015) have provided a large amount of detail regarding capacity costs and O&M costs using a variety of sources to come to conclusions. They have also commented on the need to consider both capital costs as well as O & M and equipment lifetime. The O&M cost is not particularly well described and does not give any indication of whether or not it is all-encompassing or simply a fixed cost.

Akhil et al. (2013) provides the most detail for the various types of battery technologies and their applications. Cost of alternative technologies is also represented allowing ease of comparison. For most storage capital costs it is also mentioned that costs apply only at rated DoD. It should also be noted that because of the magnitude of data presented by Akhil et al., the data found in Table 2-2 - Battery costs - Akhil et al. (2013); Cho, Jeong and Kim (2015); Luo et al. (2015); Poullikkas (2013); Zakeri and Syri (2015) is a very brief summary.

Modelling in HOMER will be carried out based on current prices advertised by retailers rather than the quoted figures in the table above. It is important however to note the huge variance in capital cost reported by the various researchers. Lead-acid is most regularly reported as the lower capital cost battery and Lithium-Ion the highest. Unfortunately, lifetime and maintenance costs are not obvious however modelling based upon the various technical inputs in HOMER should provide a better indication of the technology's usefulness in domestic storage application.

2.5.2 TEMPERATURE

Zakeri and Syri (2015) and Luo et al. (2015) state that a lead-acid battery's temperature must be kept within limits as specified by the supplier due to the battery's tendency to experience significant degradation in expected lifetime if exposed to temperatures outside these limits. These limits are stated by Zakeri and Syri as -5 to 40°C, though specific manufacturer specifications should likely be consulted.

Zakeri and Syri (2015) only seem to express concern of temperature limitations for the lead-acid and flow batteries, reporting flow battery temperature range as 10 to 35°C. There is very little discussion about appropriate means of ventilation or desired operating temperatures, though again manufacturer specifications for particular batteries would likely identify ideal operating temperatures.

Na-s and NaNiCl2 batteries are both described as high-temperature operating batteries by Akhil et al. (2013), Zakeri and Syri (2015) and Mahlia et al. (2014). No reference is given to ambient temperatures surrounding the battery installation or temperature impact on life time.
While the research seems to only describe temperature sensitivities surrounding lead-acid and flow battery technologies, it is likely that specific information regarding other battery variations would be available on manufacturer's datasheets.

While temperature can have an effect on the battery's operational capabilities, HOMER Legacy does not provide the user with a means of inputting potential temperature extremities the battery is likely to experience. Ideally and, if recommended, a means of temperature compensation will be employed in any installation with the intention of improving expected lifetime of the battery. However this is a limitation of the results provided during modelling in HOMER.

2.5.3 LIFETIME AND DoD

Luo et al. (2015) describe lifetime and cycling times as two factors that influence the overall investment cost of energy storage technologies. This idea could suggest that while lead-acid batteries have low capital costs, lifetime and the impact of DoD on cycle times might result in other battery technologies with increased lifetime and DoD resilience being favored over lead-acid.

Having said that, Cho, Jeong and Kim (2015) and Zakeri and Syri (2015) suggest that advanced valve-regulated lead acid (VRLA) batteries with carbon-featured electrodes can experience life cycles 10 times longer than conventional lead-acid batteries. Investigation into capital costs would then be required to compare the suitability of both battery types. This is not discussed within the research.

In terms of lifetime and DoD on Ni-Cd batteries, Zakeri and Syri (2015) suggest that these batteries can reach 50000 cycles if limited to a DoD of 10%. However this is merely an offered theory with little to no quantitative evidence to support the claim.

There is very little comment elsewhere about DoD and lifetime in the research other than identifying which technologies are considered to have high lifetimes and increased cycle life. These specification can be found in Appendix 3 - Energy Storage Characteristics

The various sources, for the most part, seem to agree on recorded lifetimes and cycle life.

DoD and resultant lifetime is expected to have a significant impact on the results achieved during modelling. As described in the research, while lead-acid is considerably lower in capital cost, its lifetime is limited and highly dependent on a maximum DoD of around 80% which may result in poor performance when compared with other battery types.

2.6 BATTERY MAINTENANCE

The need for battery maintenance is inferred by Akhil et al. (2013), Luo et al. (2015) and Zakeri and Syri (2015) who all offer suggestions for O & M costs for various battery technologies. However, the extent and frequency of maintenance required is either only very briefly discussed or not discussed at all.

In terms of standards, maintenance regimes are well-documented for the Lead-acid battery in various Australian and IEEE standards. AS/NZS3731.1 and AS/NZS 3731.2, StandardsAustralia (1995a, 1995b) refers to electrical tests to be carried out on Ni-Cd batteries but does not specify any specific maintenance tasks to be complete upon install. There does not appear to be any reference to any maintenance required for the Li-ion, Na-s or flow batteries in the IEEE or Australian Standards.

Different maintenance requirements exist for vented and sealed lead-acid batteries 'IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications' 2011); (IEEE 2006); IEEE (2007); StandardsAustralia (1992b, 1992a). An overview of these requirements have been presented in two separate tables found in APPENDIX 4 - EXAMPLE BATTERY MAINTENANCE SCHEDULES. The Australian and IEEE standards seem to agree on maintenance requirements and frequency.

AS/NZS 2676.1 and AS/NZS 2676.2 do make reference to Ni-Cd battery cell voltages and their cycling requirements but there is no specific mention of any other battery technology. It could be expected that these technologies would require similar maintenance routines but further investigation to support this statement is required.

For use in modelling it is estimated that maintenance costs per year will vary from $10 per year up to $150 a year. This estimation is based on personal experience carrying out maintenance, based on Australian Standards, on lead-acid batteries. The time required to perform different levels of maintenance was recorded and fees to be charged calculated in line with current wage levels.

A quarterly maintenance routine on a lead-acid battery is likely to take anywhere between 15 minutes and 1 hour, dependent on battery bank size. Assuming a call-out fee is incorporated in the total maintenance cost, a lead-acid battery bank is likely to suffer maintenance costs between $100 and $200 a year. Similar figures have been utilized in the modelling of other battery types though figures have been adjusted based on manufacturer's recommended maintenance requirements.

2.7 PHOTOVOLTAIC PANEL TECHNOLOGIES

Akinyele, Rayudu and Nair (2015) present a brief overview of current solar PV technologies stating their efficiencies as a percentage. A summary of these technologies is presented in Table 2-3.

Technology	Material	Cell Efficiency (%)
Crystalline Silicon	Monocrystalline (Mono c-Si)	15 to 20
Crystalline Silicon	Trycrystalline (Tri c-Si)	16.79
Crystalline Silicon	Polycrystalline (Poly c-Si)	15
Crystalline Silicon	Emitter wrap through (EWT)	15 to 20
Crystalline Silicon	Gallium arsenide (GaAs)	39
Thin Film	Amorphous silicon (aSi)	4 – 8 (direct sunlight) 12 (laboratory)
Thin Film	Cadmium Telluride (CdTe)	>15
Thin Film	Copper indium selenide / Copper indium gallium selenide (CIS / CIGS)	20
Hybrid	Crystalline silicon and non-crystalline silicon	21
Hybrid	Microcrystalline (μc-Si)	8.9 to 9
Organic and Polymer	Polymers, pentacene, polyphenylene vinylene, copper phthalocyanine and carbon fullerenes	4 to 5
Dye-sensitized	Iodide with titanium dioxide	11
Nanomaterial	Carbon nanotube	3 to 4

Table 2-3 – PV materials and efficiencies

Tyagi et al. (2013) have also identified the above mentioned technologies and materials as the current and emerging PV cell technologies, citing similar efficiency values. In addition to the material specifics, they name China as the leader in solar cell production with Taiwan, Japan, Europe and the United States also named as reasonably high producers.

Both Tyagi et al. (2013) and Kumar Sahu (2015) indicate that PV panel production is increasing with Kumar Sahu (2015) further stating that, “the total capacity of solar PV grew with average rates of 60% annually”. Ghazi, Sayigh and Ip (2014) agree with this sentiment but state that growth was measured at 50% between 2003 and 2008 with an estimation of 25% annually in the future. While reported growth differs, it still suggests the PV panel industry can safely expect growth in the future.

Tyagi et al. (2013) also report that the costs and prices associated with the above technologies have been decreasing due to research and development in material science. Conversely they have stated that the production costs are described as having increased due to improvements in production processes though very little evidence is offered to support this suggestion.

It has been suggested by Chen et al (2009) that future and continued development of renewable energy, specifically PV panel, and storage technologies will drive the cost of EES down as has been evidenced historically in wind and PV power generation technologies. This notion appears to be based on pure speculation as quantitative evidence is not offered within the research.

Historical trends and research, though sometimes not reinforced by quantitative evidence, do seem to offer an optimistic future for the cost, research and development of PV technologies. With increased research into PV panel technologies and material science it does seem reasonable to assume PV panel efficiencies are likely to improve. With increased research and increased production, it could also be assumed that PV technology costs will decrease as has been evidenced throughout history.

Using the theories, ideas and projections provided in the research, modelling in HOMER will include an imagined future decrease in capital costs. To preclude the consideration of decreasing PV capital costs could be considered something of an oversight and could limit the variance of results achieved during modelling.

2.8 PHOTOVOLTAIC PANEL MAINTENANCE

Di Dio et al. (2015) suggest that the PV industry is growing due to several factors, one of which is that a PV system does not require expensive maintenance regimes. However, a report delivered by the US Energy Information Administration, EIA (2013), actually demonstrated that the expected cost of maintenance of a PV installation is substantially higher per MW of nominal capacity than traditional fossil fuel installations.

This report is focused on large scale power plant installations as opposed to the domestic installations being investigated in this report. Maintenance costs may or may not be expensive but maintenance itself is a necessary requirement for increased efficiency of the PV installation.

Evidence of the need for maintenance has been provided by Cristaldi et al. (2014) Ghazi, Sayigh and Ip (2014) and Soklič et al. (2015) who all comment on the adverse effects dusty layers have on PV panel conversion efficiency.

In their research, Soklič et al. (2015) describe the impact of dust on PV panel conversion quantitatively stating that, "it is reported that a dust layer of $4g/m^2$ decreases solar power conversion by 40%". Ghazi, Sayigh and Ip (2014) found in Egypt that, "a dusty module produced between 25 and 35% lower energy when compared to a clean module after a period of three months and one year, respectively".

All of the referenced research indicates the need for maintenance and cleaning of solar panels to maintain the highest possibly efficiencies. StandardsAustralia (2014), specifically AS/NZS 5033:2014, offers maintenance recommendations for PV Panels. A maintenance schedule, provided in APPENDIX 6 - PV PANEL MAINTENANCE SCHEDULE suggests quarterly cleaning as well as yearly and five yearly visual and electrical inspections of the entire installation for both performance and safety reasons.

The research demonstrates the need for ongoing maintenance of the PV technologies. Not only is it necessary for ensuring the highest possible conversion of solar energy to electrical energy, it should also ensure the safety and electrical integrity of the PV installation. Unfortunately HOMER Legacy does not allow provision for the different potential levels of maintenance on an installation thus providing another limitation in the accuracy of results.

2.9 PHOTOVOLTAIC LIMITATIONS

The photovoltaic panel is used to convert solar energy into electrical energy. This sentence alone highlights the two immediate limitations of a photovoltaic system, photovoltaic cell technologies and the availability of solar energy.

The most discussed limitation of the PV Panel is its ability, or lack of ability, to convert solar radiation into electrical energy. With reference to Table 2-3 – PV materials and efficiencies, PV cell technologies that are reasonably cost-effective to manufacture are only capable of converting around 15 to 20% of the solar radiation applied to that cell.

In their research, Akinyele, Rayudu and Nair (2015) suggest the efficiencies of PV cells and panels are under continual improvement. This sentiment is echoed in research carried out by Tyagi et al. (2013) who quantify the gradual improvement of the Mono c-Si PV efficiencies between 1950 (15%) to now (28%).

Tyagi et al. (2013) present a chart (APPENDIX 5 - NREL PV CELL EFFICIENCIES CHART), developed by the National Renewable Energy Laboratory NREL (2015), that clearly demonstrates the increasing efficiencies of most current PV technologies. The chart highlights both the gradual increase in older technologies such as multi-junction and crystalline cells and the rapid increase of emerging technologies such as organic or dye-sensitized PV cells.

The research indicates a very optimistic future for PV cell efficiency. Projection into the future suggests the ability to convert solar radiation to electrical energy should improve. What is not readily obvious in the chart or presented research is the expense and cost of these technologies. The cost of these technologies for the domestic market will need to be investigated in further research.

In terms of solar radiation, Wild et al. (2015), using data from a variety of host institutions, have outlined projections for surface downward solar radiation, surface downward clear-sky solar radiation, near surface air temperature and total cloud fraction for a variety of regions from 2015 to 2050.

In the presented research, Australia is projected to expect a small increase in surface downwards solar radiation and near surface air temperature but a decrease in surface downward clear-sky solar radiation and total cloud fraction. Combining these projections, Wild et al. (2015) suggest a non-significant change in potential solar radiation, thus a non-significant change in PV generation, for a large part of Australia between 2015 and 2050.

HOMER Legacy allows estimation of the potential daily radiation based on the input of the installation's latitude which should allow for moderately accurate results. Considering the non-significant change in potential solar radiation in Australia, it seems that the result accuracy will not be negatively impacted by the estimation and lack of ability to consider future solar radiation changes within HOMER.

2.10 INVERTER TECHNOLOGIES

Hamid and Jusoh (2014), Patrao et al. (2011) and Islam, Mekhilef and Hasan (2015) categorize inverter technologies currently employed in grid-tied PV systems as either transformer or transformerless inverters. Islam, Mekhilef and Hasan (2015) further explain that transformer inverters can use either high frequency transformer on the DC side or low frequency inverters on the AC side.

Patrao et al. (2011) describes current issues surrounding inverter technologies as efficiency and cost. They reason that the move towards transformerless inverters is due to the cumbersome, lossy and expensive nature of the low frequency transformers as well as the reduced efficiency that occurs when using high frequency transformers due to the need to employ cascaded power converters.

The advantage of using transformers in inverters is reported by both Patrao et al. (2011) and Islam, Mekhilef and Hasan (2015) as being the galvanic isolation provided between PV modules and the grid. The galvanic isolation provided by the transformer limits or completely prevents the possibility of DC current injection into the grid. IEC61727, VDE0126-1-1 and IEEE1547 all specify maximum values of DC current injection, with IEEE1547 being the most stringent at <0.5% (Islam, Mekhilef and Hasan (2015)).

In an effort to prevent and correct these leakage currents, Patrao et al. (2011) and Islam, Mekhilef and Hasan (2015) analyze, compare and report on the various transformerless inverter topologies under investigation and development today. They both cite cost and efficiency as motivation to continue development of these technologies however no quantitative cost evidence is presented making speculation about the cost of technology in the future very difficult.

In terms of maintenance there is very little reference to maintenance requirements in the research. AS4777.1-2005 (StandardsAustralia (2005a, 2005b, 2005c) presents necessary installation, inverter and grid protection requirements for connection of energy systems via inverters though no maintenance suggestions are offered.

With the apparent lack of available research surrounding inverter technologies it becomes difficult to make any sort of recommendation or decision on which inverter is preferred to others. The most significant outcome of the presented research is the suggestion that a continued decrease in inverter costs due to future R & D will occur. Because of this, HOMER modelling will incorporate consideration of reduced capital costs.

2.11 POLICIES AND ECONOMICS

Currently the top ten countries utilizing solar PV installations are Germany, Italy, USA, China, Japan, Spain, France, Belgium, Australia and the Czech Republic Kumar Sahu (2015). Kumar Sahu (2015) describes Germany as one of the leading countries in development of the renewable energy sector being driven by an oil crisis in 1974.

In the discussions presented by Kumar Sahu (2015) for the remaining leading countries, it is commonly found that governments are actively pursuing renewable energy targets through different policies and incentives with some more ambitious than others. Currently Australia, under the Renewable Energy Target, aims to contribute 20% renewable energy by 2020.

Kumar Sahu (2015), Stetz et al. (2015) and Hosenuzzaman et al. (2015) all refer to Germany as the leader in PV installation progress. Germany, after an oil crisis in 1974 made a move towards renewable energy and now hope to achieve 50% renewable energy by 2050 Kumar Sahu (2015). The German government is now also offering incentives for domestic dwellings attempting to achieve self-sufficiency.

Detail surrounding the various policies associated with renewable energy is outside the bounds of this investigation. The many different policies employed by different countries are complex in nature and content is wide and varied. Areas of most interest are domestic and FiTs which are discussed in the following sections.

2.12 TARIFFS

2.12.1 AUSTRALIAN DOMESTIC TARIFFS

The Australian Energy Market Commission (AEMC) released a report on Residential Electricity Price Trends AEMC (2014) discussing the expected trends for the electricity market in Australian states. Not all tariff offerings are discussed, only those used by the largest proportion of residential customers.

State	**Market Offer (c/kWh)**	**Projected price trend**
Victoria	28.82	Average decrease of 0.6% to 2017
South Australia	32.65	Average decrease of 2.4%
Queensland	28.71	Average increase of 6.9% to 2017
Western Australia	26.04	Average increase of 3.3% to 2017
Australian Capital Territory	21.70	Average decrease of 4% to 2017
Northern Territory	25.90	Average increase of 1.9% to 2017
Tasmania	24.72	Average decrease of 3% to 2017
New South Wales	28.76	Average decrease of 5.8% to 2017

Table 2-4 - Australian residential tariff forecast AEMC (2014)

The table suggests a decreasing price trend across Australia. However the statistics in this table do not demonstrate the true politics and economics surrounding each state's price offerings and reasons for price increase or decrease, rather they are a brief overview of the information presented by the AEMC.

In terms of selecting appropriate tariffs for modelling, a varied approach is desired in an attempt to incorporate different potential tariff schemes currently available in Australia. After review of various tariff structures, Queensland's Tariff 11, Queensland's Tariff 12A and Victoria's Time-of-Use tariff have been selected for modelling purposes.

Queensland's Tariff 11 is a flat-rate tariff currently charged at 24.5 c/kWh, though this can vary depending on retailer. Energy used at any time of day will be charged at the same rate across the 24 hour period.

Queensland's Tariff12A is a seasonal time of use tariff. It is split into non-summer, summer peak and summer off-peak at prices of 19.1 c/kWh, 51.8 c/kWh and 23 c/kWh respectively. Peak hours are those between 3pm and 10pm, all others are considered off-peak.

Victoria's ToU tariff is split into peak, shoulder and off-peak hours at prices of 37.7 c/kWh, 23.4 c/kWh and 15.9 c/kWh respectively. Peak hours are weekdays between 3 and 9pm. Shoulder hours are weekdays between 7am and 3pm and 9 to 10pm and weekends from 7am to 10pm. This leaves off-peak hours as those between 10pm and 7am each day.

Modelling in HOMER incorporates these prices and tariff structures as well as expected service charges. As one of the aims of this work is to discover the economic feasibility of installing storage systems, the tariff prices will be entered at current rates and also increased by both 4 and 8 c/kWh.

2.12.2 AUSTRALIAN FEED IN TARIFFS

In 2014 the Clean Energy Council released a, "Guide to installing solar PV for households" CEC (2014). In this guide, the current Feed-in-Tariffs (FiTs) across Australia have been specified and the details are as listed in Table 2-5 - Australian Feed-in-Tariffs CEC (2014). The list is indicative of FiTs across Australia but does not demonstrate the variance that occurs between electricity suppliers within each state.

State	Scheme Name	Rate (c/kWh)
Victoria	Feed-in-Tariff	8
South Australia	Minimum Retailer Payment	7.6
Queensland	Negotiated Feed-in-Tariff Ergon Mandated Tariff	4 8.7
Western Australia	REBS	50 / 8.4
Australian Capital Territory	Solar Buy Back Scheme	7.5
Northern Territory	Solar PV Buy Back	27.13
Tasmania	Solar Buy Back Tariff	8
New South Wales	Solar Feed-in-Tariff Benchmark	8

Table 2-5 - Australian Feed-in-Tariffs CEC (2014)

As discussed in AUSTRALIAN DOMESTIC TARIFFS, three example tariff structures have been used for modelling in HOMER. The feed-in tariffs associated with the supply tariffs have been utilized and in each case were only 6 c/kWh.

3 CHAPTER 3

CONSEQUENTIAL EFFECTS

3.1 SUSTAINABILITY

Solar power is often described as the cleanest energy source available (Kumar Sahu (2015)) and that it has the potential to offer significant environmental benefits when compared to alternative fossil fuel technologies (Bakhiyi, Labreche and Zayed (2014)).

This project work aims to further reduce reliance on fossil fuel technologies by investigating a means or the economic feasibility of storing power generated by a domestic PV installation at a residential level. By converting the sun's energy to electrical energy for storage and self-consumption, a domestic dwelling becomes less reliant on grid-supplied electricity which is predominantly powered by fossil fuel generation systems (Kumar Sahu).

The greatest points of consideration include the impact of PV, battery and inverter technology on the environment, health and safety sectors. This is because while solar is a clean energy source, the materials used in the necessary technology are often produced using fossil fuel generation systems and can result in toxic waste and harmful substances (Bakhiyi, Labreche and Zayed (2014)).

By employing battery storage at various locations, the magnitude of potential waste will likely be significantly increased without appropriate recycling procedures. This project work intends to identify not only the most economical technology but also the technology that leaves the smallest footprint on the earth and its' resources.

This project has the potential to impact future generations as it could deliver a means of utilizing renewable energy to the fullest extent. With increased domestic use of small-scale PV installations comes a reduced reliance on grid supplied electricity. With this reduced reliance, especially in peak times, comes a reduced reliance on fossil fuel technologies with high carbon emissions.

In addition to the impact this work has on future generations there is a direct impact on the current generation. Increase in production of these technologies could likely create further opportunities for employment. Similarly an increase in installation and maintenance that could come with increased deployment of these technologies will create opportunities not only in the developed world but also in the less developed areas of the world.

Additionally, as further research is pursued across each of the discussed technologies, cost is likely to decrease (as demonstrated in the literature review). With lowering costs comes the increased ability for less developed countries to invest and utilize these technologies.

Ultimately this project work can have a significant impact on the environment and the general population in both positive and negative aspects. The intention is to identify a scenario that will have the most positive impact on current environment and climate issues as well as socio-economic.

3.2 ENVIRONMENT

Dubey, Jadhav and Zakirova (2013) describe PV systems as having the potential to provide significant social and environmental benefits with the ability to contribute to sustainable development. Hosenuzzaman et al. (2015) agree describing solar energy as, “inexhaustible and CO_2-emission-free” and having the potential to solve many problems created by fossil fuel generation.

In a report delivered by Moss, Coram and Blashki (2014), land and water use are described as potential areas of environmental impact. Land use is quickly dismissed as an area of environmental concern in both small and large-scale installations due to the abundance of appropriate land for use in large-scale installations and the installation configuration (usually installed on a roof) in small-scale.

Water use is described as an area of concern for large Concentrated Solar Power (CSP) installations, potentially worse than fossil fuel technologies. The concern is again quickly dismissed by suggesting that new technologies have the potential to cut water use by 90%. There does not seem to be any mention of concern regarding water use in PV installations.

Repeating the sentiment of Dubey, Jadhav and Zakirova (2013) and Hosenuzzaman et al. (2015) surrounding the lack of greenhouse gas emissions generated through solar energy generation, Moss, Coram and Blashki (2014) do express concern over the emissions produced during production of PV cells. These emissions while still significant are stated as being minor when compared with emissions from other forms of energy used in Australia. A comparison is found in the following figure.

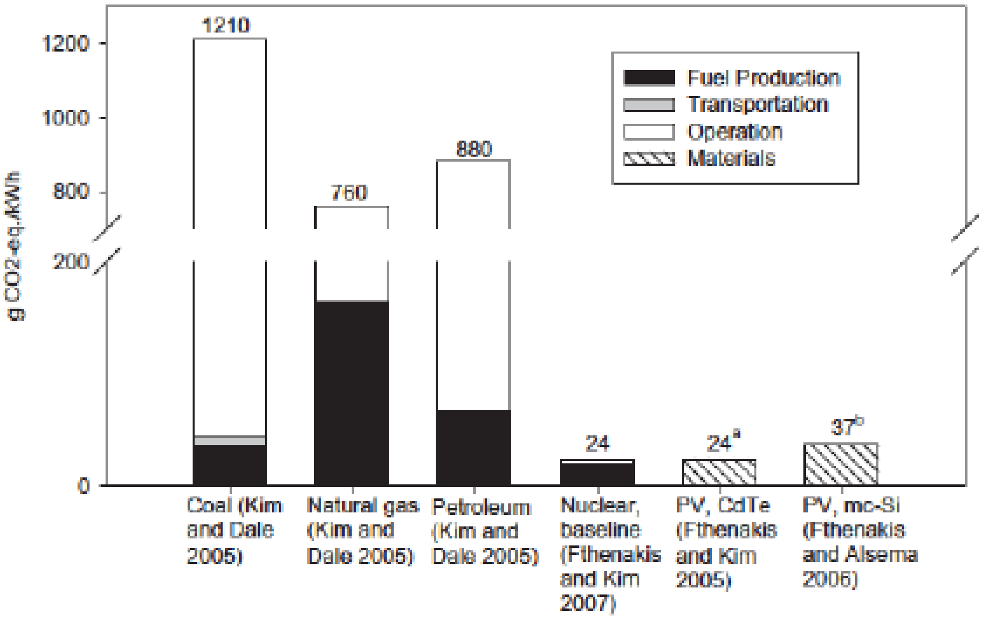

Figure 3-1 - Greenhouse gas emission comparison Moss, Coram and Blashki (2014)

Another area for consideration is the impact the researched battery technologies are likely to have on the environment. Akinyele and Rayudu (2014) briefly touch on the environmental impact on some battery technologies. Lead-acid is described as having a negative influence on the environment due to generated toxic remnants in production but is also described as having the highest recycling capacity at 95%.

Denholm and Kulcinski (2004) describe BESs as having substantially higher greenhouse gas emissions than PHS or CAES systems in production and O&M but that CAES is worse during operation. It could be suggested that if renewable energy sources provided a larger percentage of electricity generation, at some point the greenhouse gas emissions during production of batteries would eventually become negligible.

3.3 HEALTH AND SAFETY

In terms of health, Hosenuzzaman et al. (2015) suggest that the number of heart attacks and different types of asthma as well as many other serious diseases will be reduced due to the lower amount of emissions created by the use of PV technology.

Moss, Coram and Blashki (2014) describe the biggest health hazards involved in PV as being those experienced during production and installation. Similarly, for batteries, the greatest health risks are discovered during the production and disposal/recycling of these technologies however MSDSs are available from battery suppliers for reference during transportation and installation. It is expected that production health issues will improve as research continues.

StandardsAustralia (2014) provides information regarding safety requirements for PV installations in AS/NZS 5033:2014. There are rules regarding appropriate signage for installations and recommendations to observe the electrical wiring standard AS/NZS 3000:2007. AS 4777.1-2005 refers to installation of inverters where appropriate signage, specifically labelling the two sources of supply, is again noted.

Operating temperatures of PV arrays are also described as an area of concern in the standard with a potential 25°C temperature difference from ambient air temperature. The standard also gives reference to the high prospective fault currents that may exist in PV systems connected to batteries.

In terms of battery standards, there are requirements that must be observed in battery installations including items such as battery stand locations and construction, battery orientation within stands and battery ventilation requirements. These requirements are as much for personnel safety as they are for battery and equipment safety.

In general, the health and safety hazards are predominantly related to the production and installation workers rather than the customers. Ideally, a customer should not have any need to access either PV, inverter or battery installations without an appropriately trained installer or maintainer on-site. If installation has been as per the standards, the customer should ideally be protected.

4 CHAPTER 4

METHODOLOGY

4.1 PROJECT METHODOLOGY OVERVIEW

1. Use a data logger to measure a typical domestic load during the summer season. This will require that a risk assessment is completed for the measurement and testing of a domestic switchboard.
2. Begin literature reviews focusing research on current tariffs, battery technologies, photovoltaic technologies, inverter technologies and battery charger technologies as well as sustainability issues, ethical issues, social issues, environmental issues and safety issues associated with these technologies. Critically review any discovered reference material and document.
3. Carry out a risk assessment (including hazard identification, evaluation and control) for:
   - The measurement and testing of a domestic switchboard (already completed in point 2);
   - The various storage configurations of PV arrays, inverters and batteries in a domestic situation;
   - Possible hazards involved in working within a workshop and;
   - Possible hazards involved in working within a home garage.
4. Report on any potential consequential effects (sustainability, ethical, social, environmental or safety) of this project. Use information discovered during the literature review.
5. Complete HOMER modelling using information discovered during literature research and the measurement of the domestic load. Also use the summer load trend data, with Microsoft Excel, to help identify the necessary battery capacity to potentially maintain night-time load. Use the model to identify at what point, if ever, storage costs could become competitive with grid-connection.
6. Use a data logger to measure a domestic load trend for the winter season. The risk assessment established during summer season testing should still apply however a review is required.
7. Consider a typical domestic switchboard and likely loads. Use this to decide on an appropriate PLC such that the PLC will be used to carry out creative switching in an effort to help reduce reliance on the grid and ideally reduce the battery capacity required to maintain load during peak usage times and therefore financial commitment required by customers.
8. Build or simulate a typical switchboard and loads to ascertain the PLC's ability/inability to reduce reliance on the grid connection. Where possible, demonstrate the financial benefits discovered by using a PLC.

4.2 DATA COLLECTION

To estimate battery capacity requirements for an installation, it is intended that data be collected for a domestic installation representative of daily summer and winter loads. This data is then to be collated and used to identify the load trend with the intention of identify peak power usage and times that peak power usage occurs.
To achieve this the following methodology has been chosen:

- Use of AEMC type Simple Logger II, Fluke 374 Current Clamp, Fluke 177 Digital Multimeter for measurement of domestic load and PV generation;
- Risk assessment to be completed due to electrical hazards involved in live testing. Live testing will require the use of appropriate PPE such that the risk is minimized;
- Simple Logger configured to carry out measurements at eight second intervals over a 7 day period beginning the 19th of January, 2015 at 12am and finishing on the 26th of January, 2015 at 12am. Summer load profile found in Figure 6-4 - Summer load and solar comparison;
- Winter load profile to be measured from 12am, 19th of July, 2015 until the 12am 26th of July, 2015. Data logger will be configured to take measurements at eight second intervals, identical to the summer load profile;
- Dataview software used to retrieve the load and PV profiles from the Simple Logger II.
- Microsoft Excel used to calculate average hourly load across a 24 hour period to be used for battery capacity calculations as well as in Homer analysis.

The Fluke 374 current clamp and 177 digital multimeter were used to discover accuracy of the reported current and voltage measurement given by the simple logger. It was found that the simple logger had a small degree of error in current measurements. The current clamp would measure zero amps output from the inverter during hours with no sunlight however the logger was reporting up 1A. Similar variances were recorded in terms of load.

The error has been ignored in this instance as the power consumption of this dwelling (average of 12.2kWh/day) is reportedly lower than the average Australian household (17kWh/day as reported by CEC (2014)).

4.3 MICROSOFT EXCEL CALCULATIONS

Microsoft (MS) Excel will be used for several different purposes. The first purpose is to identify average hourly loads for a twenty four hour period for use as Primary Load data in HOMER analysis. The second purpose is to identify appropriate battery capacity and battery cost needed to maintain a domestic dwelling during times of significant cloud cover or darkness. Finally, it will be used to produce graphical representation of the HOMER analyses results.

The methodology employed in MS Excel for the purpose of discovering hourly loads is:

1. Import all datapoints gathered by the Simple Logger II from the Dataview software;
2. Calculate the power in kW at each of these datapoints. To complete this calculation, a power factor of 0.8 has been assumed as an accurate value was not measured during summer data collection.
3. Use the 'Average' function within Excel to calculate the average hourly load (449 data points per hour) across the twenty four hour period.
4. Again use the 'Average' function to discover the weekly average hourly power consumption as required by HOMER.

The methodology employed for the purpose of identifying battery capacity is as follows:

1. Identify number of days of autonomy, battery derating factors from manufacturer's specification, maximum DoD, dwelling daily power usage and battery bank voltage.
2. Calculate the total kWh to be supported by the battery bank in dark hours and on cloudy days. This is essentially over sizing the battery bank to ensure it maintains the load when required. Use the following formula:

$$Autonomy = kWh_{ave} \times Autonomy_{desired} \times DF \times DoD$$

Equation 4-1

Where

Autonomy is the total kWh to be maintained by the battery system (kWh)

kWh_{ave} is the average daily usage (kWh)

$Autonomy_{desired}$ is the number of days of desired battery back-up (days)

DF is the manufacturer's derating factor or estimation of inefficiency

DoD is the maximum DoD permitted from the battery type

3. Calculate the battery bank Ah desired in order to identify an appropriate battery type:

$$Ah = \frac{Autonomy}{V_{bank}}$$

Equation 4-2

Where Ah is the desired battery bank capacity (Ah)
V_{bank} is the desired battery bank voltage (V)

4. Identify the dwelling's highest expected discharge rate (the highest total load expected to be supported by the battery bank) and calculate the highest discharge rate the battery is likely to expect.

$$A_{peak} = \frac{P_{peak}}{V_{bank}}$$

Equation 4-3

Where A_{peak} is the highest expected discharge current (A)

5. Finally, use the calculated peak current to identify the peak C rating the battery bank is required to deliver. C rate refers to the charge and discharge current of a battery. 1C refers to the current the battery is expected to deliver over one hour.

$$C_{peak} = \frac{Ah}{A_{peak}}$$

Equation 4-4

Where C_{peak} is the peak C rating of the battery bank (C).

The data found in this part of the analysis can then be used to identify an appropriate battery bank configuration (number of strings, battery type and Ah rating) capable of delivering the necessary power required by the dwelling. The methodology employed is as follows:

1. Identify a battery technology and its nominal battery voltage and Ah rating;
2. In order to achieve the required Ah rating the battery bank may require more than one ‘string’ of batteries e.g. a battery bank capacity of 767Ah will require four strings of 200Ah giving a totally capacity of 800Ah. The following calculation is used to discover the number of strings required.

$$No.of\ strings \quad = \quad \frac{Ah}{Battery\ capacity\ rating}$$

Equation 4-5

Where: No. of strings is the required number of strings to achieve desired capacity.
Ah is the desired battery bank capacity as calculated above.
Battery capacity rating is the specified capacity of the battery as per manufacturer’s data.

3. Identify the number of batteries per string required to achieve the desired bank voltage.

$$No.of\ batteries = \frac{V_{bank}}{V_{batt}}$$

Equation 4-6

Where: No. of batteries is the number of batteries required per string.
V_{bank} is the desired bank voltage.
V_{batt} is the battery voltage as per manufacturer’s specifications.

4. Finally, use the total number of batteries and the cost as quoted by the battery supplier to identify the largest expected cost for the batteries.

$$Total\ cost = Battery\ cost\ \times No.of\ batteries\ \times No.of\ strings$$

Equation 4-7

This gives an initial indication of cost of the battery, though cycle life and lifetime has not been accounted for at this point. This data is only a means for comparison between battery suppliers. The aim for the immediate future is to expand the list of battery technologies and potential suppliers as well as include some consideration of cycle life and lifetime for quick comparison. This is intended to help limit the many variations that could be investigated using Homer.

Finally, the methodology employed in the analysis of HOMER results will be to:

1. Import HOMER analyses from a .txt file.
2. Convert the .txt file into a .csv file and then save as an .xlsx file in order to use the various functions available to .xlsx that cannot be used for .csv files.
3. Sort data by tariff to ensure any graphs produced follow a similar format.
4. Delete any results where no data has been returned for ease of comparison in graphical format.
5. For Queensland Tariff 11 analyses, produce line graphs that demonstrate the various Levelized Cost of Energy, Net Present Cost and Capital Costs returned from each simulation in HOMER. The intent of this is to demonstrate at what point each battery technology becomes economically feasible when being used with Queensland's Tariff 11.
6. For Queensland Tariff 12A and Victorian Time of Use tariffs, produce radar graphs for ease of analysis demonstrating the Levelized Cost of Energy compared with the results of analyses performed without PV, battery or converter technologies in use. The intent of this analysis is to demonstrate at what point each battery technology becomes economically feasible.
7. Find an appropriate sensitivity and identify the NPC, COE, Autonomy time and expected life of a battery technology. Do the same thing on the exact same sensitivity of each battery technology on each tariff. Tabulate this data and create a series of 3D column graphs that demonstrate the differences between each technology.

4.4 HOMER ANALYSIS

In order to identify the point at which grid-tied PV installations with battery storage become competitive with current and future electricity prices, an appropriate analysis tool is required.

HOMER software provides a means of designing renewable microgrids with or without attachment to the grid. It provides a means of optimization and sensitivity analysis allowing economic and technical investigation of the potential technology arrangements proposed in this research.

HOMER Legacy version 268 Beta has been used to complete the economic analysis of the available technology and associated research. The methodology employed in this analysis is as follows:

- Load profile discovered during data collection is loaded into homer and identified as the Primary Load. Initial analysis will only be representative of the summer load due to timing.
- A variety of PV system sizes, capital costs, replacement costs and expected O&M costs will be provided as the PV input to the system. Additional means for sensitivity analysis will be provided by offering HOMER the opportunity to consider decreasing capital, replacement and O&M costs.
- Similar to PV, a variety of converter sizes will be loaded into HOMER along with capital, replacement and O&M costs. Sensitivity analysis will be carried out by again offering HOMER opportunities to consider decreasing capital, replacement and O&M costs.
- Several calculations will need to be carried out in order to investigate different Australian state tariff regimes. Tariff rates and schedules will need to be entered under the grid option with various files needing to be created to represent the differing Tariff rates and associated schedules.
- The battery input will also require the creation of various HOMER files in order to investigate the various battery technologies investigated in the research. In a similar vain to PV and converter technologies, decreasing capital, replacement and O&M costs will be used to identify at what point the cost of the battery technology becomes competitive with grid only supply.
- The results of each HOMER simulation are reported through optimization and sensitivity analysis. The sensitivity results will be referred to most often due to the optimization result is based on net present cost (NPC) rather than cost of energy (COE).

As previously described, results of the various simulations are to be tabulated and graphed for ease of comparison and reporting. This will be done in MS Excel after exporting the results as a .txt file from HOMER.

4.5 PLC AND DOMESTIC SWITCHBOARD DEVELOPMENT

No specific methodologies are to be employed in this part of the project work as a lot of this work will be purely experimental.
The aim here is to identify a way in which domestic loads could be switched in a type of load-shifting/load-smoothing scenario such that electricity usage during peak hours is minimalized.

Initial steps will require identification of equipment that could achieve the desired outcome. Steps following will include experimentation with PLC programs and sequences and identifying best practices for control of the domestic load.
As is specified, the intention is to develop and build a smart domestic switchboard however time constraints may hinder the opportunity for a complete prototype.

5 CHAPTER 5

RESULTS

5.1 RESULTS INTRODUCTION

Reaching a defined result for this project work occurred over a series of phases. In order to adequately describe the results phases, they have been separated into the following:

1. Analysis based on a desired 48hr autonomy time;
2. Analysis based on a peak-lopping scenario where, generally, only one 12V battery was investigated;
3. Analysis of a peak-lopping scenario, investigating the economic feasibility of various Lead Acid battery capacities.

5.2 RESULTS PHASE 1

This phase began with discovering the necessary battery capacity to achieve 48hours of autonomy based on the measured summer and winter loads of a domestic residence. From this data an appropriately sized battery could be identified using the methodology presented in MICROSOFT EXCEL CALCULATIONS and the associated cost and battery specifications could be entered into HOMER for analysis.

The average daily usage of the chosen domestic dwelling amounted to 14.86kWh during winter. With de-rating applied, it was calculated that the necessary battery capacity would be 851Ah in order to achieve 2 days autonomy. To begin modelling, the 875Ah Enersun Gel Lead Acid battery was chosen as its price and specifications appeared average when compared with others.

An initial analysis using only the Queensland Tariff 11 data was completed with results suggesting that in order to achieve any sort of financial benefit to a customer the capital costs of the PV panels, inverter and battery technologies would need to decrease to less than half of their current value. In addition to that, the Tariff would need to increase to greater than 32.5c/kWh in order to achieve installation of a 48V battery bank.

In an attempt to improve these results the battery bank size was reduced to 24V. On Queensland Tariff 11, if the Tariff price were to increase to 32.5c/kWh, the capital costs of the PV and converter were reduced by 25% and the battery costs were reduced by 50% the COE would then be 32.4c/kWh, marginally less than the tariff cost. Similar improvements could be discovered by again reducing the battery bank voltage to 12V, though tariff prices still needed to rise to 32.5c/kWh to see any obvious benefit to the customer.

The less than desirable results inspired a shift in approach to the utilization of battery storage. The second phase commenced with an investigation into a peak-lopping scenario where battery storage would ideally be used during peak grid supply hours.

5.3 RESULTS PHASE 2

In the second phase of result gathering and analysis, investigation into four different types of battery storage with smaller capacities commenced across three different tariff scenarios.

While many different technologies were discussed in the research, accurate pricing and specifications of different battery types were often difficult to find. For this reason, the number of battery technologies investigated was substantially smaller than originally desired but still offered an insight into the varying advantages and disadvantages of each battery type. The four different battery types used were:

1.	Enersun 205Ah Gel Lead Acid	\$1056/12V battery
2.	Smartbattery 200Ah Lithium Ion	\$2399.99/12V battery
3.	Alcad 200Ah Nickel Cadmium	\$150/1.5V cell
4.	Ironcore 225Ah Nickel Iron	\$160/1.2V cell

The three different tariffs investigated represent a broad approach to tariff schemes in Australian states. Queensland offers Tariff 11, a fixed price tariff as well as Tariff 12A with varying prices for summer and winter loads and peak, shoulder and off-peak prices. Victoria offers a Time of Use tariff where electricity consumer during peak, shoulder and off-peak hours is priced differently. A summary is below:

1.	Queensland Tariff 11	24.5c/kWh
2.	Queensland Tariff 12A	Non-summer – 19.1 c/kWh, Summer Peak – 51.8 c/kWh and Summer Off-Peak – 23c/kWh.
3.	Victoria ToU	Peak – 37.7 c/kWh, Shoulder – 23.4 c/kWh and Off-Peak – 15.9c/kWh.

The Feed-in-Tariffs for excess PV energy production offered with each of the supply tariffs was 6 c/kWh, though it should be noted that different electricity retailers will offer different Feed-in-tariffs. This is often limited by the location of the domestic dwelling and the number of retailers offering services in that location.

It should also be noted that the Victorian tariff prices described above were discovered by suggesting that the solar installation was found in Airport West, a suburb outside of Melbourne. The load and potential solar energy production would obviously then be significantly different to that of the measured Queensland domestic dwelling.

In order to gain accurate results, the actual load and potential solar energy of a dwelling in Victoria would have to have been measured and modelled. For this reason, the ToU tariff results are to be used only as an indication of what could occur if such a scheme was available to the domestic dwelling measured in Queensland.

5.3.1 INITIAL DATA INTERPRETATION

Interpretation of the data was achieved in MS Excel. Initially, the aim was to identify at what point the COE of each analysis variation dropped below the tariff price. This was easy to compare for the Queensland Tariff 11 scenarios as the tariff price was consistently either 24.5c/kWh, 28.5 c/kWh or 32.5 c/kWh.

In order to compare the Queensland Tariff 12A and Victorian ToU results a baseline average tariff was produced by conducting a HOMER analysis with no PV, inverter or battery technologies included. This analysis delivered a COE based solely on the grid supplied energy and the measured domestic load.

To identify the point at which the COE becomes less than the tariff/baseline, a line graph was produced for Tariff 11 results and radar plots were produced from Tariff 12A and ToU results obtained from HOMER analysis. The various line and radar graphs can be found in APPENDIX 10 - HOMER ANALYSIS GRAPHS - LITHIUM ION, APPENDIX 11 - HOMER ANALYSIS GRAPHS - NICKEL CADMIUM and APPENDIX 12 - HOMER ANALYSIS GRAPHS - NICKEL IRON.

Using this visual tool, the tables, Table 5-1 - Queensland Tariff 11 results, Table 5-2 - Queensland Tariff 12A results and Table 5-3 - Victorian ToU Tariff results could be produced after identifying applicable data points. The tables demonstrate the first point at which the COE dropped below the tariff/baseline for each technology on each tariff scheme.

5.3.1.1 TARIFF ANALYSIS

To summarize the results of the tables in terms of tariff, the current tariff prices, as at 1st July 2015, have been highlighted in red. Considering those highlighted figures, the use of battery storage appears to favour the Victorian ToU tariff schedule. In this tariff structure, only the Nickel Iron cell requires an increase in price, specifically the shoulder tariff price. The remaining battery technologies could be installed assuming a significant drop in the various technology's capital costs.

QLD's Tariff 12A sees the potential installation of both Nickel Cadmium and Nickel Iron at current prices though Nickel Iron would need to see an increase in the Non-Summer price. QLD's Tariff 11 could only see the Nickel Cadmium cell installed though significant reduction in capital costs would be required.

With reference to each of these tables, it becomes apparent that, generally speaking, the only battery technology that has the ability to be used under current day tariff prices is the Nickel Cadmium cell. Having said that, for installation of this technology to actually be of economic advantage to the customer, current PV Panel, inverter and battery prices will need to decrease.

Queensland Tariff 11	PV Cap. Mult.	PV Repl. Mult.	Battery Cap. Mult.	Battery Repl. Mult.	Conv. Cap. Mult.	Conv. Repl. Mult.	Tariff 11 Price ($/kWh)	Min. RF (%)	PV (kW)	Battery	Converter (kW)	Dispatch strategy	Grid (kW)	Initial capital	Operating cost ($/yr)	Total NPC	COE ($/kWh)	Renewable fraction
Nickel Cadmium	0.5	0.5	0.75	0.75	0.75	0.75	**0.245**	10	3	9	2	LF	1000	$4,173	763	$13,926	0.245	0.66
Nickel Iron	0.5	0.5	0.75	0.75	0.5	0.5	0.285	10	3	1	2	LF	1000	$3,804	962	$16,096	0.283	0.64
Lead Acid	0.5	0.5	0.75	0.75	0.5	0.5	0.325	50	6	1	4	LF	1000	$5,526	1,134	$20,018	0.318	0.79
Lithium	0.5	0.5	0.5	0.5	0.75	0.75	0.285	10	3	1	2	LF	1000	$4,259	1,101	$18,333	0.281	0.58

Table 5-1 - Queensland Tariff 11 results

Queensland Tariff 12A	PV Cap. Mult.	PV Repl. Mult.	Battery Cap. Mult.	Battery Repl. Mult.	Conv. Cap. Mult.	Conv. Repl. Mult.	Tariff 12A Non-Summer All Price ($/kWh)	Tariff 12A Summer Peak Price ($/kWh)	Tariff 12A Summer Off-peak Price ($/kWh)	Min. RF (%)	PV (kW)	Battery	Converter (kW)	Dispatch strategy	Grid (kW)	Initial capital	Operating cost ($/yr)	Total NPC	COE ($/kWh)	Renewable fraction	Baseline
Nickel Cadmium	0.5	0.5	0.75	0.75	0.75	0.75	**0.191**	**0.518**	**0.23**	10	3	9	2	LF	1000	$4,342	773	$14,226	0.218	0.63	0.219
Nickel Iron	0.5	0.5	0.75	0.75	0.5	0.5	0.271	**0.518**	**0.23**	10	3	1	2	LF	1000	$3,804	939	$15,812	0.278	0.66	0.28
Lead Acid	0.5	0.5	0.5	0.5	0.5	0.5	**0.191**	**0.518**	0.31	10	3	1	2	LF	1000	$3,302	922	$15,083	0.231	0.62	0.232
Lithium	0.5	0.5	0.5	0.5	0.5	0.5	0.231	**0.518**	0.31	10	3	1	2	LF	1000	$3,974	1,023	$17,050	0.261	0.58	0.262

Table 5-2 - Queensland Tariff 12A results

Victoria ToU	PV Cap. Mult.	PV Repl. Mult.	Battery Cap. Mult.	Battery Repl. Mult.	Conv. Cap. Mult.	Conv. Repl. Mult.	Vic_Peak Price ($/kWh)	Vic_Shoulder Price ($/kWh)	Vic_Offpeak Price ($/kWh)	Min. RF (%)	PV (kW)	Battery	Converter (kW)	Dispatch strategy	Grid (kW)	Initial capital	Operating cost ($/yr)	Total NPC	COE ($/kWh)	Renewable fraction	Baseline
Nickel Cadmium	1	1	0.5	0.5	0.5	0.5	**0.377**	**0.234**	**0.159**	10	3	9	2	LF	1000	$5,363	846	$16,181	0.225	0.61	0.23
Nickel Iron	0.5	0.5	0.75	0.75	0.5	0.5	**0.377**	0.274	**0.159**	10	3	1	2	LF	1000	$3,804	799	$14,014	0.246	0.66	0.247
Lead Acid	0.5	0.5	0.75	0.75	0.5	0.5	**0.377**	**0.234**	**0.159**	10	3	1	2	LF	1000	$3,566	985	$16,158	0.225	0.59	0.23
Lithium	0.5	0.5	0.5	0.5	0.5	0.5	**0.377**	**0.234**	**0.159**	10	3	1	2	LF	1000	$3,974	976	$16,452	0.229	0.55	0.23

Table 5-3 - Victorian ToU Tariff results

5.3.1.2 LEAD ACID ANALYSIS

The lead acid battery found the best results on the Victorian ToU tariff when comparing COE though capital costs would still need to reduce overall by 33%. If considering a smaller reduction in capital costs rather than the overall COE then peak, shoulder and off-peak prices would need to increase by 4c/kWh, 8c/kWh and 0c/kWh, respectively requiring only an 8.33% reduction in capital costs.

If we were to consider a trade-off between capital costs and tariff prices, the capital costs could be reduced by 25% overall, resulting in a need for peak, shoulder and off-peak price increases of 0 c/kWh, 4c/kWh and 0 c/kWh. This scenario seems the most likely as it sits somewhere between the two extremes and offers greater economic benefit to the customer as the COE (24 c/kWh) is 0.7 c/kWh cheaper than the baseline. This is notably different to the scenario presented in the table.

On QLD's Tariff 12A, based on COE, capital costs would need to reduce by 50% and COE was marginally higher than Victorian ToU COE in the tables above. In consideration of the other extreme (smaller reduction of capital costs), if capital costs only reduce by 25%, the non-summer, summer peak and summer off-peak prices would need to increase by 8 c/kWh, 8 c/kWh and 0 c/kWh respectively.

A happy medium between these two extreme scenarios would be a capital cost reduction of only 33% and non-summer, summer peak and summer off-peak prices increases of 8 c/kWh, 0c/kWh and 0c/kWh. It becomes obvious here that the potential installation is dictated largely by tariff prices.

On QLD Tariff 11, the tariff price would need to increase by 8c/kWh, capital costs would need to reduce by 42% and the COE was the highest when compared with alternative battery technologies at 31.8c/kWh. Because the best result on this tariff required the maximum simulated increase in tariff price there is no potentially better options in terms of changes in capital costs to be offered.

The lead acid's poor performance could most likely be attributed to the higher maintenance requirements and therefore cost as well as its reduced expected life. This will be further examined and is demonstrated in the graphs presented in Figure 5-1 - Overview of battery technologies comparing expected life, NPC and COE and Figure 5-2 - Overview of battery types comparing autonomy, NPC and COE.

5.3.1.3 LITHIUM ION ANALYSIS

The Lithium Ion performed similarly to the Lead Acid in that it performed best on the Victorian ToU tariff in terms of COE. Having said that, this performance required a 50% reduction in capital cost. If a 25% reduction in capital cost was preferred, the peak, shoulder and off-peak price would need to increase by 8 c/kWh, 8 c/kWh and 8 c/kWh, respectively.

In search for a trade-off between the two extremities, the capital cost reduction might be increased again to 33% and the peak, shoulder and off-peak prices all increased by 4 c/kWh.

On QLD's tariff 12A, capital costs again need to reduce by 50% and the COE is slightly higher again than the Victorian ToU. If a smaller reduction in capital costs was preferred, the smallest possible reduction with any favourable COE result would be 33% requiring a non-summer, summer peak and summer off-peak price increases of 8c/kWh.

The happy medium in this scenario still requires a capital cost decrease of 42% but non-summer, summer peak and summer off-peak prices increases would be limited to 8 c/kWh, 0 c/kWh and 4 c/kWh, respectively.

On QLD's tariff 11, capital costs again need to reduce by 50% and the tariff price needs to increase by 4c/kWh. This result cannot be improved by further analysis as again, the result in the table is the best case scenario on this tariff structure.

5.3.1.4 NICKEL CADMIUM ANALYSIS

As previously mentioned, the Nickel Cadmium cell is an extremely high performer. On the VIC ToU tariff, the earliest evidence of COE becoming less than the baseline came from a decrease in cell costs of 50% and a decrease in Converter/Inverter costs of 25%. No decrease in PV capital cost was required.

If focusing on reduction in capital cost, the capital costs of the entire system need not be reduced at all if the peak, shoulder and off-peak tariff prices were to increase by 4 c/kWh, 8c/kWh and 0 c/kWh, respectively. If there were an even trade-off between capital cost and tariff price the capital cost could be reduced by 16.67% and the peak, shoulder and off-peak tariff prices would increase by 0 c/kWh.

On QLD tariff 12A, COE is actually lower than the Victorian ToU tariff and capital cost reduction are identical suggesting that the Nickel Cadmium favours the QLD tariff. If a reduced capital cost only is investigated, capital costs could be reduced by 8.33% if non-summer, summer peak and summer off-peak tariff prices increase by 8 c/kWh, 0 c/kWh and 8 c/kWh, respectively.

If we were to trade-off evenly between reduced capital cost and increased tariff prices the capital costs would be reduced by 16.67% and non-summer, summer peak and summer off-peak prices would increase by 4 c/kWh, 0 c/kWh and 4 c/kWh, respectively.

On QLD's tariff 11, capital costs need to reduce by 33% but the tariff price can remain at its current value of 24.5 c/kWh, once again re-iterating the high performance in terms of economic feasibility of the Nickel Cadmium cell.

5.3.1.5 NICKEL IRON ANALYSIS

The Nickel Iron, follows a similar pattern to the Lead Acid and Lithium variations. It performs best on the Victorian ToU tariff, recording the COE dropping below the baseline first off at a capital cost required reduction of 42% and a 4 c/kWh increase in the shoulder tariff price.

If a reduction in capital costs is preferred, the capital costs could be reduced by only 16.67%, requiring peak, shoulder and off-peak tariff price increases of 8 c/kWh. If the intention is to find the happy medium between capital cost and tariff prices, the capital costs could be reduced by 25% and the peak, shoulder and off-peak tariff prices would increase by 0 c/kWh, 8 c/kWh and 0 c/kWh, respectively.

On QLD's tariff 12A, the earliest instance of COE below baseline occurs when capital costs have reduced by 42% and only the non-summer price has increased by 8 c/kWh. If a reduction in capital cost is preferred, capital costs could be reduced by only 33% if non-summer, summer peak and summer off-peak tariff prices increased by 8 c/kWh, 0 c/kWh and 8 c/kWh. The trade-off between capital cost and tariff price would be a capital cost reduction between 33 and 42% and tariff prices to suit.

In terms of QLD's tariff 11, the tariff price would need to increase by 4 c/kWh to 28.5 c/kWh and the capital cost would also need to reduce by 42%. This is the best case scenario for the Nickel Iron battery on QLD's tariff 11.

5.3.2 ALTERNATIVE INTERPRETATION OF DATA

As previously mentioned, Figure 5-1 - Overview of battery technologies comparing expected life, NPC and COE and Figure 5-2 - Overview of battery types comparing autonomy, NPC and COE provide an alternative means of analyzing the data capture during the various HOMER analyses. The column graphs were created by gathering figures for the NPC, COE, battery autonomy and expected battery life of the various battery technologies.

The conditions that were set to ensure that the data was retrieved for identical scenarios are as follows:

1. PV Capital and Replacement Cost Multipliers = 0.5
2. Battery Capital and Replacement Cost Multipliers = 0.5
3. Converter Capital and Replacement Cost Multipliers = 0.5
4. Queensland Tariff 11 = 32.5 c/kWh
5. Queensland Tariff 12A = Non-Summer Peak = 27.1 c/kWh, Summer Peak = 59.8 c/kWh and Summer Off-Peak = 31 c/kWh
6. Victorian ToU = Peak = 45.7 c/kWh, Shoulder = 31.4 c/kWh, Off-Peak = 23.9 c/kWh.

The first graph depicts the NPC, COE and expected life of the battery technology under these conditions. The Lithium Ion battery achieves the highest expected life in every scenario though the COE and NPC figures are some of the highest. HOM ER seemed to oppose the use of the batteries, rarely discharging lower than 20%. The constraints, system control, battery and economics parameters were compared with the other battery files but there is no obvious difference thus suggesting that the use of PV or grid-supplied energy achieved the best economic response.

In this analysis, the Nickel Iron battery appears to enjoy a high expected life, a low NPC but a high COE. The Lead Acid battery has a very low expected life, a high NPC and a high COE making it the least desirable of the technologies. The Nickel Cadmium battery technology again appears to be the front-runner with an average expected life, one of the lowest NPCs and the lowest COE in all tariff schemes.

The Nickel Cadmium battery is again favoured in the NPC, COE and autonomy graph. It appears to provide the highest potential autonomy time. In fact its autonomy time is almost if not definitely twice the time of the other battery technologies. This autonomy time would most likely be attributed to the fact that its capacity is almost 50Ah more than the other technologies. Unfortunately, a similarly sized Nickel Cadmium battery was not available in terms of price.

It could be suggested that the additional 50Ah would not have had such a drastic impact on the autonomy figures but this is merely speculation and has no quantitative evidence to back it up. But the question of battery capacity has now been raised which leads into the third phase of result analysis. A comparison of one battery technology's results using different battery capacities.

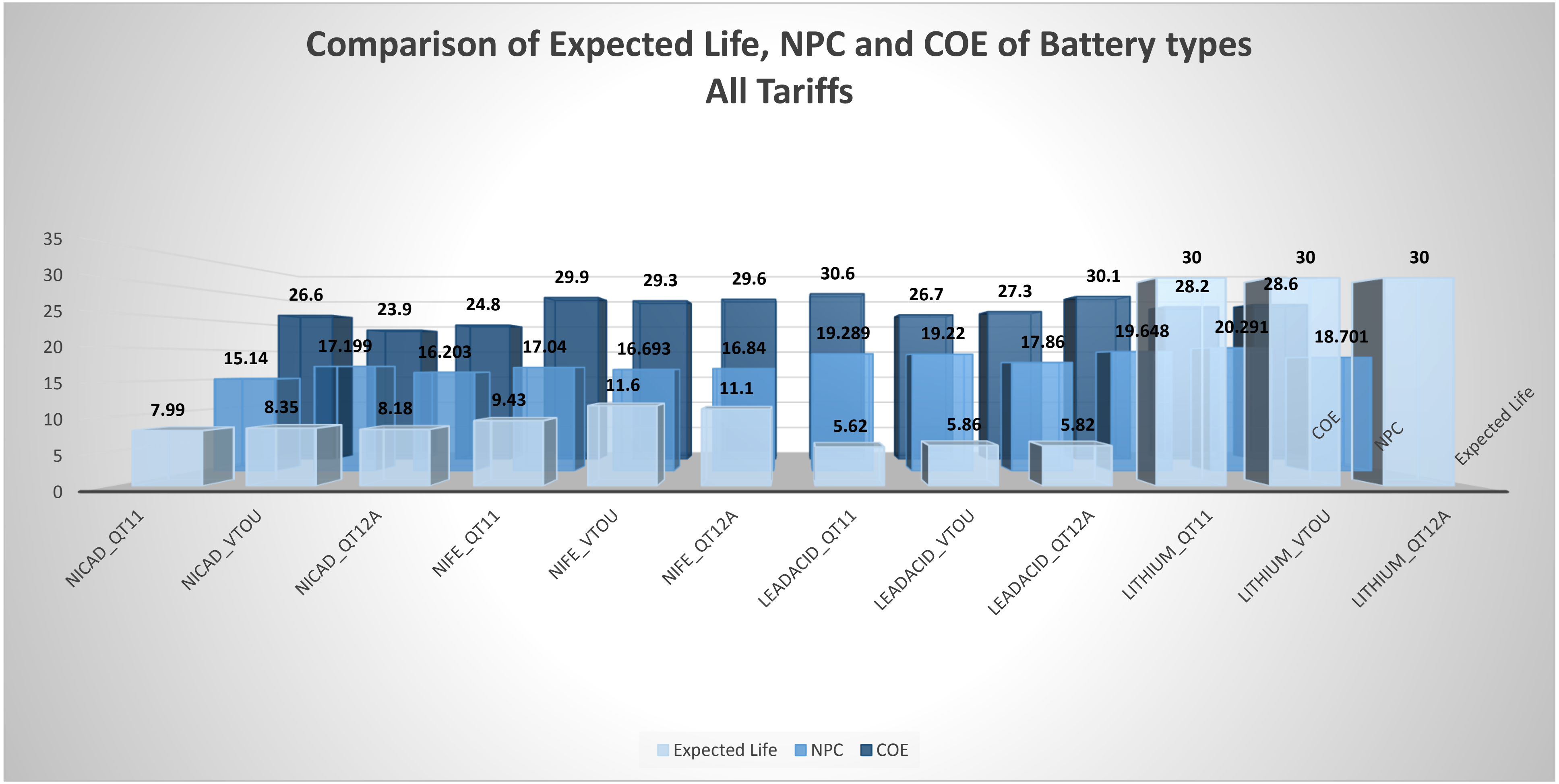

Figure 5-1 - Overview of battery technologies comparing expected life, NPC and COE

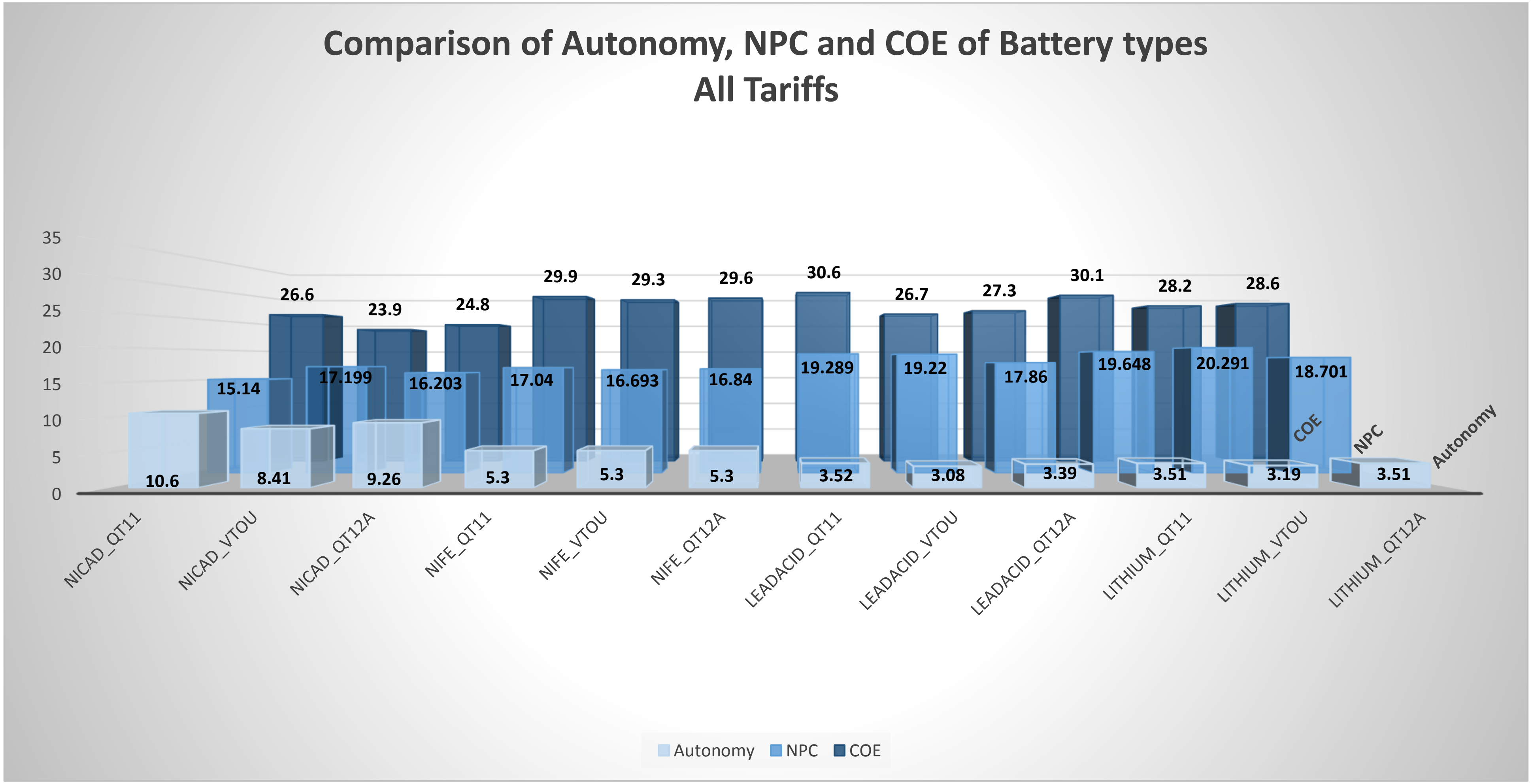

Figure 5-2 - Overview of battery types comparing autonomy, NPC and COE

5.4 RESULTS PHASE 3

The final phase of analysis focuses on battery capacities. Specifically, the lead acid battery has been analysed at three different capacities these being 205Ah, 450Ah and 875Ah. Because this analysis is purely curiosity based only the one battery technology is reviewed and only one tariff scheme, Queensland Tariff 11, is utilized.

It should also be mentioned that further analysis of the other battery technologies was also limited by current available capacities. Specifically, the Lithium Ion battery under investigation had a maximum capacity of 300Ah. Analysis could have been conducted in order to demonstrate the differing capacities but not to the same extent that the Lead Acid battery could be analysed thus a comparison is not possible.

The intention of this analysis and comparison is to discover whether or not the smallest battery capacity, with the smallest capital cost, is always the best option for use in domestic energy storage. To do this, the HOMER analyses were completed for each different capacity level and the results were compiled within MS Excel.

An additional means of comparison has been provided by creating a Capital Cost Index. This index is the average of the PV Capital, PV Replacement, Battery Capital, Battery Replacement, Converter Capital and Converter Replacement multipliers. The results are displayed in both Figure 5-3 -Comparison of attributes of different capacity lead acid batteries and Table 5-4 - Comparison of battery capacities.

With reference to the COE, NPC and Capital Cost Index, it becomes immediately apparent that the 875Ah battery is in fact the most financially beneficial choice in this format of analysis. While the tariff does still need to increase, the COE is significantly less than the tariff price, the NPC is substantially less than the other battery capacity types and the capital cost index demonstrates that the cost of the various technologies does not have to decrease quite as much as it does in the 205 and 450Ah capacity batteries.

This suggests that the data presented in RESULTS PHASE 2 could actually be improved further by carrying out additional analyses with increased battery capacities. This provides additional work in the future in line with the hopeful decrease in capital costs and extension of capacity range of some technologies.

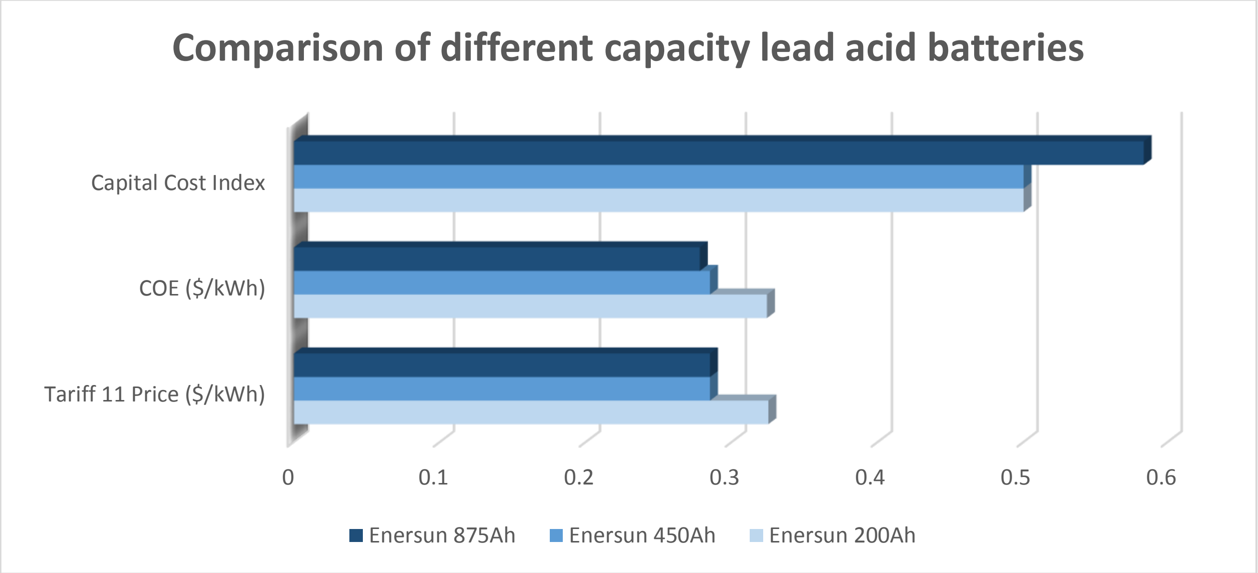

Figure 5-3 -Comparison of attributes of different capacity lead acid batteries

Battery Capacity	PV Cap. Mult.	PV Repl. Mult.	SSR875-6 Cap. Mult.	SSR875-6 Repl. Mult.	Conv. Cap. Mult.	Conv. Repl. Mult.	Tariff 11 Price ($/kWh)	Min. RF (%)	PV (kW)	SSR875-6	Converter (kW)	Dispatch strategy	Grid (kW)	Initial capital	Operating cost ($/yr)	Total NPC	COE ($/kWh)	Net grid purchases ($/kWh)	Renewable fraction	Capital Cost Index
Enersun 200Ah	0.5	0.5	0.5	0.5	0.5	0.5	0.325	80	6	2	4	LF	1000	$5,790	1,145	$20,434	0.324	-3,561	0.82	0.5
Enersun 450Ah	0.5	0.5	0.5	0.5	0.5	0.5	0.285	10	6	2	4	LF	1000	$5,801	953	$17,979	0.285	-3,516	0.83	0.5
Enersun 875Ah	0.5	0.5	0.5	0.5	0.75	0.75	0.285	10	6	2	4	LF	1000	$6,738	844	$17,531	0.278	-3,550	0.88	0.583333333

Table 5-4 - Comparison of battery capacities

6 CHAPTER 6

SMART SWITCHBOARD INVESTIGATION

6.1 DOMESTIC SWITCHBOARD BACKGROUND

As previously discussed, the load of a domestic installation was measured for use in the HOMER analyses. In addition to that, the solar generation of the system installed at the premises was also measured in an effort to accurately depict the potential energy usage and generation of a domestic household.

The graph in Figure 6-1 - Average daily load profile - Summer & Winter, demonstrates the difference in energy use in this domestic installation between summer and winter seasons. During winter, the peak usage occurs in the morning hours, typically between 4 and 9am. In summer there are two peaks, one in the middle of the day and another in the evening. It is likely each of these peaks are due to an increase in use of air-conditioning/heating appliances.

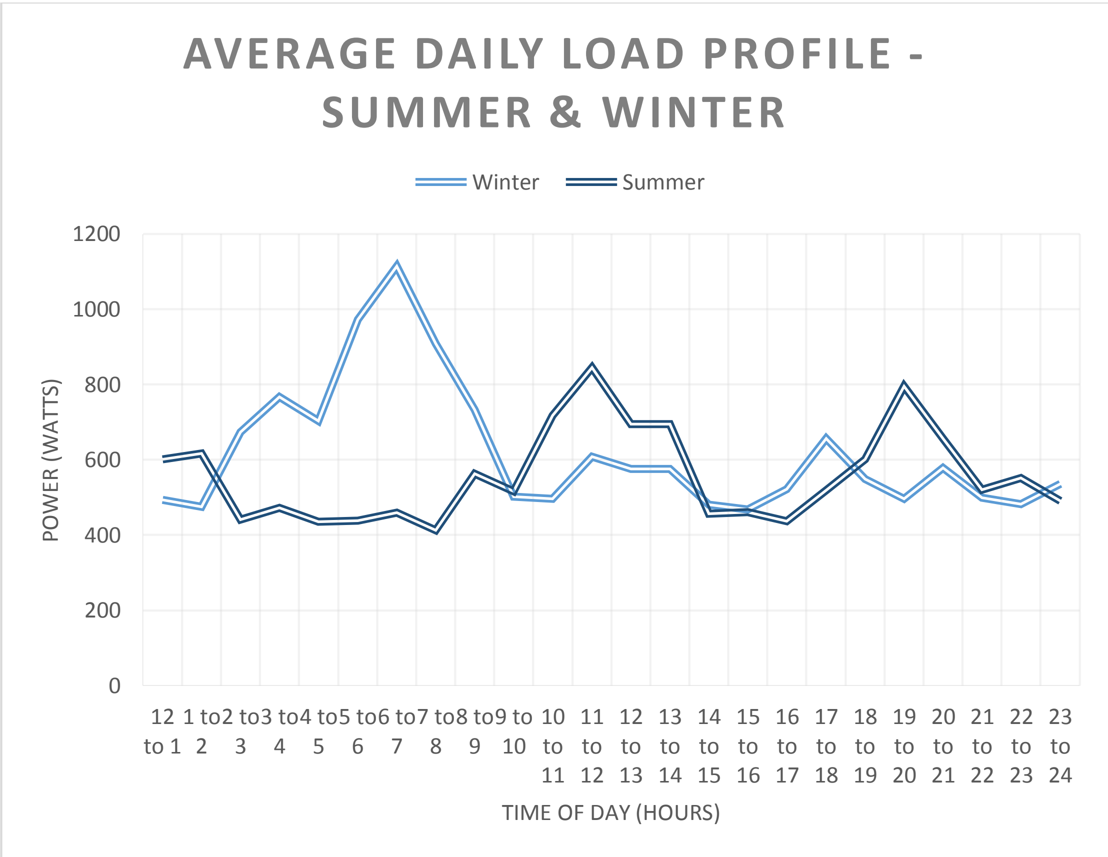

Figure 6-1 - Average daily load profile - Summer & Winter

The graph in Figure 6-2 - Average daily solar profile - Summer & Winter, depicts the measured solar generation at the same premises in both the summer and winter seasons. The peaks for both seasons occur during the middle of the day, as expected. What is surprising is that the measured solar generation in winter at its peak is substantially greater than that of the summer.

Some potential explanation for this could include an optimal angle of incidence of the sun rays to the panel surface, cleaner surface due to a reduction in dust, variation in cloud cover or possibly even cooler operating temperatures allowing for improved efficiency. These differences are important to note as initial inspection suggests that the installation is likely to have notable surplus energy during the day in winter but not quite as much during summer.

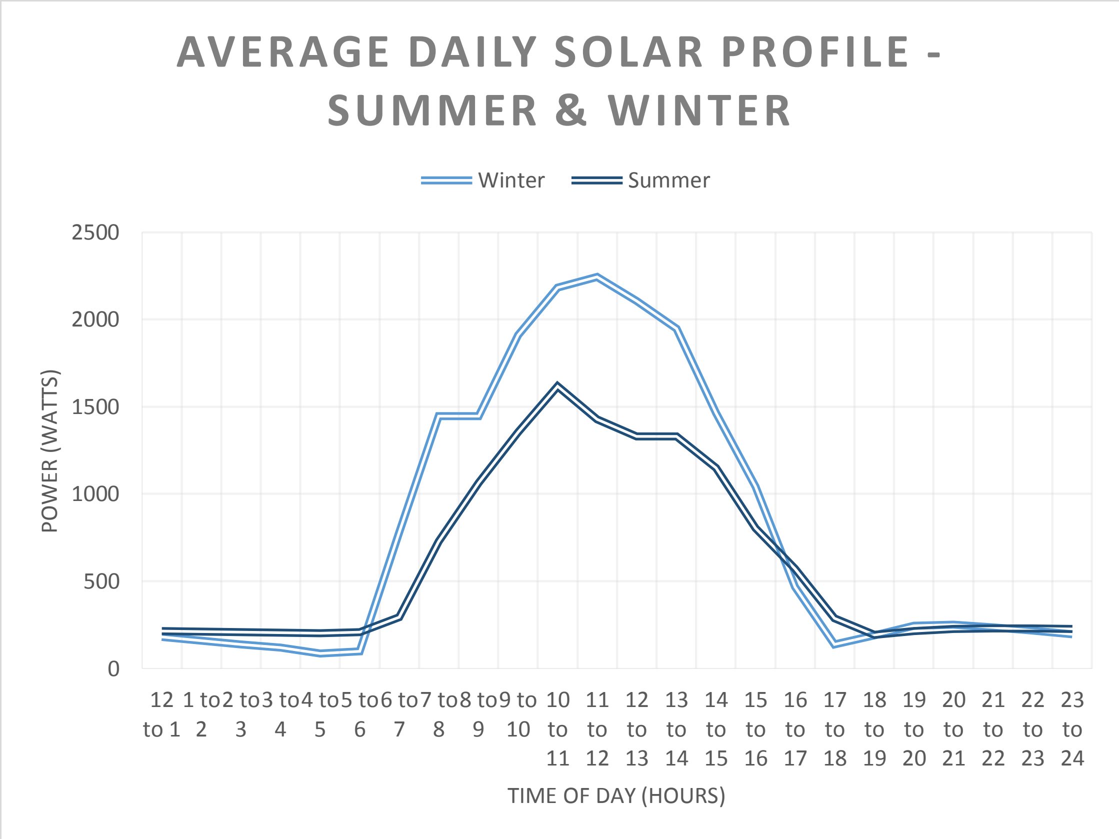

Figure 6-2 - Average daily solar profile - Summer & Winter

Figure 6-3 - Winter load and solar comparison and Figure 6-4 - Summer load and solar comparison demonstrate the mentioned surplus of energy during the day time hours, most notable in the winter chart where the solar generation peaks at 2200 Watts but the load at peak time is only 500 Watts.

In summer, the solar peaks at a little over 1600 Watts and the daytime peak load is a little over 800 Watts. This is something that should be taken into consideration when attempting to improve energy storage and usage in this particular household.

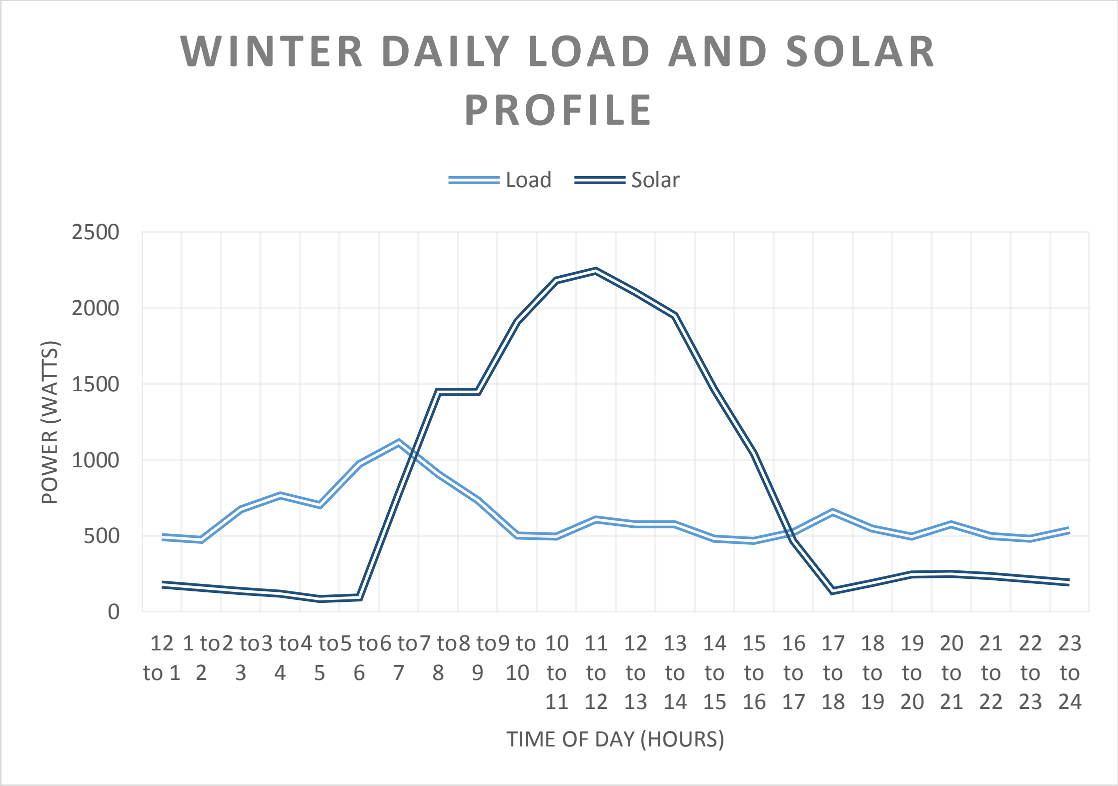

Figure 6-3 - Winter load and solar comparison

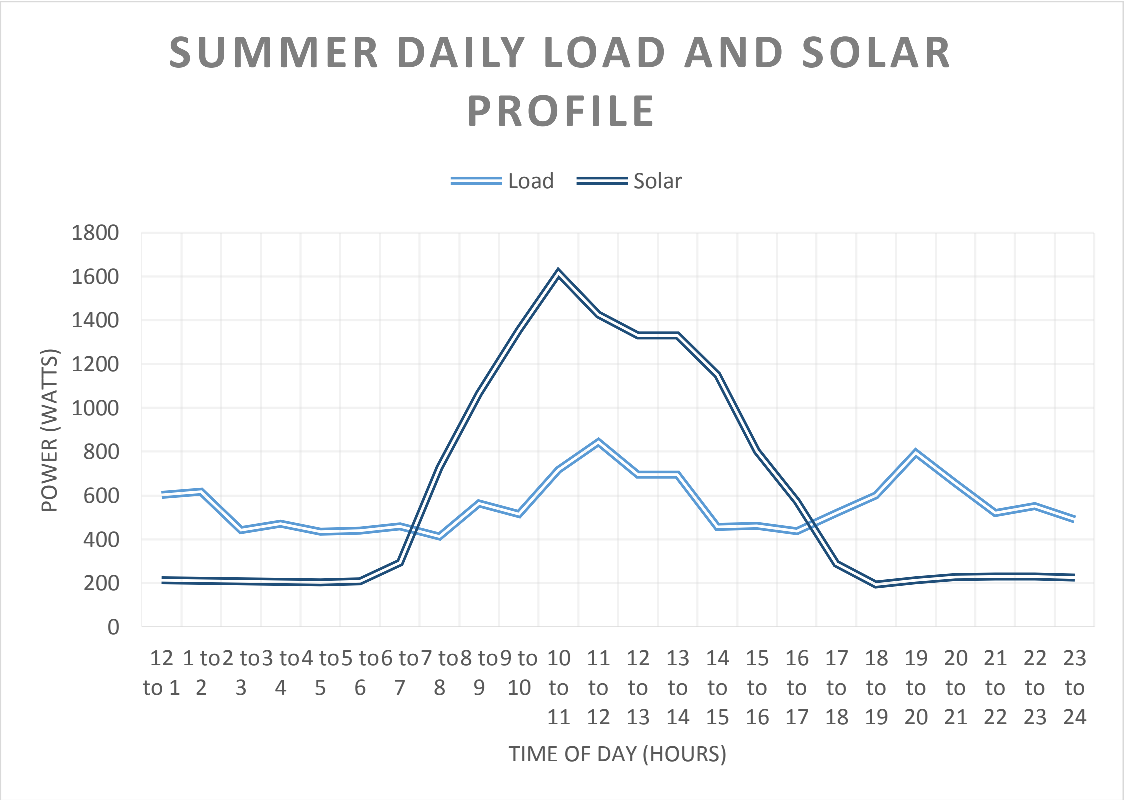

Figure 6-4 - Summer load and solar comparison

Taking these factors into consideration it becomes immediately apparent that the charging of batteries should occur during the day around these peak hours where the surplus energy is greatest and can be stored for use during peak hours, ideally reducing the reliance on grid-supplied energy. This is the first design consideration.

In continuation to that, the literature surrounding the various battery technologies suggests that there are ideal charge rates. If a 200Ah battery was required to be charged at a level of 0.1C, this would mean the battery should be charge at 20A. During the winter season, the maximum input from PV array is 2200W, concurrent with a load of about 500W leaving 1700W surplus.

This 1700W when divided by 240V gives a current of 7A (assuming 100% efficiency of the inverter). This suggests the need to supplement the PV-supplied energy with grid-supplied energy to ensure battery charging at the desired rate. This provides an additional factor for consideration in the design of a smart switchboard.

The highest evening load experienced in both summer and winter seasons is 795W and the highest morning load is 1115W requiring 3.3A and 4.65A respectively. The battery autonomy time will be largely dependent on this load but assuming high discharge currents are not experienced over a long duration it is unlikely grid-supplied energy will be required to support these loads, however this scenario should be considered in the smart switchboard design.

Finally, consideration towards identification of an appropriate charge controller is required to ensure battery state of charge monitoring and safety considerations are included in the installation. The type of charger will depend on the battery technology chosen but for this work a lead-acid charger has been selected due to the abundance of variety and ease of access to technical information.

In terms of the switchboard itself, a typical Australian domestic switchboard will include the following circuits:

- Lighting;
- 2 x general power;
- Air-conditioning;
- Oven and;
- Hot water system.

Typically, there are no sensors installed in a standard domestic switchboard to allow smart switching of the domestic load based on temperature, light levels or even power usage. This is another area of consideration in design, specifically, the additional expense of installing appropriate sensors for smart switching of the domestic load and what type/s of sensors might be required to carry out necessary load shifting.

In terms of sensors, consideration needs to be given towards the use of sensors to either allow or inhibit operation of certain circuits during specified hours of the day. Implementation of a smart switchboard would potentially require the re-configuration of circuits within the household to allow smart switching or even load-shifting to occur.

This smart switching will also be dependent on household routines and will likely require education into tariff prices during different times of day. It will also depend largely on the cost of grid-supplied energy during different times of day. Due to the perceived desirability of the Victorian ToU tariff, its structure will be used here to determine appropriate hours for usage of different load types.

6.1.1 HOT WATER

Typically, hot water is used for hygiene purposes such as showering, washing clothes, washing dishes and cleaning floors. Showering generally occurs in the morning between the hours of 6am and 9am and in the evening between the hours of 6pm and 9pm. In this application only, heating of the hot water system could occur in the middle of the day or night.

Washing clothes is an activity that can occur at any time of the day but is expected in this scenario to occur between the hours of 7am and 7pm. Washing dishes or any other cleaning activity likely to require hot water could also occur at any point of the day but in this scenario is expected to occur between similar hours to the washing of clothes.

Based on these assumptions, the heating of hot water would ideally occur after 9pm at night and finish before 6am in the morning. This suits the Victorian ToU tariff as off-peak prices occur between the hours of 10pm and 7am all week. The question of whether or not battery storage could be used to assist in the heating of water will depend largely on battery state of charge and ability to charge the battery economically during daylight hours.

6.1.2 OVEN

The use of the oven is largely dependent on the household's preferences. It could be suggested that the oven is likely to be used at any point of the day between the hours of 7am and 7pm. On weekdays that places the usage in both shoulder and peak hours and on weekends only in the shoulder prices.

Inhibition of this appliance is very likely impractical and would probably be best handled by educating the inhabitants of the household allowing awareness of tariff prices at particular hours of the day. Potential output from the smart switchboard's 'brain' via a HMI (Human to machine interface) such as an LCD screen might be a good consideration here.

6.1.3 AIR-CONDITIONING

This electrical appliance appears to be one of the larger load requirements in this particular installation. Again inhibition of this appliance does seem impractical however the use of timers within the 'brain' of the smart switchboard might be more effective than the use of timers within the air-conditioning unit itself.

In winter months the peak load appeared to occur in the morning between 4 and 9am. If the use of heating or air-conditioning to heat the house is the source of this load, the air-conditioning circuit could be timed to allow usage in off-peak hours (10pm to 7am) and then inhibit use after 7am until the evening. Air-conditioning use could then be support by the battery storage during peak hours and then switched back to grid-supplied energy after 10pm.

In summer months the peak load occurred in the evening during peak hours. The same switching scenario could be applied for the summer months as well. Specifically air-conditioning use is supported by the battery storage from 3pm until 10pm and then switched to grid-supplied energy after 10pm.

Alternatively, if the battery state of charge is still quite high, the air-conditioning could be supported by the battery storage until a specified maximum DoD is discovered. This would require monitoring of the battery state of charge and consideration towards the expected charge time of the battery storage based on how deeply discharged it becomes during peak hours.

Where usage has been inhibited, this could potentially be over-ridden by use of a temperature sensor located near the duct or evaporator unit allowing usage at a pre-determined temperature. Best practice as described by Ergon Energy (ErgonEnergy 2015)suggests thermostats in winter should be set to 18°C and in summer they should be set at 25°C so these are the values that could be chosen as the "pre-determined" temperatures to over-ride inhibition.

6.1.4 LIGHTING

Lighting could be maintained by either AC or DC voltage depending on the style or type of light fitting and lamp installed. Regardless of voltage requirements, lighting could be supported by the battery storage during peak or night hours. The potential load is likely to be significantly less than air-conditioning, hot water or oven loads and should ideally be supported by the battery storage at any possible opportunity.

Assuming the battery bank enters a charging state between 7am and 5pm the lighting load would need to be supported by grid-supplied energy. If the intention is to inhibit the lighting circuits then lighting sensors should be included to allow inhibition override in times of dense cloud cover. Having said that, inhibition of the lighting circuit seems impractical as a large number of photosensitive devices would be required to be mounted in each of the residence’s rooms.

Instead, the PLC could be used to measure or estimate battery state of charge and expected future demand and switch the lighting load between battery and grid-supplied energy as the situation permits.

6.1.5 GENERAL POWER

General power is a difficult scenario to consider. In a new installation, circuits could be split in such a manner that one circuit is inhibited during certain hours of the day while the other is maintained at all hours of the day allowing for appliances such as TVs, which often utilize a standby mode, to be completely de-energized when not in use. This would require appropriate labelling of outlets to ensure customers are aware of the potential loss of power during certain hours of the day.

Older installations might not have this capability, though investigation of current circuits might provide clarity and allow for the possibility of inhibiting one circuit during the day.

In either scenario, the biggest question is that surrounding which power circuit to inhibit and at what times. As discussed in HOT WATER and OVEN, there is the potential for cooking, cleaning and washing of clothes to occur between the hours of 7am and 7pm suggesting that the kitchen and laundry power should be installed on a circuit that is not inhibited at all. To further cement that fact, refrigerators will require access to 24 hour power thus the kitchen power outlets should not be de-energized at any point.

Other rooms and appliance use are highly dependent on the customer's typical daily activity. In some houses, the entire house is empty during a typical working day thus now power is required in that situation. Alternatively, a customer might work nights or might be domestically based thus requiring access to power during the day. The situation would be highly dependent on the inhabitant's daily routine.

Ideally, in a new installation, two outlets would be available in every room of the house. One outlet would be supplied by the power circuit that remains energized throughout the day and the other would be inhibited. This would likely result in increased cable costs but would allow the customer the opportunity to choose which appliances could be installed on each circuit. It is this scenario that will be considered in the implementation of any switching logic.

6.2 CHARGE CONTROLLER

The ‘smart’ switchboard’s functional requirements are largely dependent on the inverter/converter/charger installed. The analyses carried out in HOMER were based around inverter technologies that have no capacity for consideration of battery storage and manipulated to include the cost of a battery charge controller. However, there are currently various inverter technologies available on the domestic market suitable for use in both off and on-grid battery storage system configurations.

An example of this type of technology is the SMA Solar Sunny Island (SMA-Solar 2014) that can perform in off-grid, battery backup or increased self-consumption types of configured systems. This particular technology can support VRLA, FLA and Li-Ion battery types and system performance can be manipulated via various different settings.

This type of system removes the need for the ‘smart’ switchboard to consider battery state of charge and time management of battery charging and discharging in its switching routines as this function is managed by the inverter. Having said that, the smarter inverter comes at a cost. The HOMER analyses included various different sizes of converters including a 4.6kWh version at a capital cost of $2179.00. The Sunny Island variation is quoted at $7100.00 (Rainbow-Power-Company 2015), substantially more expensive than the modelled converter in HOMER.

Ultimately, the choice of system installed will be dependent on the capital costs of the many system components. As the potential costs of installing a PLC with potential for battery current and voltage measurement inputs are yet to be discovered, the potential of using the smarter inverter is difficult to consider with no current basis of comparison.

6.3 LOAD SHEDDING

The concept of load shedding in a domestic installation could be applied in a variety of ways. The PLC could continually monitor household demand and elect to shed entire circuits in an effort to reduce usage during peak hours. Alternatively with appropriate control in place, a particular appliance referred to as a postponable appliance (Vanthournout et al. 2015), such as a washing machine, tumble dryer or dishwasher, could be inhibited from operation when the household load reaches a pre-determined level.

A project in Belgium has been investigating the concept of dynamic pricing and automated response from smart appliances (Vanthournout et al. 2015). The Linear pilot in Belgium was discussed where day-ahead dynamic pricing was experimented with and a significant shift to lower pricing levels of electricity consumption was experienced. This concept removes the necessity for load shedding by controlling appliances based on future expected load requirements and shifting certain appliance usage into hours of lower price levels.

The concept of dynamic pricing meant that users were not able to consult prices and thus relied on the smart appliance to ensure operation occurred at a time when the lowest possible electricity price was expected in the 24 hour period. It is a pre-emptive rather than reactive concept that requires the end-user make small changes to personal habits and to employ a reasonable level of forward thinking.

While this concept is of great interest, the concept might best be investigated in future work. In the interim, load shedding should be considered in the PLC logic. The household generally experiences peak usage at different times in different seasons as discussed in DOMESTIC SWITCHBOARD BACKGROUND. Winter sees a peak of 1100W and summer sees two peaks of about 800W. Each of the peaks occur at different hours of the day. The PLC could be set to commence load shedding as the total load passes 700W.

Initially it could load shed the power circuit that can be inhibited. It could wait for 5 minutes, check the total load again and if it’s still too high, load shed the air-conditioning. Obviously this is removing basic comforts and could be considered a nuisance but the aim is not to improve comfort, rather improve energy awareness.

6.4 CONCEPTUAL LOAD SHIFTING LOGIC

6.4.1 LOGIC MINIMUM REQUIREMENTS

To summarize the previous sections:

- Hot Water circuit can be inhibited between 7am and 10pm;
- Oven Circuit probably need not be inhibited but an output from the 'smart switchboard' could educate household inhabitants on peak, shoulder and off-peak times;
- Air-conditioning to be supported by battery bank during peak hours and further support by battery bank is dependent on battery bank state-of-charge;
- Air-conditioning to be inhibited between 7am and 3pm unless room ambient temperature drops below 18°C or increases above 24°C thus potentially requiring an analog input;
- Lighting should ideally be supported by the battery bank at all times. However, if lighting is required while battery bank is in a charging state, PLC could consider battery bank state of charge and historical discharging trends before switching lighting load between battery or grid-supplied energy;
- Power circuits should ideally be split in two allowing the inhibition of one circuit during whichever hours the customer deems appropriate;
- Battery bank voltage and current measurements to be input to the PLC thus PLC requires a minimum of two analog inputs, possibly more if temperature sensing of various rooms in the house are required and;
- Load shedding requiring AC load current and voltage measurements, thus an additional two analog inputs to allow computation of total load and comparison to a pre-determined load shedding value.

6.4.2 PLC LISTING

A list of potential PLC inputs and outputs based on the information described above are listed in the following table:

INPUT TYPE	INPUT NAME	OUTPUT TYPE	OUTPUT NAME
Analog	Battery Current	Digital	Hot Water Inhibit
Analog	Battery Voltage	Digital	Peak Hours
Analog	Room Temperature 1	Digital	Off-peak Hours
Analog	Room Temperature 2	Digital	Shoulder Hours
Analog	Load Voltage	Digital	Air-Conditioning Inhibit
Analog	Load Current	Digital	Power Circuit 1 Inhibit

Table 6-1 - PLC I/O Listing

This list is by no means exhaustive and can be expanded upon selection of an inverter/converter/charger. Where possible, any potential outputs from these technologies could be incorporated within the program to improve system reliability and functionality.

6.5 PLC IMPACT

While implementation of the theorized PLC switching conditions has yet to occur, it is expected that provision of circuit inhibition within a domestic installation during specific hours of the day will immediately reduce demand on grid or storage supplied energy. In addition to the inhibition, ensuring particular circuits are only operable in shoulder or off-peak hours will also improve the total cost of electricity to the customer.

The restriction of air-conditioning use, which appeared to be the likely cause of the various peaks identified in summer and winter measured loads, will provide provision for further improvement though might be considered unnecessarily strict and could potentially reduce a resident's comfort.

The difficulty in designing such a system is the unpredictable nature of human behavior. This was a factor that was not researched in the early stages of the project, possibly to the detriment of the theorized PLC switching conditions. The possibility of employing some sort of output to the resident notifying them when they are in peak, shoulder or off-peak hours might assist in the education of a resident and thus improve the total cost of electricity, but that is purely speculation.

7 CHAPTER 7

CONCLUSIONS

7.1 CONCLUSIONS OVERVIEW

As previously described within the introduction, there are three main questions this project has attempted to answer. The initial question is a question of economic feasibility and the potential for energy storage in a domestic grid-tied application to provide financial benefit to the resident. In addition to the economic feasibility, consideration towards social and environmental factors were also required.

Secondly, an investigation into the automatic switching of domestic loads was required to consider whether or not it has the potential to improve the feasibility of storage systems or if the costs involved would be unreasonably high.

Finally, the project aimed to review different storage technologies, both current and future, and discuss the desirability of each. As the project was largely tailored towards investigation of battery technologies, it was also necessary to consider if battery storage was the way of the future for domestic energy storage or if an alternative technology might be better suited.

7.2 ECONOMIC FEASIBILITY

The discovery of the economic feasibility of battery storage was firstly largely dependent on the tariff structure employed. Of the four different battery technologies modelled in HOMER, the results clearly favoured the Victorian ToU tariff.

Lithium-Ion and Lead-Acid batteries both experienced smaller required reductions in capital costs on the Victorian ToU tariff than with both of the Queensland Tariffs. Nickel Cadmium and Nickel Iron both experienced the same overall capital cost reduction across each of the tariffs, though Nickel Cadmium could be installed at current tariff prices on all tariff structures while Nickel Iron needed increases in price across all tariffs.

In terms of cost of energy, the Victorian ToU tariff is again favoured by most technologies. Nickel Cadmium was the exception here as it performed best on Queensland's Tariff 12A. Ultimately the assertion is that these battery technologies favour the ToU tariffs rather than the flat-rate or, in general, seasonal tariffs.

To further narrow down a point at which battery storage could become economically feasible, a mid-point between extreme capital cost reduction and extreme tariff increase for each of the technologies was sought. Lead-acid batteries could be installed if capital costs decreased by 25% and the shoulder price increased by 4 c/kWh.

Lithium-ion batteries could be installed if capital costs decreased by 33% and peak, shoulder and off-peak prices all increased by 4 c/kWh. Nickel Cadmium batteries only require a capital cost reduction of 16.67% and no tariff increase. Nickel Iron would need to see capital cost reduction of 25% and a shoulder price increase of 8 c/kWh.

The figures described suggest that installation of battery storage is currently not a feasible or advisable option. The Nickel Cadmium cell appears to be the closest to becoming economically feasible though will still need to realize decreases in capital costs in order to be installed. For those Australian residents without access to a tariff structure similar to Victoria's ToU tariff, the feasibility of installing storage is even further removed. Significant changes in tariff and capital costs would be required.

Finally, the question of the battery's suitability over other storage technologies should be considered. Is the battery favoured over other energy storage technologies from an economic perspective? With the lack of available retail information for some of the other technologies discussed it is difficult to make any type of comparison. Though that in itself might be answer enough. Currently, with no basis for comparison possible, the electrochemical battery is the favoured technology for use in domestic energy storage.

7.3 SOCIAL, HEALTH AND ENVIRONMENTAL FEASIBILITY

While the NiCd cell was, arguably, the winner in terms of economic feasibility, it does lose some ground in terms of social and environmental aspects. Both the NiCd and Lead-acid batteries are constructed with a heavy metal thus presenting a significant hazard when considering production and disposal/handling of the technology.

The NiFe cell actually presented as a particularly favourable technology because of its ability to recycle the electrolyte at around 20 years of life. The ability to do this reduces the need to recycle the entire battery as often resulting in less waste and reduced disposal and handling hazards.

The Li-ion battery has been reported as future high-performer but further research is required before it could be definitively named as a highly feasible technology in terms of environmental impact.

From a more holistic perspective, it was discussed that the increased use of renewable energy sources with storage systems should reduce the reliance on ‘dirty’ fuel sources. The benefits of this being that carbon emissions will reduce and is theorized to result in a reduced number of heart attacks, asthma and other serious diseases.

The greatest concern, most regularly discussed regarding PV, battery and inverter technologies are the hazards created and faced during production, handling and disposal. Future research is again cited as potential factor for mitigation of these concerns but currently none of the named technologies have been highly recommended in terms of environmental feasibility.

Is the electrochemical battery the most suitable technology for energy storage in terms of the environment? Because of the limited retail and technical specifications available for many of the other energy storage technologies d, it is difficult to comment on its usefulness in the future.

The Metal-air and different variations of the flow battery present with exciting potential in terms of the materials used in their construction however it is still moderately early days for these technologies leaving room for further investigation in the reasonably near future.

7.4 THE 'SMART' SWITCHBOARD

Unfortunately the conceptual design was not able to be implemented in PLC logic or tested in a prototype. Having said that, the impact of installing a PLC and automatically disconnecting loads or carrying out load-shedding when usage reaches unnecessarily high limits during peak hours theoretically should provide massive advantages for the resident.

The biggest issue that was discussed was the reduction in comfort levels one might expect if air-conditioning was restricted to particular hours of use, inhibited or lost due to load-shedding. While the economic benefits in terms of grid-supplied energy costs might be enough motivation to pursue automated switching, the level of supposed personal sacrifice required might be enough to dissuade a resident from employing such a scenario.

7.5 FUTURE WORK

The subject of domestic energy storage leaves a lot of room for future work. The first opportunity for further research is continual review of existing storage technologies and analysis of new and emerging storage and battery technologies. As the research has suggested, future research of these technologies should drive costs down and new technologies are being released to the domestic market moderately frequently.

A second potential research area comes from the discovery that higher capacity lead-acid batteries actually performed better than the lower capacity batteries. Because the Li-ion battery is still a relatively new technology, it could be expected that higher capacity batteries will become available in the future. If this does occur future work could include a review of different battery technologies at different capacities as the results reported in this work might actually be able to be improved upon.

In terms of an environmental consideration, a whole life review of the various energy storage technologies will help deliver a more thorough understanding of which type of energy storage should be considered the environmental front-runner. A lot of the research viewed during this project had limited environmental content so a paper discussing purely environmental aspects would be useful.

The smart switchboard theory presented in this project is rudimentary and could be expanded on and tested to see if the presented logic is possible and how it would be received by the general public. In addition to the smart switchboard, further investigation into smart appliances or the possibility of implementing a dynamic tariff structure in Australia would also be of great interest.

Finally, the idea of the smart switchboard could be modified somewhat to include the smarter converters that were discussed earlier. While initial research seemed to suggest capital costs were rather high, it would be interesting if the smarts of the newer converter could be used in a modelling program like HOMER.

The suggestions here are by no means the limit of future work possibilities associated with this project, they are simply a reflection of the limitations discovered during this project work.

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APPENDICES

APPENDIX 1 - PROJECT SPECIFICATION

University of Southern Queensland
FACULTY OF ENGINEERING AND SURVEYING
ENG4111/4112 Research Project
PROJECT SPECIFICATION
FOR: SHARON GRAHAM
TOPIC: INVESTIGATING BATTERY COST TO BECOME COMPETETIVE WITH GRID TARIFFS
SUPERVISOR: MR. ANDREAS HELWIG
PROJECT AIM: To identify a scenario within which domestic customers could install a battery storage system in conjunction with a photo-voltaic installation resulting in reduced reliance on grid supplied energy and potential financial benefits for the customer.
PROGRAMME: (Issue A, 26 November 2014)

1. Research current battery technologies and identify factors including battery specifications, price, expected lifetime, lifetime limiting factors, maintenance requirements and maintenance costs. Also research current inverter and battery charger technologies available to the Australian domestic market.
2. Research current tariffs available to domestic customers in Australia from a random selection of providers.
3. Research current battery storage options available to the Australian domestic market and investigate efficiency and capability of current domestic Photovoltaic installations.
4. Gather data from an Australian household to establish expected load and trends over a week long period in summer and winter seasons. Model the real domestic data, in real time using the HOMER Energy application. Use modelling and research to devise ideal battery storage requirements and calculate overall expected financial commitment associated with an installation.
5. Investigate possible switching scenarios such that the domestic load is almost completely supported by the PV and storage system reducing the reliance on the grid.
6. Design and test desirable switching scenarios in a PLC-based environment.
7. Carry out a safety risk audit for each potential battery storage system and investigate the potential impact on customer's insurance.

As time permits:

8. Build prototype Domestic Switchboard or model.
9. Investigate alternative means of electrical energy storage.

APPENDIX 2 - PROJECT RISK ASSESSMENT

Risk register and Analysis - Domestic Dwelling										
Step 1	Step 2	Step 2a	Step 3			Step 4				
Hazard Identification	**The Risk - What can happen?**	**Existing Controls - What controls are already in place?**	**Risk Assessment**			**Additional Controls - What controls will help mitigation of the risk?**	**Risk assessment with additional controls**			**Controls Implemented?**
			Consequence	**Possibility**	**Risk Level**		**Consequence**	**Possibility**	**Risk Level**	**Yes/No**
Live testing in domestic switchboard	Electrocution leading to serious personal injury/death	Situational awareness, training, electrical licence	Catastrophic	Possible	High	Use of PPE specifically electrical insulating gloves, long sleeve/pant clothing, safety glasses, safety boots.	Catastrophic	Unlikely	Moderate	Yes
Working outside in high temps and direct sunlight	Heat stress/heat stroke leading to serious personal injury/death	Situational awareness, water available	Catastrophic	Possible	High	Maintain hydration, limit time outside, use of insect repellent, use of sunscreen, use of PPE - long sleeve/pant, hat	Catastrophic	Unlikely	Moderate	Yes
Working outside in storms	Electrocution or burns from exposure to switchboard or lightning	Option to complete activity in suitable weather instead	Catastrophic	Unlikely	Moderate	No additional controls required as work will not proceed in stormy weather	Catastrophic	Unlikely	Moderate	Yes
Use of hand tools near electrical hazard	Electrocution when accessing switchboard	Barriers in place at switchboard, situational awareness, training	Catastrophic	Unlikely	Moderate	Use of PPE until hazard is removed (power is isolated using main switch and solar isolator)	Catastrophic	Rare	Moderate	Yes
Assessment Date	29-Dec-14									
Assessor	Sharon Graham									

Table 0-1 - Risk assessment chart for domestic dwelling

Risk register and Analysis - Office										
Step 1	Step 2	Step 2a	Step 3			Step 4				
Hazard Identification	**The Risk - What can happen?**	**Existing Controls - What controls are already in place?**	**Risk Assessment**			**Additional Controls - What controls will help mitigation of the risk?**	**Risk assessment with additional controls**			**Controls Implemented?**
			Consequence	**Possibility**	**Risk Level**		**Consequence**	**Possibility**	**Risk Level**	**Yes/No**
Working with computers	Personal injury due to repetitive movements, glare, eye strain and poor posture	Awareness of ergonomics and eye health	Moderate	Possible	High	Stretching, ergonomics refresher training	Moderate	Unlikely	Moderate	Yes
Working with computers	Personal injury/death, burns or fire due to electrical hazards including cords	RCDs installed	Catastrophic	Possible	High	Electrical cords now located behind furniture removing trip hazard	Catastrophic	Rare	Low	Yes
Assessment Date	11-Nov-14									
Assessor	Sharon Graham									

Table 0-2 - Risk assessment chart for office

Risk register and Analysis - Workshop											
Step 1	Step 2	Step 2a	Step 3			Step 4					
Hazard Identification	**The Risk - What can happen?**	**Existing Controls - What controls are already in place?**	**Risk Assessment**			**Additional Controls - What controls will help mitigation of the risk?**	**Risk assessment with additional controls**			**Controls Implemented?**
			Consequence	**Possibility**	**Risk Level**		**Consequence**	**Possibility**	**Risk Level**	**Yes/No**
Live testing of electrical equipment	Electrocution leading to serious personal injury/death	Situational awareness, training, electrical licence	Catastrophic	Possible	High	Use of PPE specifically electrical insulating gloves, long sleeve/pant clothing, safety glasses, safety boots.	Catastrophic	Unlikely	Moderate	Yes
Use of hand and power tools	Electrocution when using power tools. Nicks and cuts while using hand tools.	Training	Catastrophic	Unlikely	Moderate	Testing and tagging of electrical tools. Use of PPE when using power and hand tools.	Catastrophic	Unlikely	Moderate	Yes
Manual handling tasks involved in equipment handling	Strain or sprain involved in lifting of heavy equipment.	Awareness of legislation regarding safe lifting weights - specifically only lifting what is possible	Major	Possible	High	Use of lifting tools such as pallet jacks, block and tackle and trolleys if equipment requires.	Major	Unlikely	Moderate	Yes
Slips/trips/falls while working in workshop	Personal injury, strain or sprain while moving about in workshop.	Workshop is open plan for ease of movement	Major	Possible	High	Workshop was cleaned, objects on floor presenting hazard have been removed.	Major	Unlikely	Moderate	Yes
Assessment Date	2-May-15									
Assessor	Sharon Graham									

Table 0-3 - Risk assessment chart for workshop

Eg 1. Enter Consequence

Eg 2. Enter Probability

	Consequence				
Probability	**Insignificant** No Injury 0-$5K	**Minor** First Aid $5K-$50K	**Moderate** Med Treatment $50K-$100K	**Major** Serious Injuries $100K-$250K	**Catastrophic** Death More than $250K
Almost Certain 1 in 2	M	H	E	E	E
Likely 1 in 100	M	H	H	E	E
Possible 1 in 1000	L	M	H	H	H
Unlikely 1 in 10 000	L	L	M	M	M
Rare 1 in 1 000 000	L	L	L	L	L

Eg 3. Find Action

Recommended Action Guide
E =Extreme Risk – Task ***MUST NOT*** proceed
H=High Risk – Special Procedures Required (See USQSafe)
M=Moderate Risk – Risk Management Plan/Work Method Statement Required
L=Low Risk – Use Routine Procedures

Figure 0-1 - Risk assessment matrix USQ (2015)

APPENDIX 3 - ENERGY STORAGE CHARACTERISTICS

Table 3
Comparison of large scale energy storage systems.

Energy storage technology	Advantages	Disadvantages	Power applications	Energy applications
Lead–acid batteries	Low power density and capital cost	Limited life cycle when deeply discharged	Fully capable and suitable	Feasible but not quite practical or economical
Lithium-ion batteries	High power and energy densities, high efficiency	High production cost, requires special charging circuit	Fully capable and suitable	Feasible but not quite practical or economical
Sodium–sulfur batteries	High power and energy densities, high efficiency	Production cost, safety concerns (addressed in design)	Fully capable and suitable	Fully capable and suitable
Flow batteries	High energy density, independent power and energy ratings	Low capacity	Suitable for this application	Fully capable and suitable
Flywheels	High efficiency and power density	Low energy density	Fully capable and suitable	Feasible but not quite practical or economical
Pumped hydro-energy storage systems	High capacity	Special site requirement	Not feasible or economical	Fully capable and suitable
Compressed air energy storage systems	High capacity, low cost	Special site requirement, needs gas fuel	Not feasible or economical	Fully capable and suitable

Table 0-4 – Energy storage advantages/disadvantages Poullikkas (2013)

Table 10
Technical comparisons of energy storage technology.

Technology	System energy density (Wh/kg)	Efficiency of recovery (%)	Development	Capital cost (€/kW)	Advantages	Disadvantages	Suitability for		
							Energy management	Power quality	Transport
Super capacitors	0.1–5	85–98	Developing	200–1000	Long life cycle, high efficiency	Low energy density, toxic and corrosive compound	√ √	√ √ √	√ √ √
Nickel batteries	20–120	60–91	Available	200–750	High power and energy density, good efficiency	NiCd highly toxic, NiZn, NiMH and NA-NiCL$_2$ require recycle	√ √	√ √ √	√ √ √
Lithium batteries	80–150	90–100	Available	150–250	High power and energy density, high efficiency	High cost Lithium oxide & salt require recycling, Polymer solvents and carbon must be made inert	√	√ √ √	√ √ √
Lead acid battery	24–45	60–95	Available	50–150	Low capital cost	Lead require recycling	√ √	√ √ √	√ √ √
Zinc Bromine flow battery	37	75	Early phase of commercialization	900 €/kWh	High capacity	Low energy density	√ √ √	√ √	x
Vanadium flow batteries	–	85	Early phase of commercialization	1280	High capacity	Low energy density	√ √ √	√ √	x
Metal air battery	110–420	~50	Developing	–	High energy density, low cost environmentally benign	Poor electrical recharge ability, short recharge lifetime	√ √ √	√	√
Sodium sulfur battery	150–240	> 86	Available	170	High energy density, high efficiency	High production cost, Na requires recycling	√ √ √	√ √	√
PHES	–	75–85	Available	140–680 m for 1000 MW	High capacity, relatively low cost per unit capacity	Disturbs local wildlife and water level	√ √ √	√ √	x
CAES (Alabama plant)	–	80	Available	400	High capacity, relatively low cost per unit capacity	Problematic in obtaining sites for use	√ √ √	√ √	×
Flywheel	30–100	90	Available	3000–10,000	High power	Low energy density	√ √	√ √ √	√
SMES	–	97–98	Developed up to 10 MW, potential to increase to 2000 MW	350	High power	Health impact for large scale sites	√	√ √ √	×
H_2 fuel cell	–	25–58	Research/ developing/ marketed	6000–30,000	Can stored long term, Range of cell types for different applications	Expensive catalyst or processing often required	√ √ √	√ √ √	√ √ √
H_2 for vehicle	–	–	Developing		–	–	√	√	√ √ √

Table 0-5 - Energy storage advantages/disadvantages Mahlia et al. (2014)

Table 4
Technical characteristics of large scale energy storage systems.

Technology	Power rating (MW)	Discharge duration	Response time	Efficiency (%)	Lifetime
Lead–acid batteries	< 50	1 min–8 h	< 1/4 cycle	85	3–12 years
Nickel–cadmium batteries	< 50	1 min–8 h	N/A	60–70	15–20 years
Sodium–sulfur batteries	< 350	< 8 h	N/A	75–86	5 years
Vanadium redox flow batteries	< 3	< 10 h	N/A	70–85	10 years
Zinc–bromine flow batteries	< 1	< 4 h	< 1/4 cycle	75	2000 cycles
Flywheels	< 1.65	3–120 s	< 1 cycle	90	20 years
Pumped hydro energy storage systems	100–4000	4–12 h	s–min	70–85	30–50 years
Compressed air energy storage systems	100–300	6–20 h	s–min	64	30 years

Table 0-6 - Energy storage system technical characteristics Poullikkas (2013)

Table B1
Technical characteristics of electrical energy storage (EES) systems, based on the review of the references in Table 2.

EES technology	Power range (MW)	Discharge time (ms–h)	Overall efficiency	Power density (W/kg)	Energy density (Wh/kg)	Storage durability	Self-discharge (per day)	Lifetime (yr)	Life cycles (cycles)
PHS	10–5000	1–24 h	0.70–0.82		0.5–1.5	h–months	Negligible	50–60	20000–50000
CAES (underground)	5–400	1–24 h	0.7–0.89		30–60	h–months	Small	20–40	> 13,000
CAES (aboveground)	3–15	2–4 h	0.70–0.90			h–days	Small	20–40	> 13,000
Flywheel	Up to 0.25	ms–15 m	0.93–0.95	1000	5–100	s–min	100%	15–20	20,000–100,000
Lead–acid	Up to 20	s–h	0.70–0.90	75–300	30–50	min–days	0.1–0.3%	5–15	2000–4500
NaS	0.05–8	s–h	0.75–0.90	150–230	150–250	s–h	20%	10–15	2500–4500
$NaNiCl_2$ (ZEBRA)	50	2–5 h	0.86–0.88	150–200	100–140	s–h	15%	15	2500–3000
Ni–Cd	Up to 40	s–h	0.60–0.73	50–1000	15–300	min–days	0.2–0.6%	10–20	2000–2500
Li-ion	up to 0.01	m–h	0.85–0.95	50–2000	150–350	min–days	0.1–0.3%	5–15	1500–4500
VRFB	0.03–3	s–10 h	0.65–0.85	166	10–35	h–months	Small	5–10	10,000–13,000
Zn–Br	0.05–2	s–10 h	0.60–0.70	45	30–85	h–months	Small	5–10	5000–10,000
Fe–Cr	1–100	4–8 h	0.72–0.75					10–15	> 10,000
PSB	15	s–10 h	0.65–0.85			h–months	Small	10–15	2000–2500
SMES	0.1–10	ms–8 s	0.95–0.98	500-2000	0.5–5	min–h	10–15%	15–20	> 100,000
Capacitors	Up to 0.05	ms–60 m	0.60–0.65	100,000	0.05–5	s–h	40%	5–8	50,000
SCES	Up to 0.3	ms–60 m	0.85–0.95	800–23,500	2.5–50	s–h	20–40%	10–20	> 100,000
Hydrogen (fuel cell)	0.3–50	s–24 h	0.33–0.42	500	100–10,000	h–months	Negligible	15–20	20,000

Table 0-7 - Technical characteristics of EES Zakeri and Syri (2015)

Table 10
Technical characteristics of electrical energy storage technologies.

Technology	Energy density (W h/L)	Power density (W/L)	Specific energy (W h/kg)	Specific power (W/kg)	Power rating (MW)	Rated energy capacity (MW h)
PHS	0.5–1.5 [4], 1–2 [26]	0.5–1.5 [4], ~1 [26],	0.5–1.5 [4]	–	100–5000 [4], 30 [34], < 4000 [114]	500–8000 [4], 180 Okinawa PHS[34,77]
Large-scale CAES	3–6 [4], 2–6 [26]	0.5–2 [4], ~1 [26]	30–60 [4]	–	Up to 300 [4], 110 & 290 [39], 1000 [70]	~ < 1000[10], 580 & 2860 [38,42]
Overground small CAES	Higher than large-scale CAES	Higher than large-scale CAES	140 at 300 bar [174]	–	0.003–3 [51] Potential ~10 [175]	~0.01[10], ~0.002–0.0083 [51]
Flywheel	20–80 [4,26,123]	1000–2000 [4], ~5000 [26]	10–30 [4], 5–100 [57], 5–80 [176]	400–1500 [4]	<0.25 [4], 3.6 [60], 0.1–20 [13,177]	0.0052 [60], 0.75 [70], up to 5 [177]
Lead-acid	50–80 [4], 50–90 [70]	10–400 [4]	30–50 [4], 25–50[178]	75–300 [4], 250 [70], 180 [57]	0–20 [4], 0–40 [14], 0.05–10 [179]	0.001–40 [179] More than 0.0005[180]
Li-ion	200–500 [4], 200–400 [26], 150 [70]	1500–10,000 [26]	75–200 [4], 90 [70], 120–200 [181]	150–315 [4], 300 [70], 500–2000 [57]	0–0.1 [4], 1–100 [73], 0.005–50 [182]	0.024 [79], ~0.004–10 [182]
NaS	150–250 [4], 150–300 [26]	~140–180 [26]	150–240 [4], 100 [183], 174 [184]	150–230 [4], 90–230 [9], 115 [13],	<8 [4], <34 [14]	0.4–244.8 [81], 0.4 [185]
NiCd	60–150 [4], 15–80 [26], 80 [70]	80–600 [26]	50–75 [4], 50 [70], 45–80 [71]	150–300 [4], 160 [13], 150 [70],	0–40 [4], 27 [88], 40 [186]	6.75 [57,88]
VRB	16–33 [4], 25–35 [19]	~ < 2 [26]	10–30 [4]	166 [187]	~0.03–3 [4], 2 [188] possible 50 [5]	<60 [13], 2 [88], 3.6 [189]
ZnBr	30–60 [4], ~55–65 [26]	~ < 25 [26]	30–50 [4], 80 [190], 75 [191]	100 [190], 45 [191]	0.05–2 [4], 1–10 [73]	0.1–3 [13], 4 [14], 0.05 & 0.5 [192]
PSB	~20–30 [123]	~ < 2 [26]	~15–30 [123]	–	1–15 [4], 1 [193], 0.004 [194]	Potential up to 120 [193], 0.06 [194]
Capacitor	2–10 [4], ~0.05 [124]	100,000+ [4],	0.05–5 [4], <~0.05 [121,124]	~100,000 [4], >~3000–10^7[124]	0–0.05 [4]	–
Super-capacitor	10–30 [4], ~10–30 [123]	100,000+ [4],	2.5–15 [4], ~0.05–15 [124]	500–5000 [4], ~10,000 [124]	0–0.3 [4], ~0.3+[26] ~0.001–0.1 [70]	0.0005 [70]
SMES	0.2–2.5 [4], ~6 [26]	1000–4000 [4], ~2500 [26]	0.5–5 [4], 10–75 [195]	500–2000 [4]	0.1–10 [4,14], ~1–10 [70]	0.0008 [70], 0.015 [138], 0.001 [196]
Solar fuel	500–10,000 [4]	–	800–100,000 [4]	–	0–10 [4], 6 and developing 20 [197]	–
Hydrogen Fuel cell	500–3000 [4]	500+ [4]	800–10,000 [4], ~150–1500 [124]	500+ [4], ~5–800 [124]	<50 [4], <10 [26], 58.8 [199]	0.312 [198], developing 39 [200]
TES	80–120, 120–200, 200–500 [4]	–	80–120, 80–200 [4], 150–250 [4]	10–30 [4]	0.1–300 [4], 15 [165], 10 [201]	–
Liquid air Storage	4–6 times than CAES at 200 bar [202]	–	214 [174]	–	10–200 [8], 0.3 [168]	2.5 [168]

Table 0-8 - Technical characteristics of EES Luo et al. (2015)

Table 11
Additional technical characteristics of electrical energy storage technologies.

Technology	Daily self-discharge (%)	Lifetime (years)	Cycling times (cycles)	Discharge efficiency (%)	Cycle efficiency (%)	Response time
PHS	Very small [4,192]	40–60 [4], 40+[69], 30+[175]	10,000–30,000 [14]	~87 [114]	70–85 [4], 70–80 [175] 87 [33], 75–85 [203]	Minutes [114], not rapid discharge [203]
Large-scale CAES	Small [4], Almost zero [192]	20–40 [4], 30 [70], 20+[69,203]	8000–12,000 [14]	~70–79 [114]	42,54 [4,42] AA-CAES 70 [43,203]	Minutes [114]
Over-ground small CAES	Very small [51]	23+[51]	Test 30,000stop/starts [51]	~75–90 [51]	–	Seconds–minutes [114]
Flywheel	100 [4], ≥20% per hour [57]	~15 [4], 15+[69], 20 [114]	20,000+ [4], 21,000+[69]	90–93 [114]	~90–95 [4], 90 & 95 [70]	<1 cycle [114], seconds [203]
Lead–acid	0.1–0.3 [4], <0.1 [57], 0.2 [69]	5–15 [4,57], 13 [69]	500–1000 [4], 200–1800 [13]	85 [114]	70–80[4], 63–90 [14], 75–80 [204]	<1/4 cycle [114] milli-seconds
Li-ion	0.1–0.3 [4], 1 & 5 [13]	5– 15 [4], 14–16 [205]	1000–10,000 [4], up to 20,000 [9]	85 [114]	~90–97 [4], 75–90 [73]	Milliseconds, <1/4 cycle [14]
NaS	Almost zero [13,185]	10–15 [4], 15 [69], 12–20 [192]	2500 [4], 3000[206] 2500–4500 [14]	85 [114]	~75–90 [4], 75 [206], 75–85 [204]	–
NiCd	0.2–0.6 [4],0.3 [57], 0.03–0.6 [14]	10–20 [4], 3–20 [13], 15–20 [57]	2000–2500 [4], 3500 [179]	85 [114]	~60–70 [4], 60–83 [14]	Milliseconds, <1/4 cycle [14]
VRB	Small [4], very low [13]	5–10 [4], 20 [193]	12,000+ [4], 13,342 [69]	~75–82 [207]	75–85 [4,62], 65–75 [73]	<1/4 cycle [14]
ZnBr	Small [4,100]	5–10 [4], 10 [69], 8–10 [205]	2000+ [4], 1500 [69]	~60–70 [208]	~65–75 [4], 66–80 [14], 66 [114]	<1/4cycle [114]
PSB	Small [4] Almost zero [193]	10–15 [4], 15 [209]	–	–	~60–75 [4], 60–75 [209]	20 ms [116]
Capacitor	40 [4], ~50 in about 15 minutes [122]	~5 [4], ~1–10 [122]	50,000+ [4], 5000 (100% DoD) [210]	~75–90 [127]	~60–70 [4], 70+[210]	Milliseconds, <1/4 cycle [14]
Super-capacitor	20–40 [4], 5 [10], 10–20 [211]	10–30 [4], 10–12 [66]	100,000+ [4], 50,000+[69]	95 [114] Up to ~98 [127]	~90–97 [4], 84–95 [66]	Milliseconds, ¼ cycle [114]
SMES	10–15 [4]	20+[4], 30 [114]	100,000+4], 20,000+ [14]	95 [114]	~95–97 [4], 95–98 [66], 95 [70]	Milliseconds, <1/4 cycle [114]
Solar fuel	Almost zero [4]	–	–	–	~20–30 [4], planned eff.>54 [197]	–
Hydrogen Fuel cell	Almost zero [4,192]	5–15 [4], 20 [119] 20+[212]	1000+ [4], 20,000+[212]	59 [114]	~20–50 [4], 32 [106], 45–66 [213]	Seconds, <1/4 cycle [114]
TES	0.05–1 [4]	10–20 [4], 5–15[4], 30 [203]	–	–	~30–60 [4]	Not for rapid response [203]
Liquid air Storage	Small [169,214]	25+[214]	–	–	55–80+[214]	Minutes [215]

Table 0-9 – Additional technical characteristics of EES Luo et al. (2015)

Table 12
Other technical and economical characteristics of electrical energy storage technologies.

Technology	Suitable storage duration	Discharge time at power rating	Power capital cost ($/kW)	Energy capital cost ($/kW h)	Operating and maintenance cost	Maturity
PHS	Hours–months [4], long-term [27]	1–24 h+[4], 6–10 h [73] 10 h [175]	2500–4300 [73], 2000–4000 [175]	5–100 [4], 10–12 [114]	0.004 $/kW h [70], ~3 $/kW/year [72]	Mature
Large-scale CAES	Hours–months [4], long-term [27]	1–24 h+ [4], 8–20 h [73]	400–800 [4], 800–1000 [175]	2–50 [4], 2–120 [8], 2 [70]	0.003 $/kW h [70], 19–25 $/kW/year [72]	CAES commercialized, AA-CAES developing
Over-ground small CAES	Hours–months, long-term [27]	30 s–40 min [51], 3 h [216]	517 [114], 1300–1550 [216]	1MVA from £296 k [51], 200–250 [216]	Very low [51]	Early commercialized
Flywheel	Seconds–minutes [4] short-term(<1 h)[27]	Up to 8 s [4], 15 s–15 min [175]	250–350 [4]	1000–5000 [4], 1000–14,000 [8]	~0.004 $/kW h[70], ~20 $/kW/year [72]	Early commercialized
Lead–acid	Minutes–days [4], short-to-med. term	Seconds–hours [4], up to 10 h [14]	300–600 [4], 200–300 [114], 400 [206]	200–400 [4], 50–100 [57], 330 [206]	~50 $/kW/year [72]	Mature
Li-ion	Minutes–days [4], short-to-med. term	Minutes–hours [4], ~1–8 h [209]	1200–4000[4], 900–1300[57], 1590[73]	600–2500 [4], 2770–3800 [73]	–	Demonstration
NaS	Long term[82]	Seconds–hours [4], ~1 h [209]	1000–3000 [4], 350–3000 [8]	300–500 [4], 350 [206], 450 [217]	~80 $/kW/year [72]	Commercialized
NiCd	Minutes–days [4], Short and long term	Seconds–hours [4], ~1–8 h [209]	500–1500 [4]	800–1500 [4], 400–2400 [57]	~20 $/kW/year [72]	Commercialized
VRB	Hours–months [4], Long term [27]	Seconds–24 h+ [4], 2–12 h [106]	600–1500 [4]	150–1000 [4], 600 [217]	~70 $/kW/year [72]	Demo/early commercialized
ZnBr	Hours–months [4] long term [27]	Seconds–10 h+ [4], ~10 h [209]	700–2500 [4], 400 [87], 200 [114]	150–1000 [4], 500 [71]	–	Demonstration
PSB	Hours–months [4] long term [27]	Seconds–10 h+ [4], ~10 h [209]	700–2500 [4]	150–1000 [4], 450 [217]	–	Developing
Capacitor	Seconds–hours [4], ~5 h [210]	Milliseconds–1 h [4]	200–400 [4],	500–1000 [4],	13 $/kW/year [72], <0.05 $/kW h [210]	Commercialized
Super-capacitor	Seconds–hours [4] short-term(<1 h)[27]	Milliseconds–1 h [4], 1 min[209], 10 s[216]	100–300 [4], 250–450 [216]	300–2000 [4]	0.005 $/kW h [70], ~6 $/kW-year [114]	Developing/demo.
SMES	Minutes–hours [4] short-term (<1 h)[27]	Milliseconds–8 s [4], up to 30 min [209]	200–300 [4], 300 [114], 380–489[216]	1000–10,000 [4], 500–72,000 [114]	0.001 $/kW h [70], 18.5 $/kW/year [72]	Demo/early commercialized
Solar fuel	Hours–months [4]	1–24 h+ [4]	–	–	–	Developing
Hydrogen Fuel cell	Hours–months [4]	Seconds–24 h+ [4]	500 [114], 1500–3000 [154]	15 [114], 2–15€/kW h [204]	0.0019–0.0153 $/kW [154]	Developing/demo.
TES	Minutes–days [4], minutes–months [4]	1–8 h [4], 1–24 h+ [4], 4–13 h [203]	200–300[4], 250 [203], 100–400[203]	20–50 [4], 30–60 [4], 3–30 [4]	–	Demo/early commercialized
Liquid air Storage	Long-term [214]	Several hours [168,214]	900–1900 [214]	260–530 [214]	–	Developing/demo.

Table 0-10 - Other characteristics of EES Luo et al. (2015)

APPENDIX 4 - EXAMPLE BATTERY MAINTENANCE SCHEDULES

VENTED LEAD-ACID

Maintenance Action	Frequency
Measure float voltage at the battery terminals	Monthly
Check general appearance and cleanness of the battery area	Monthly
Check charger output current and voltage	Monthly
Check electrolyte levels	Monthly
Check for cracks in cells or leakage of electrolyte	Monthly
Check for corrosion at terminals or connections	Monthly
Check condition of ventilation equipment	Monthly
Check voltage, electrolyte density and temperature of the pilot cells	Monthly
Battery float charging current or pilot cell specific gravity	Monthly
Unintentional battery grounds	Monthly
Check of all battery monitoring systems (if installed)	Monthly
Check electrolyte density of each cell	Quarterly
Check temperature of electrolyte in pilot cells or temperature of a representative sample of 10% of the battery cells	Quarterly
Check voltage of each cell	Quarterly
Inspection of each cell checking for distortion or lateral expansion on the plates, irregular colour or appearance of the plates.	Yearly
Tightness of bolted connections to manufacturer's recommended torque, check of terminal connection, resistance.	Yearly
Check integrity of battery stand or enclosure	Yearly
Performance test	Yearly (in solar applications)

Table 0-11 - Vented Lead-acid maintenance 'IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications' 2011); StandardsAustralia (1992b)

SEALED LEAD-ACID

Maintenance Action	Frequency
Measure float voltage at the battery terminals	Quarterly
Check charger output current and voltage	Quarterly
Ambient temperature	Quarterly
Check condition of ventilation and monitoring equipment	Quarterly
Visual individual cell/unit condition check to include: Terminal, connection, rack or cabinet corrosion; General appearance and cleanliness of the battery area; Cover integrity and check for creaks of leakage of electrolyte.	Quarterly
Excessive jar/cover distortion	Quarterly
DC float current (per string)	Quarterly
Cell or unit internal ohmic values	Quarterly
Temperature of the negative terminal of each cell/unit or battery	Quarterly
Check voltage of each cell/unit	Quarterly
Cell to cell and terminal connection detail resistance of entire battery	Yearly
AC ripple current and/or voltage imposed on the battery	Yearly
Check integrity of battery stand or enclosure	Yearly
Performance test	Yearly (in solar power applications)

Table 0-12 - Sealed Lead-acid maintenance IEEE (2006, 2007); StandardsAustralia (1992a)

APPENDIX 5 - NREL PV CELL EFFICIENCIES CHART

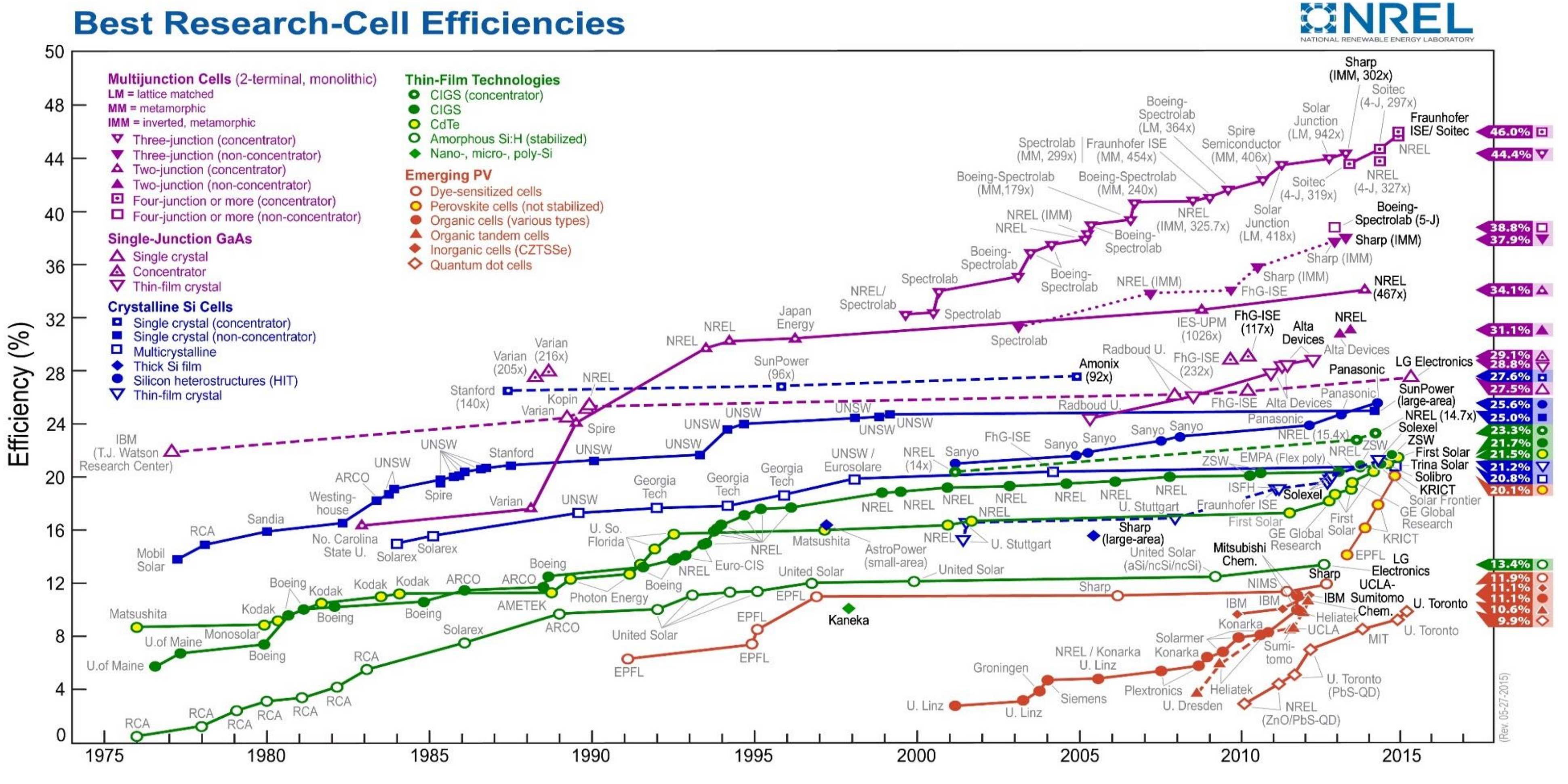


Figure 0-2 - Best Research-Cell Efficiencies, NREL (2015)

APPENDIX 6 - PV PANEL MAINTENANCE SCHEDULE

TABLE C1

EXAMPLE MAINTENANCE SCHEDULE

Subsystem or component	Maintenance action*	Frequency†	Remarks
Site	Verify the following: (a) Cleanliness (accumulation of debris around or under the array). (b) No shading of the array.	Quarterly	Clean site as required Trim trees, if required
PV modules	Verify cleanliness (accumulation of dust or fungus on array).	Quarterly	Clean if necessary
	Check for visual defects including— (a) fractures; (b) browning; (c) moisture penetration; and (d) frame corrosion.	1 year	PV modules with visual defects should be further inspected for performance and safety to determine the need for replacement
	Inspect junction boxes for— (a) tightness of connections; (b) water accumulation/build-up; (c) integrity of lid seals; (d) integrity of cable entrance, glands and conduit sealing; and (e) integrity of clamping devices. Verify bypass diodes.	1 year	Replace defective seals, clamps and bypass diodes
Wiring installation	Verify mechanical integrity of conduits.	5 year	Replace damaged conduit
	Verify insulation integrity of cables installed without conduit.	5 year	Replace damaged cable
	Check junction boxes for— (a) tightness of connections; (b) water accumulation/build-up; (c) integrity of lid seals; (d) integrity of cable entrance and/or conduit sealing; and (e) integrity of clamping devices. Verify the following: (i) Blocking diodes. (ii) Surge arresters for degradation.	1 year	Replace defective seals, clamps blocking diodes and surge arresters
	Check connections for— (a) tightness; and (b) corrosion.	1 year	

(*continued*)

TABLE C1 *(continued)*

Subsystem or component	Maintenance action*	Frequency†	Remarks
Electrical characteristics	Measure open circuit voltages	1 year	
	Measure short circuit currents	1 year	
Protective devices	Verify integrity of fuses and fuse holders	1 year	
	Verify operation of CBs and RCDs	1 year	
	Verify operation of earth fault protection system	1 year	
	Verify operation of solar array isolation device	1 year	
Mounting structures	Verify tightness and integrity of bolts and other fastening devices	1 year	
	Inspect for corrosion	5 year	

* This list of items is not exhaustive but provides examples only.

† Values for frequency are examples. Frequency will be site dependent.

Figure 0-3 - AS/NZS 5033:2014, StandardsAustralia (2014)

APPENDIX 7 - INITIAL BATTERY COST DATA

Manufacturer	Battery Type	Battery Voltage (V)	Ah rating (Ah)	Strings required	Number of batteries per string	Cost ($)	Total Cost ($)	Notes
Century Yuasa	SSR1025	4	1025	0.748981627	12	1324	15888	Price quoted by CY, CY battery capacity at 100hr rate
Century Yuasa	SSR1320	4	1320	0.581595582	12	1487	17844	Price quoted by CY, CY battery capacity at 100hr rate
Century Yuasa	SSR450	6	450	1.706013707	8	1067	17072	Price quoted by CY, CY battery capacity at 100hr rate
Century Yuasa	SSR535	6	535	1.4349648	8	1174	18784	Price quoted by CY, CY battery capacity at 100hr rate
Century Yuasa	SSR700	6	700	1.096723097	8	1346	21536	Price quoted by CY, CY battery capacity at 100hr rate
Century Yuasa	SSR875	6	875	0.877378478	8	1538	12304	Price quoted by CY, CY battery capacity at 100hr rate
Century Yuasa	GEL135	12	135	5.686712357	4	796	19104	Price quoted by CY, CY battery capacity at 100hr rate
Century Yuasa	GEL200	12	200	3.838530841	4	1056	16896	Price quoted by CY, CY battery capacity at 100hr rate
Hoppecke	OPzV 620	2	620	1.238235755	24	672	32256	Price from www.lockstarenergy.com.au
Hoppecke	OPzV 1000	2	1000	0.767706168	24	972	23328	Price from www.lockstarenergy.com.au
Hoppecke	OPzV 1250	2	1250	0.614164935	24	1057	25368	Price from www.lockstarenergy.com.au
Hoppecke	OPzV 1700	2	1700	0.451591864	1	1535	1535	Price from www.lockstarenergy.com.au
Smartbattery	SB200	12.8	200	3.838530841	4	1535	24560	Price from www.lockstarenergy.com.au

Table 0-13

APPENDIX 8 - HOMER SCREENSHOTS

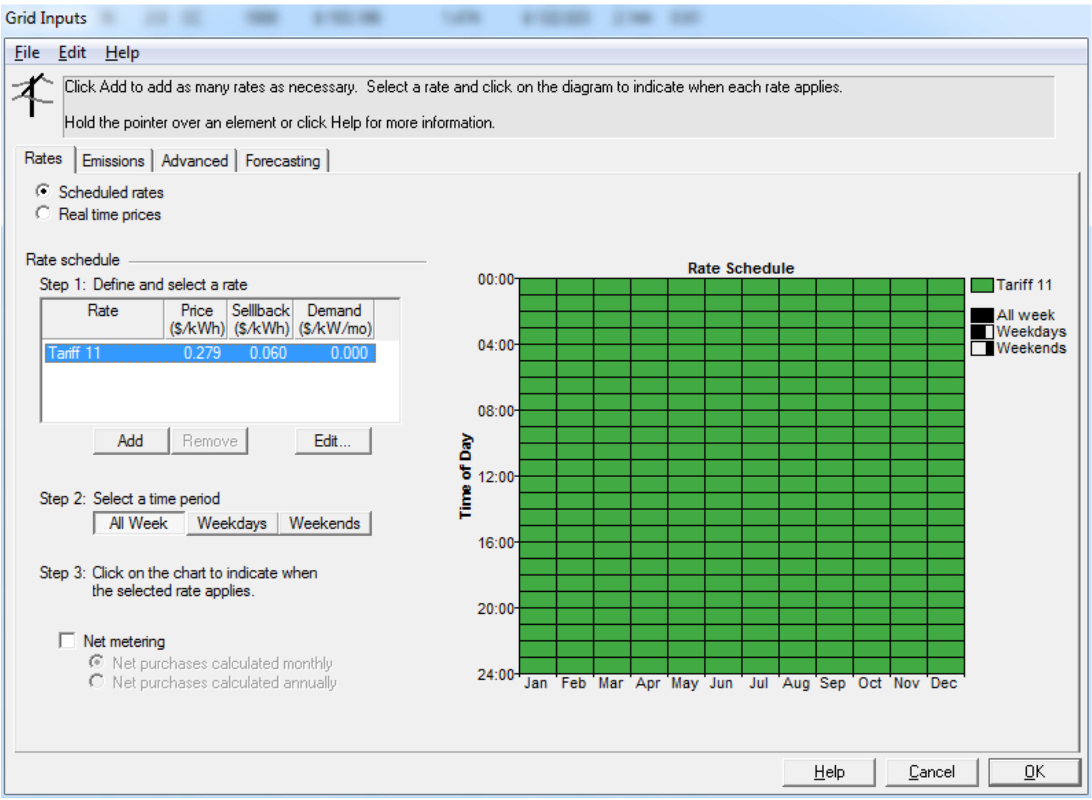


Figure 0-4 - Tariff 11 in Homer

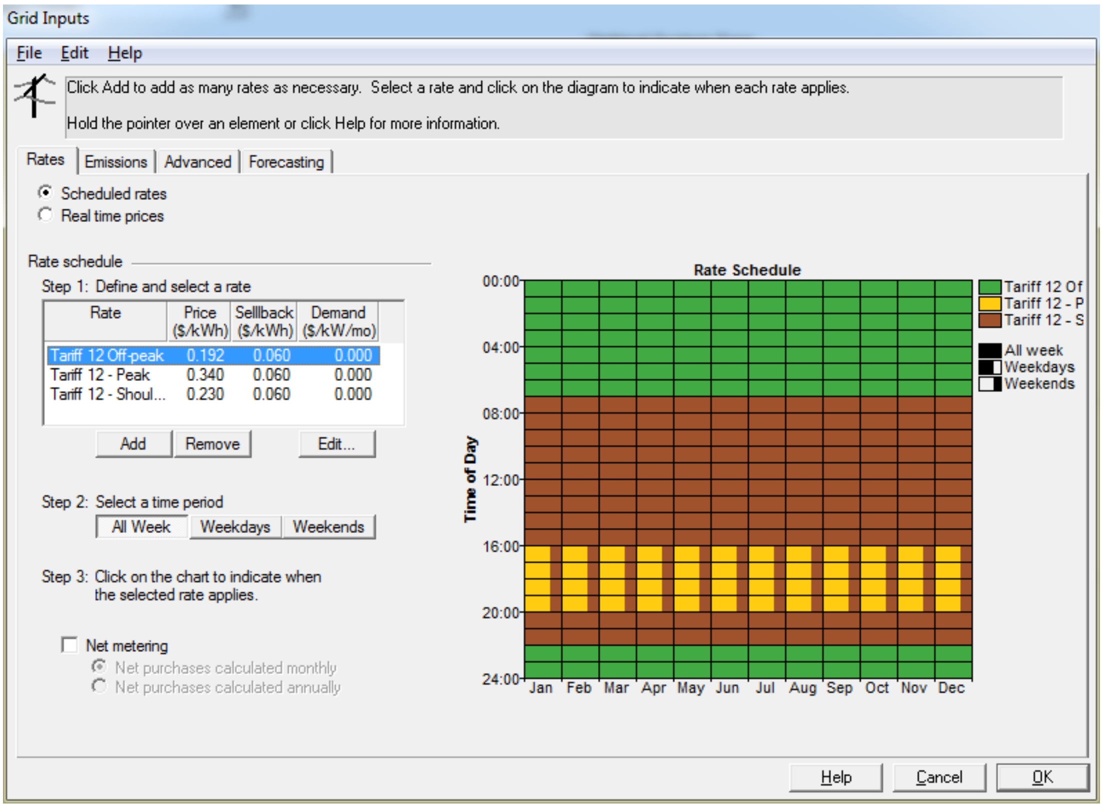


Figure 0-5 - Tariff 12 in Homer

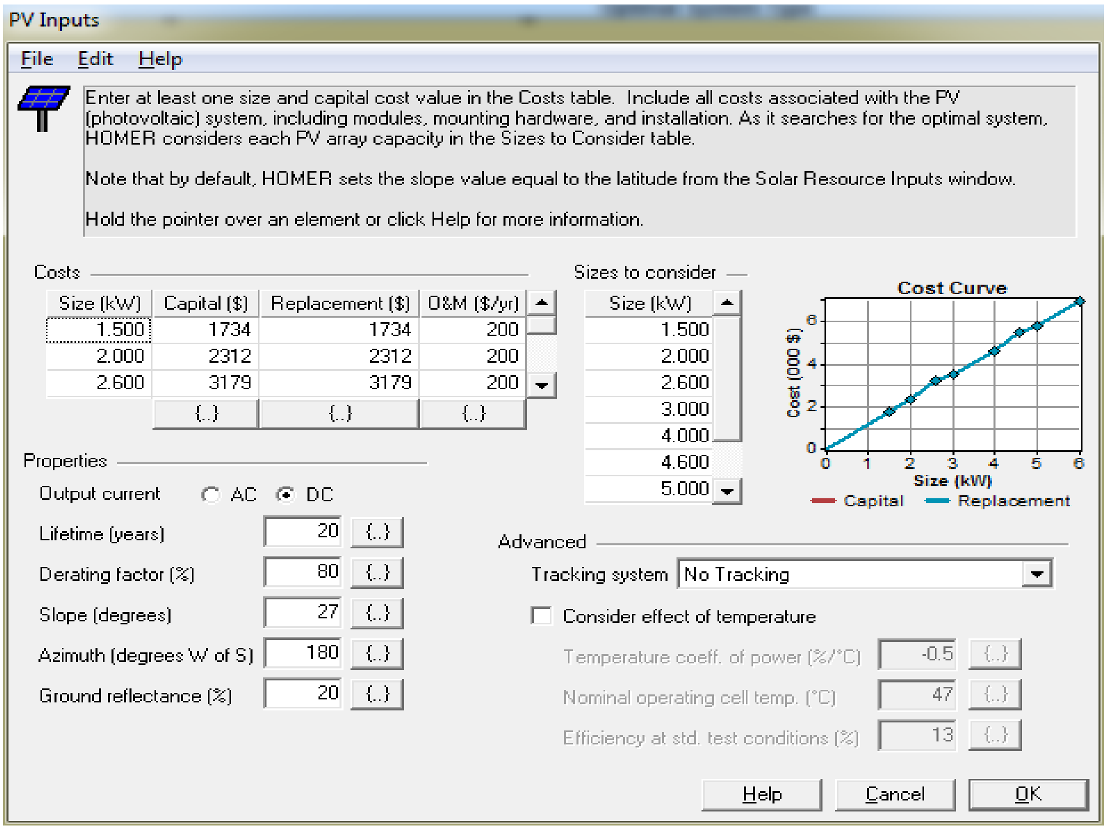


Figure 0-6 - Homer PV input

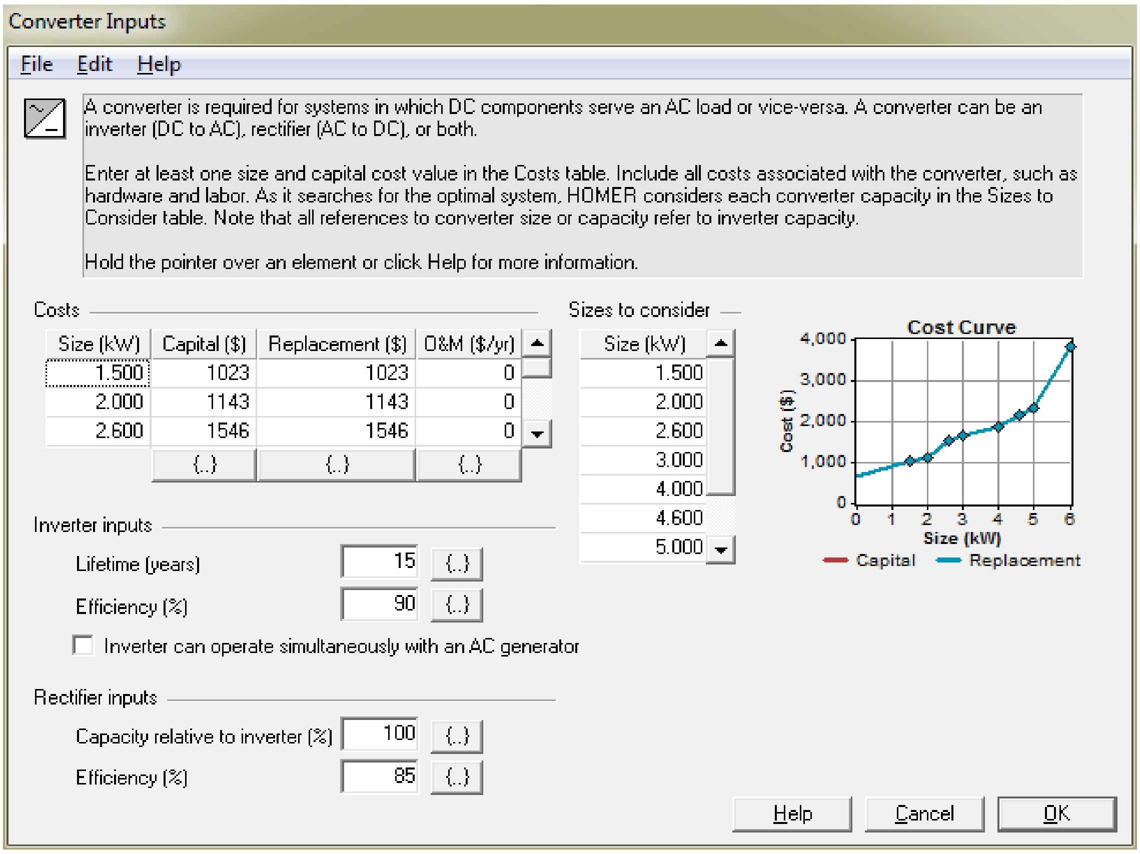


Figure 0-7 - Homer Converter input

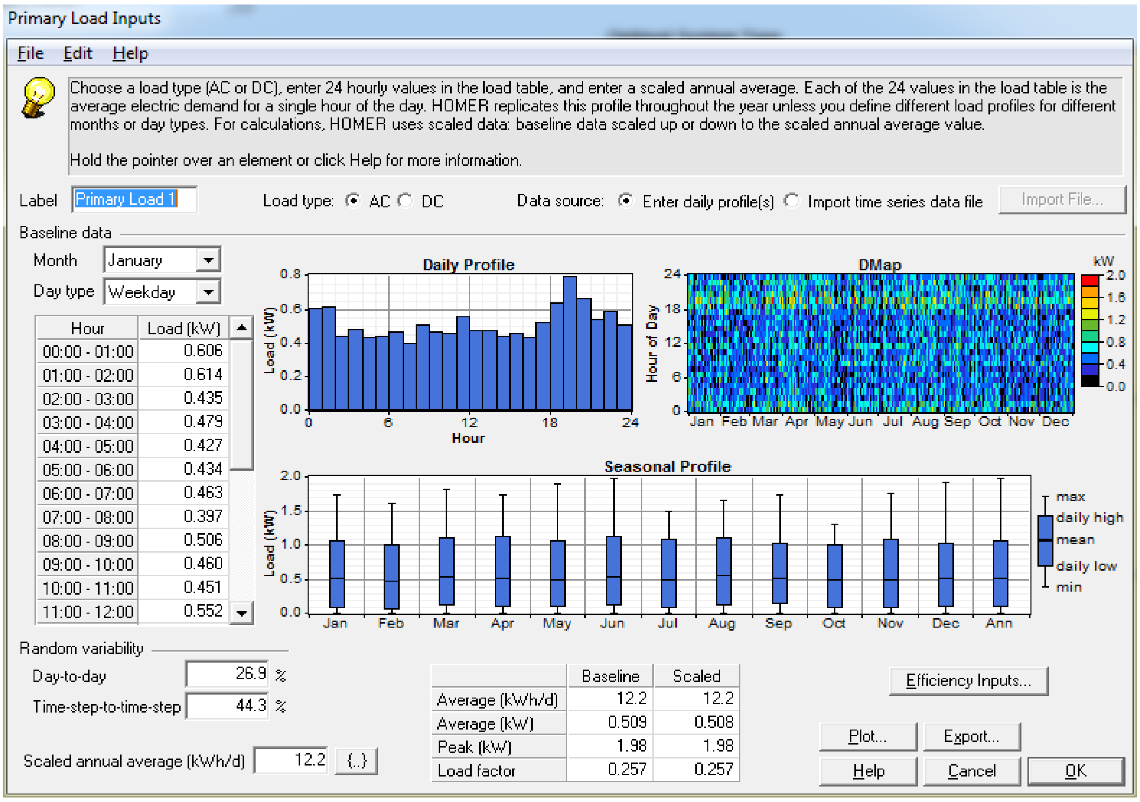


Figure 0-8 - Homer primary load input

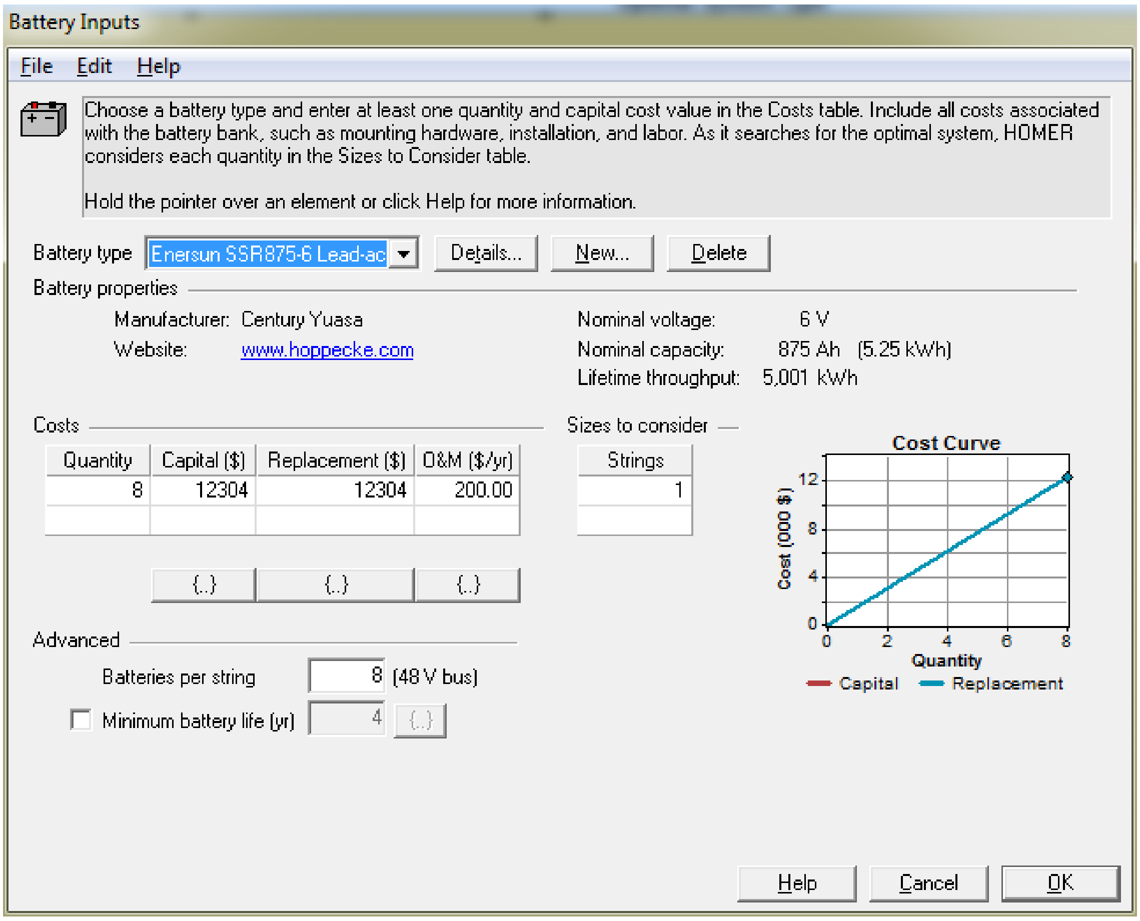
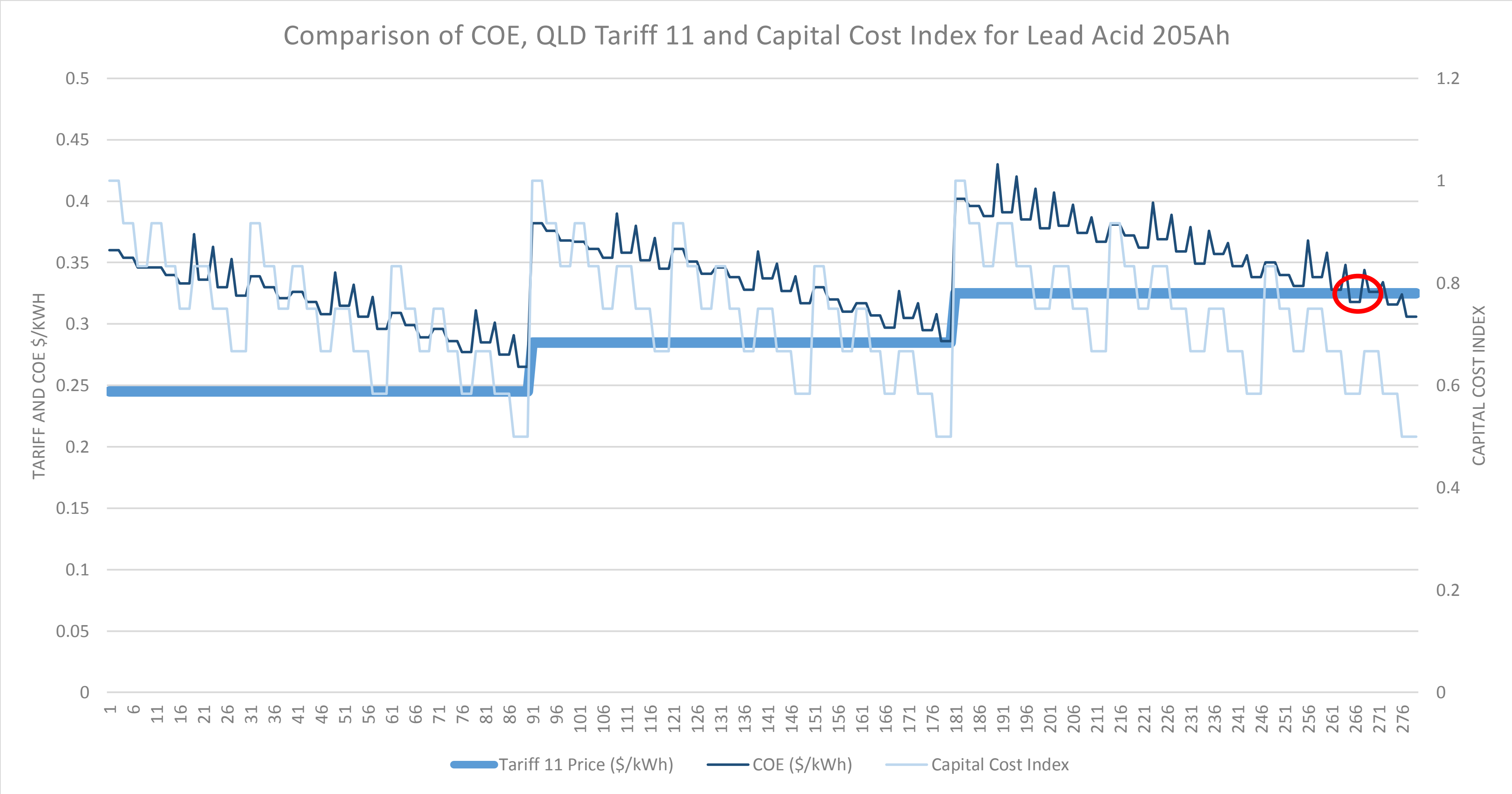
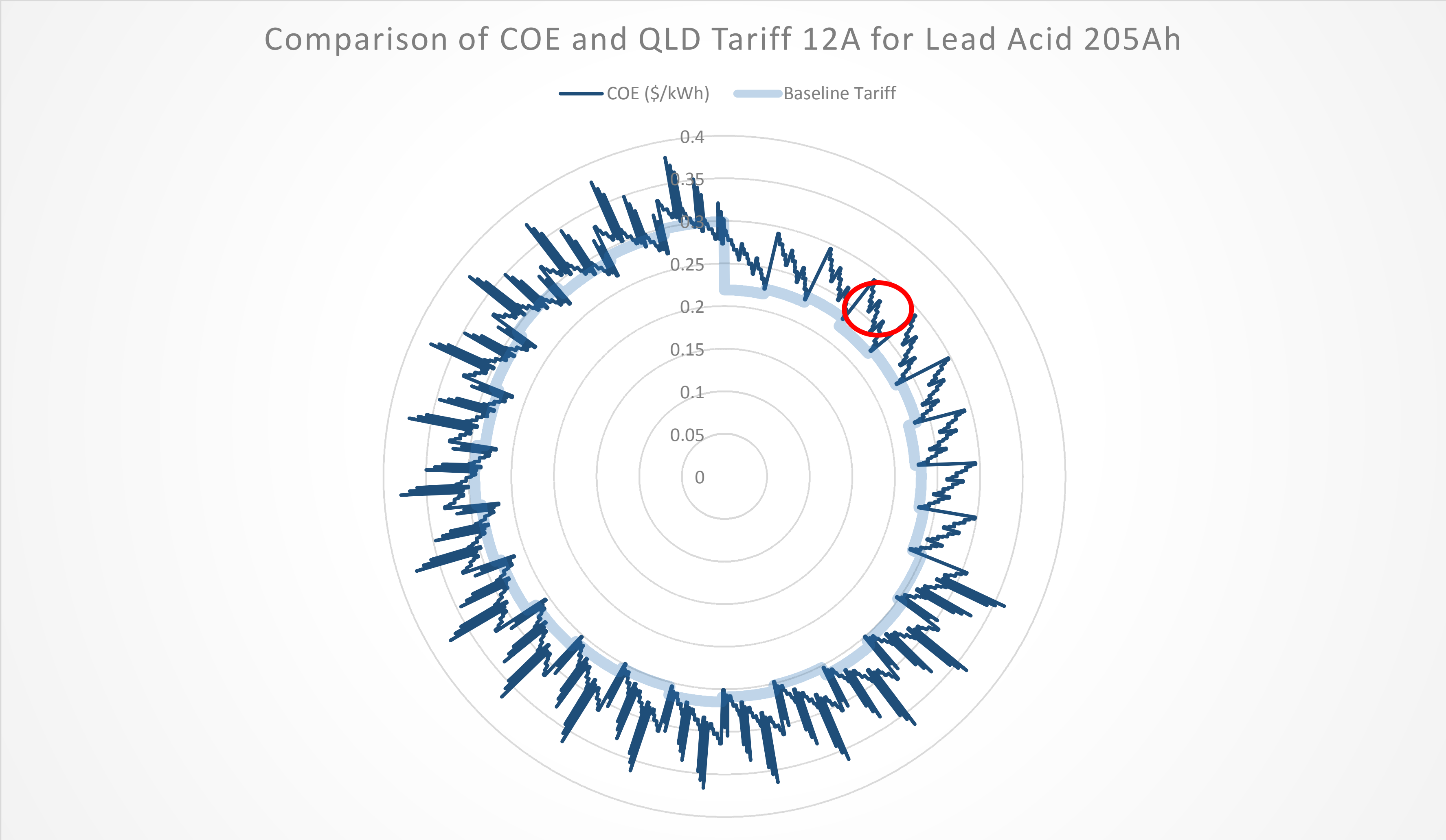
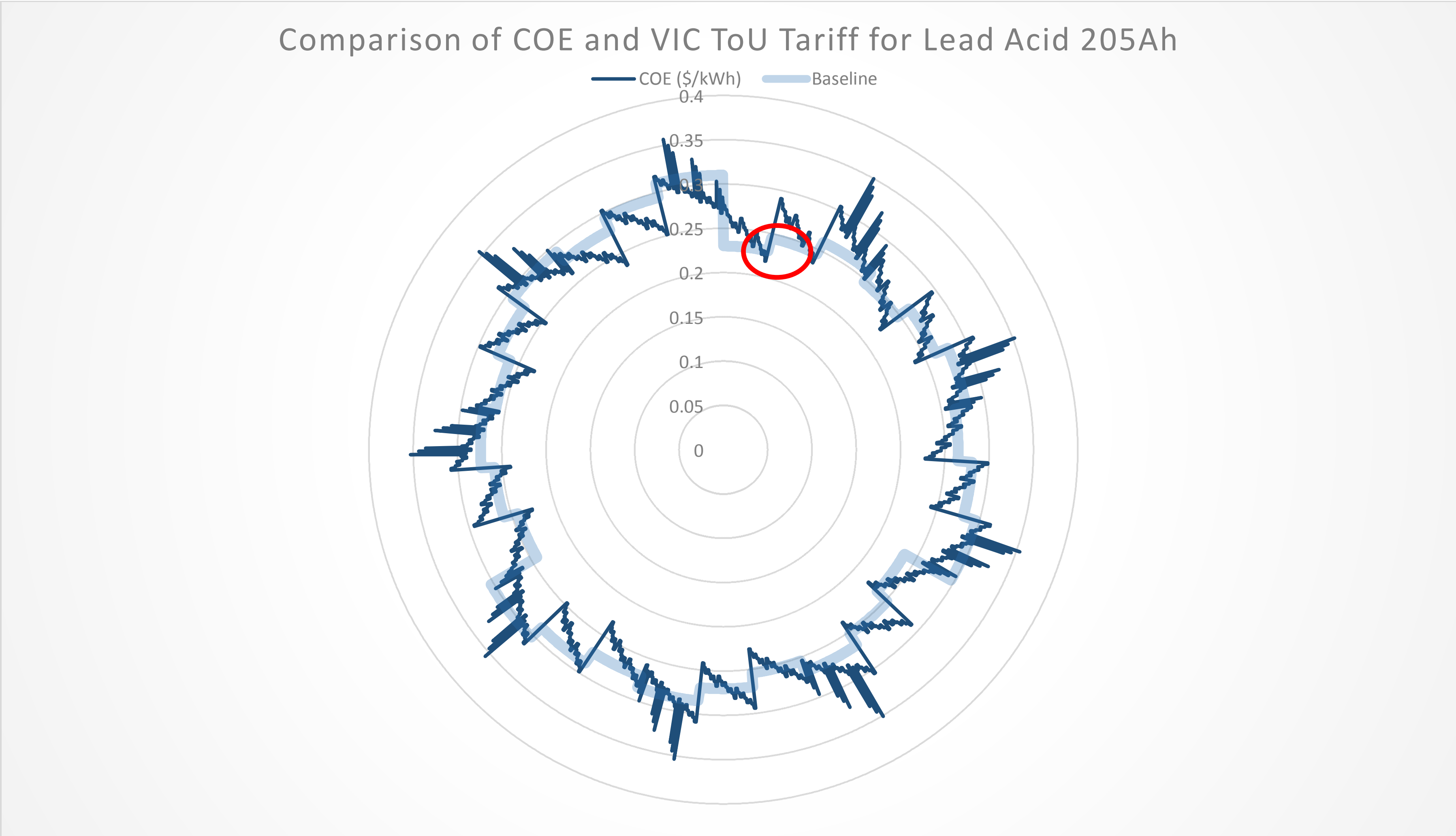


Figure 0-9 - Homer battery input

APPENDIX 9 - HOMER ANALYSIS GRAPHS – LEAD ACID

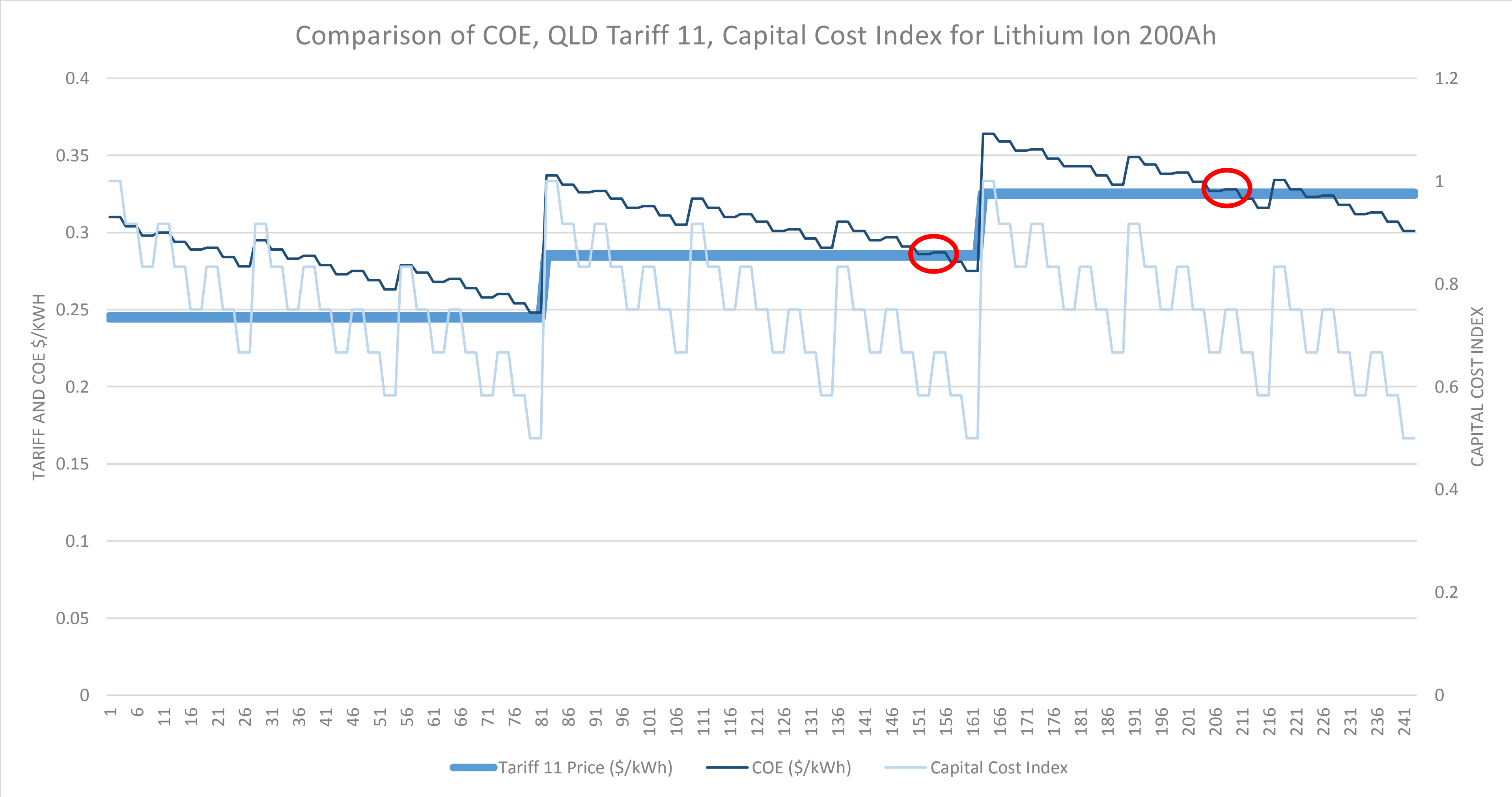


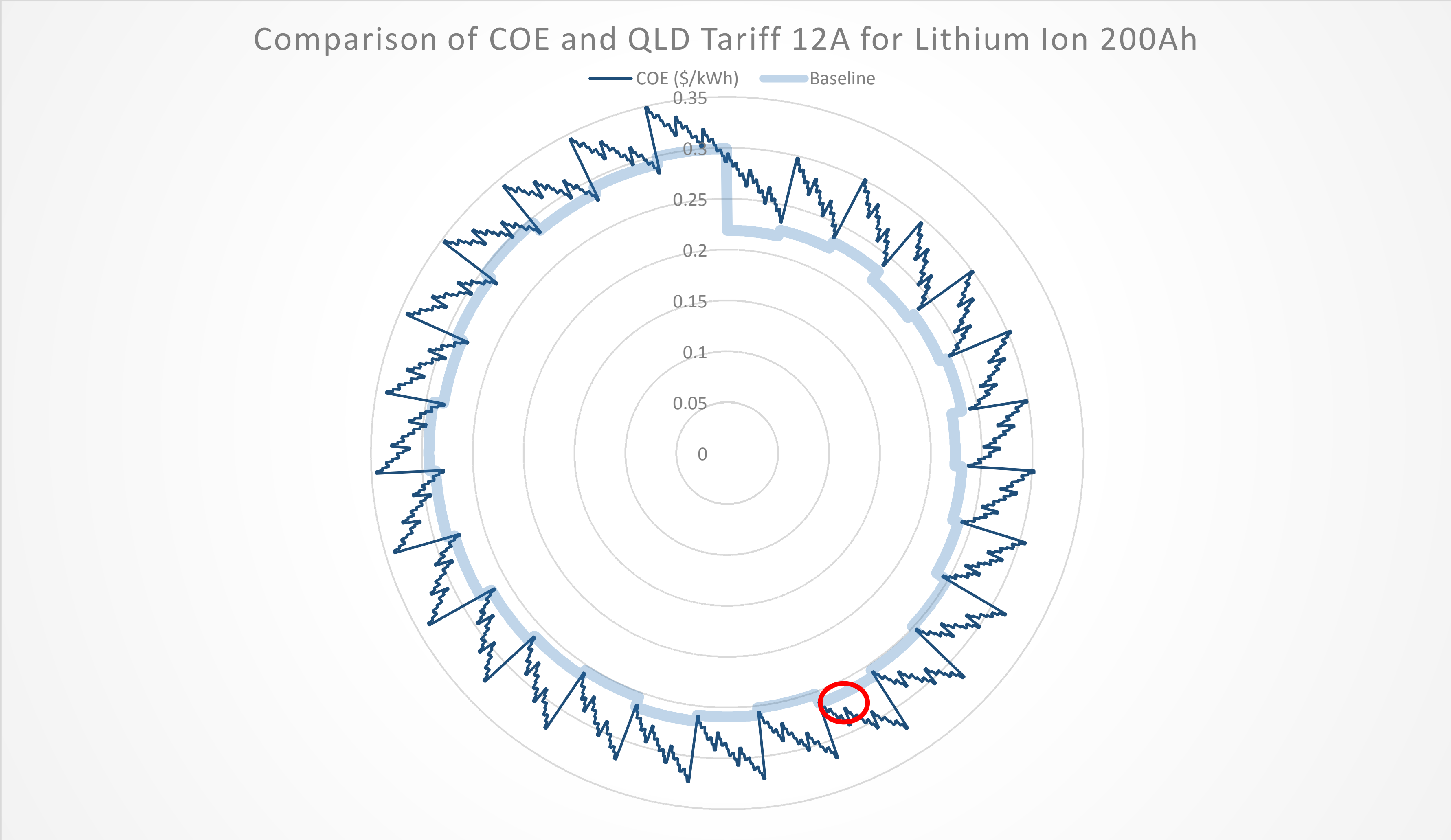

Comparison of COE and QLD Tariff 12A for Lead Acid 205Ah
COE ($/kWh)
Baseline Tariff
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0

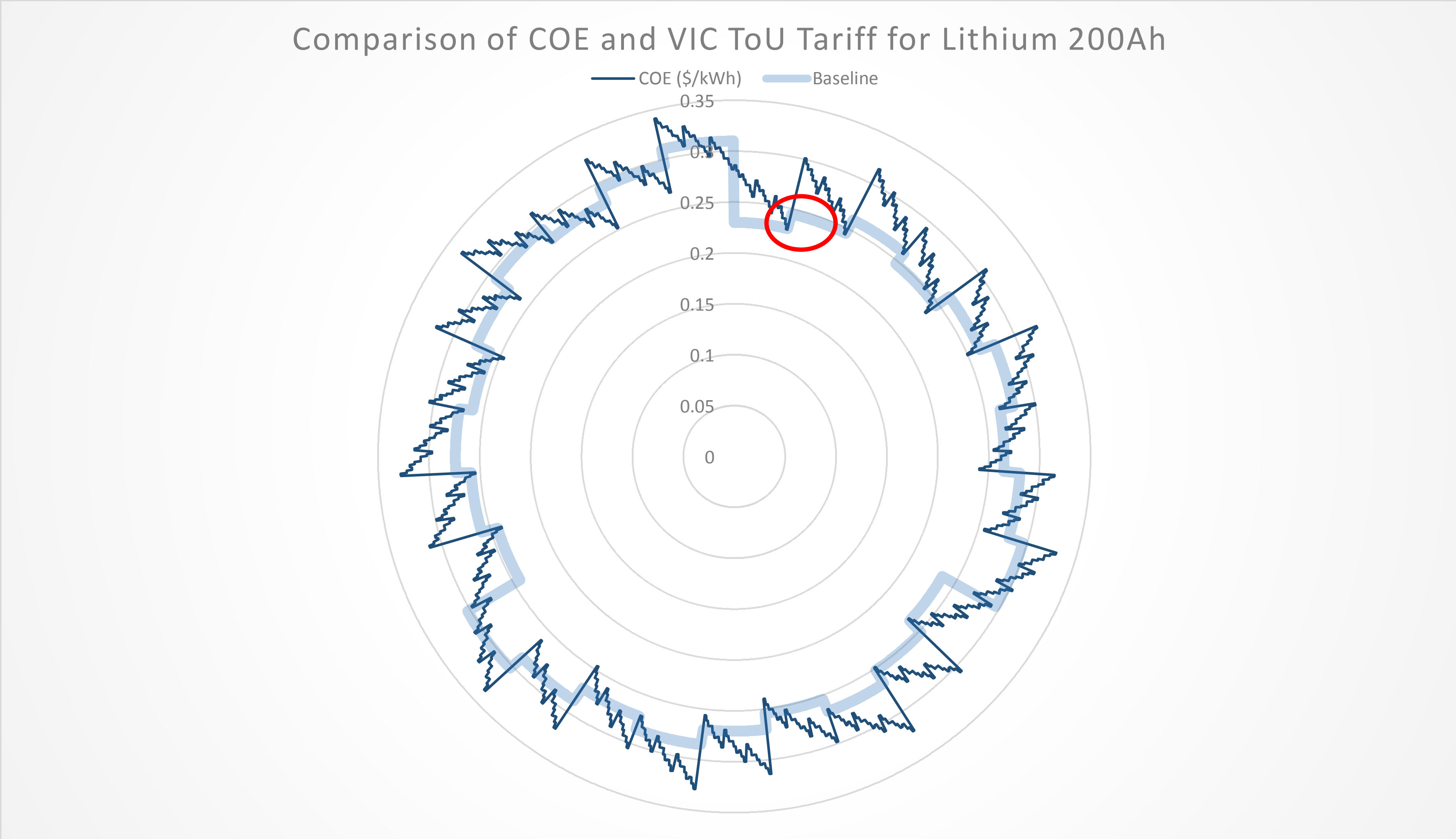


Comparison of COE and VIC ToU Tariff for Lead Acid 205Ah
COE ($/kWh)
Baseline
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0

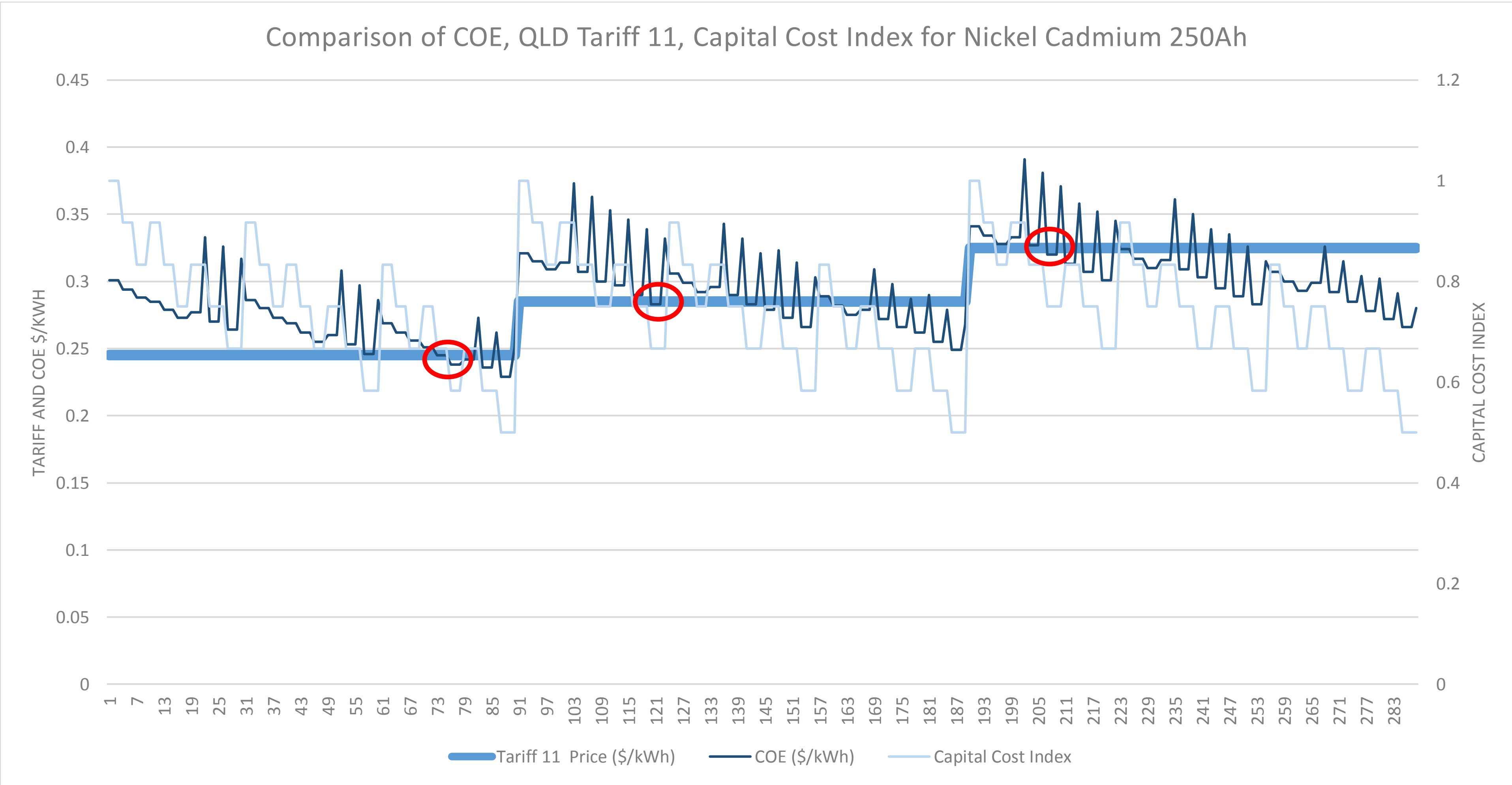
APPENDIX 10 - HOMER ANALYSIS GRAPHS - LITHIUM ION

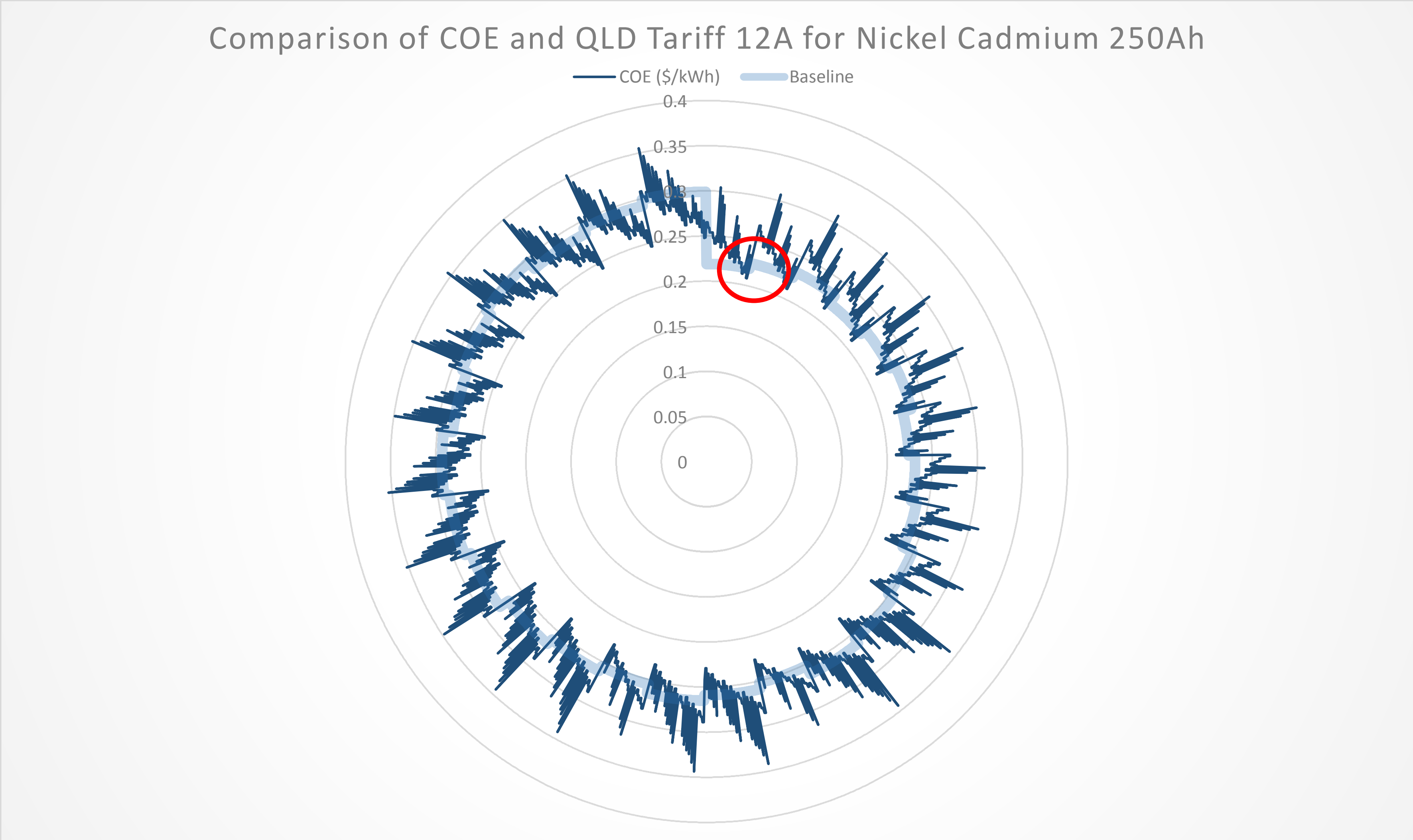


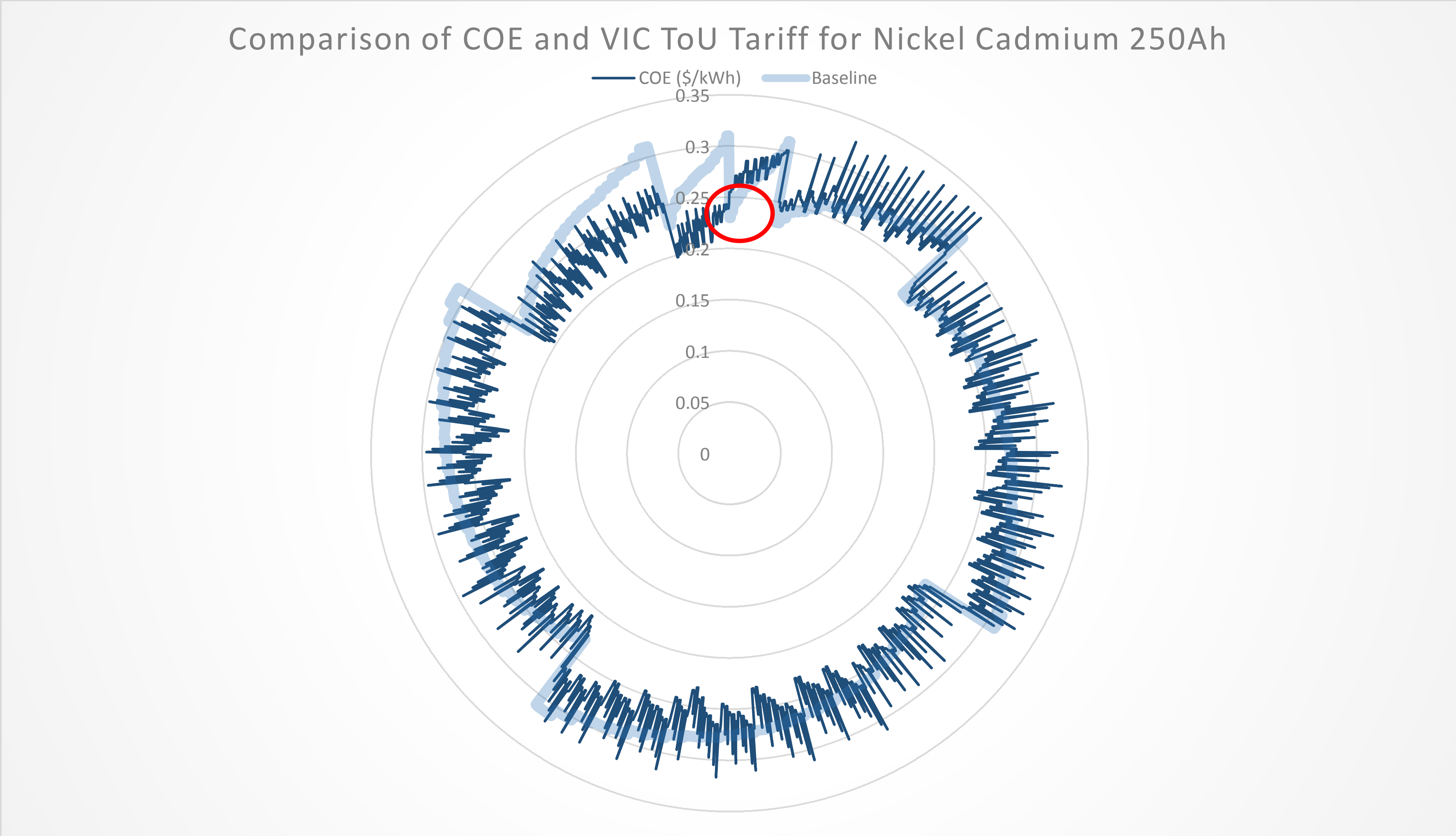

Comparison of COE and QLD Tariff 12A for Lithium Ion 200Ah
COE ($/kWh)
Baseline
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0


Comparison of COE and VIC ToU Tariff for Lithium 200Ah
COE ($/kWh)
Baseline
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0

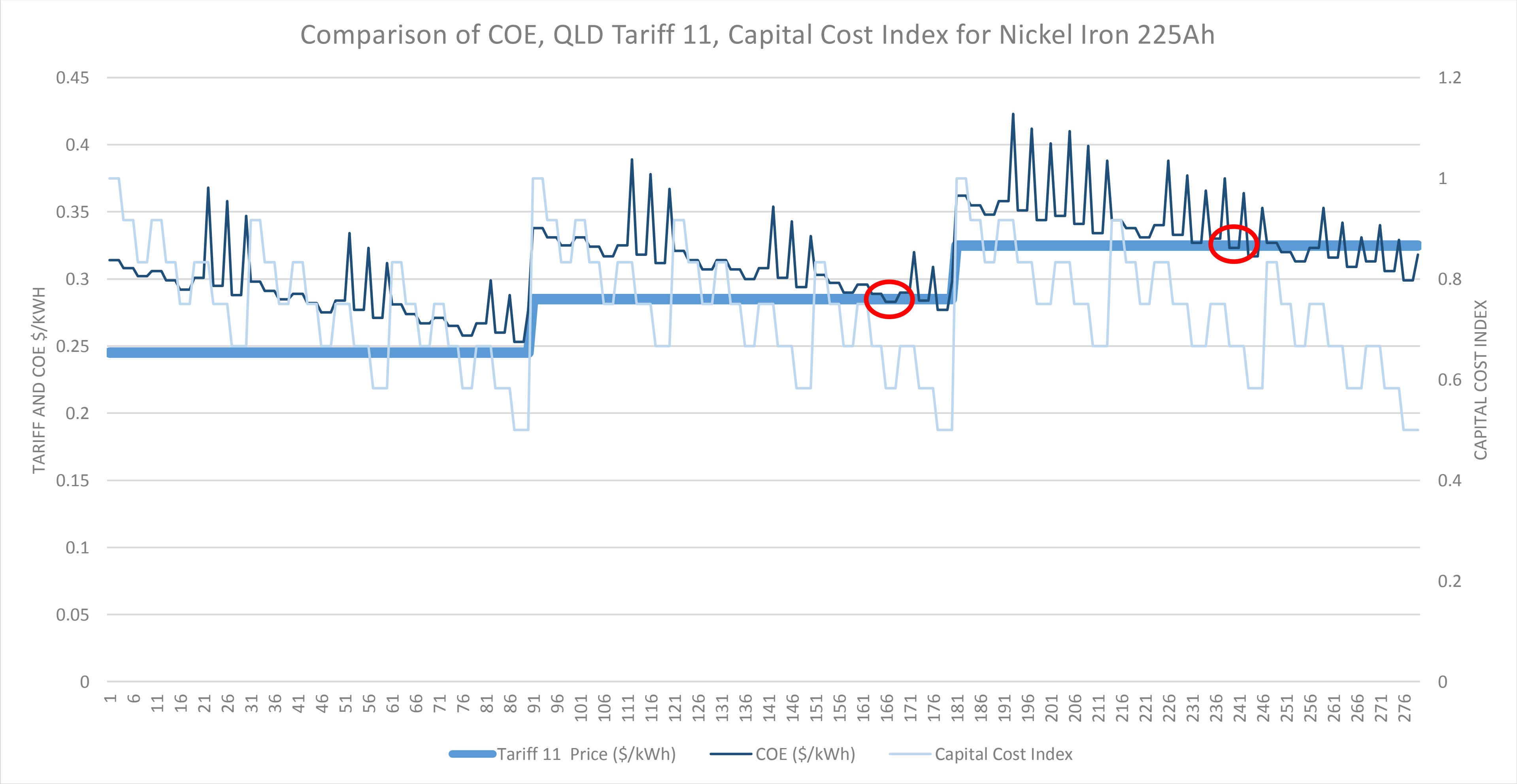
APPENDIX 11 - HOMER ANALYSIS GRAPHS - NICKEL CADMIUM

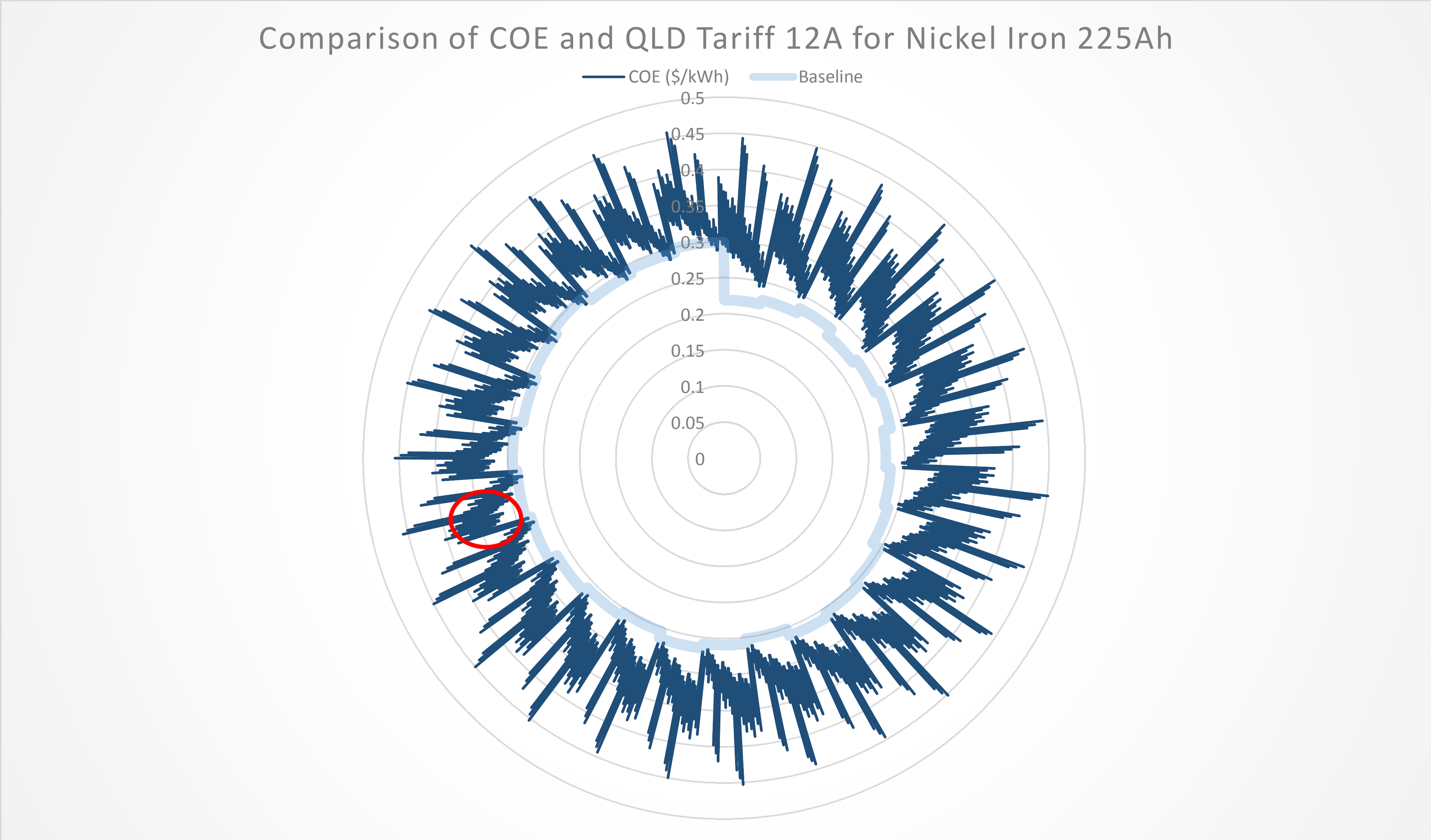


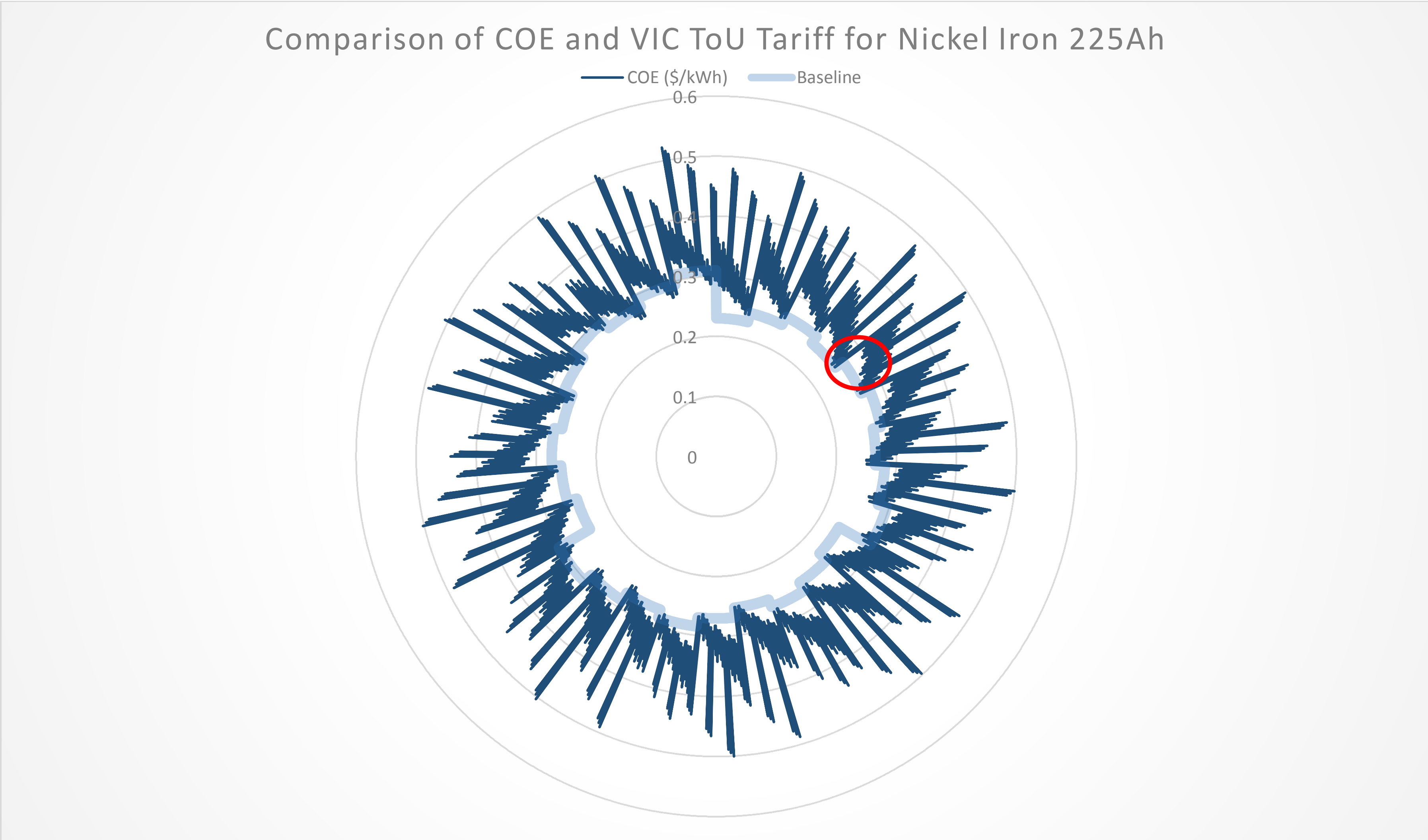

Comparison of COE and QLD Tariff 12A for Nickel Cadmium 250Ah
COE ($/kWh)
Baseline
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0


Comparison of COE and VIC ToU Tariff for Nickel Cadmium 250Ah
COE ($/kWh)
Baseline
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0

APPENDIX 12 - HOMER ANALYSIS GRAPHS - NICKEL IRON




Comparison of COE and QLD Tariff 12A for Nickel Iron 225Ah
COE ($/kWh)
Baseline
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0


Comparison of COE and VIC ToU Tariff for Nickel Iron 225Ah
COE ($/kWh)
Baseline
0.6
0.5
0.4
0.3
0.2
0.1
0