University of Southern Queensland

Faculty of Health, Engineering and Sciences

Balanced, controllable, distributed BESS, to assist with counteracting renewable generation fluctuations.

A dissertation submitted by

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Abstract

Given the increased investment in grid connected battery energy storage systems, that are controlled to minimise fluctuations in renewal generation, for grid stabilisation, could a 150 MW BESS be instead installed as distributed 5 kW installations, spread across 30,000 domestic and/or commercial properties, controlled in a similar manner to a battery farm, whilst delivering an individual profit comparable to the single installation? Mathematical modelling of history data from the 150 MW Hornsdale Power Reserve for the 2022 year, scaled to single 5 kW system, calculated with the AMEO price history, is used to determine an estimated annual income for the 2022 year. The estimated annual income for 2022 was extrapolated to evaluate the profitability of a standalone battery inverter system over it's warranted (serviceable) life. Which determined that the proposed design is not commercially profitable, as it does not return the capital investment cost within five years. It will return the initial cost in approximately eleven years, reliant on the additional five year or total of 15 year conditional factory warranty.

Lithium-ion is the standard battery chemistry for commercially sold products of this nature. Is there an alternative battery chemistry, that has a lower environmental impact at end of serviceable life, without compromising on serviceable performance? Using HOMER Pro, simulated a comparison between lithium-ion and lithium iron phosphate battery energy storage systems, with modelling based on history operating data captured from the 150 MW Hornsdale Power Reserve, to determine a superior battery chemistry for purpose. Simulation shows that lithium iron phosphate consistently maintains a higher average state of charge, peaking at twice the average monthly state of charge percentage, when compared to lithium-ion in December, however also has a 37% higher rate of storage depletion and losses. Literature review demonstrated lithium-iron phosphate to be the superior option environmentally, as there are no toxic materials after recycling of the battery at end of serviceable life, unlike both lithium-ion and lead acid.

Despite all of these factors, including improved performance over a shorter timeframe and environmental benefits that could be obtained through a change from lithium-ion battery chemistry, the benefits do not equate to an increase in profitability.

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I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Shane Dale

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Nomenclature

AC	- Alternating Current
AEMO	- Australian Energy Market Operator
AGM	- Advanced Glass Matt
BESS	- Battery Energy Storage System
DC	- Direct Current
FCAS	- Frequency Control Ancillary Services
LiFeP04	- Lithium iron phosphate
PEV	- Plug-in Electric Vehicle
SoC	- State of Charge

Chapter 1 - Introduction

1.1 - Thesis General Technology Topic

Given the increased investment in grid connected battery energy storage systems, that charge or discharge dependent on distribution network requirements, to assist with minimising the inherent fluctuations in renewal generation, could a distributed battery energy storage system equivalent to the size of a large battery farm, be a financially viable option instead of a single large facility. Also, lithium-ion is the standard battery chemistry for commercially sold products of this nature, is there an alternative battery chemistry, that has a lower environmental impact at end of serviceable life, without compromising on serviceable performance.

1.2 - Background/ Justification

Large scale implementation of grid connected, battery supplied inverters, that are controllable based on grid demand, aka battery energy storage systems, aiming to minimise supply fluctuations cause by the inherent fluctuations in renewable energy generation, or put simply, for grid stabilisation, are becoming more common. However, could a 150 MW battery energy storage system (BESS) be instead installed as distributed 5 kW installations, spread across 30,000 domestic and/or commercial properties, controlled in a similar manner to a battery farm whilst delivering an individual profit comparable to the large scale installation? Negating the need for significant land masses and the lump sum financial investment, allowing for more progressive investment and deployment. Lithium-ion batteries are the most commonly utilised battery chemistry for commercially supplied battery inverter products, however are they the best battery chemistry for this purpose, as well as the environment? Reducing or ultimately eliminating environmental waste at end of life for a project, especially of this scale, needs to considered.

1.3 - Aims, Objectives and Research Questions

- Model an individual 5 kW battery energy storage system, using actual history operating parameters for a 150 MW battery farm, most notably charging and discharging rates, to determine a scaled estimate of energy stored, then sold back to the grid. Then compare these figures against actual market pricing, to determine the profitability of a standalone 5 kW system over its warranted I 0-year life.
- Using HOMER Pro™, modelling the parameters above, evaluate differing battery chemistries to determine which has the best performance, as well as perform literature review to determine recycling or full life cycle options for each of the battery chemistries, with aim to determine the best option in environmental terms.

- Despite lithium-ion being the predominate commercial battery, could lead acid deep cycle advanced glass matt (AGM) variations, lithium iron phosphate or other alternative provide similar or better performance and life cycle characteristics?
- Do other lithium-based alternatives such as lithium iron phosphate provide environmental benefits compared to lithium-ion?
- Could a distributed, grid connected, domestic 5kW battery energy storage system, be individually profitable?
- Could performance and profitability be improved through a change from lithium-ion battery chemistry?

Advantages of a distributed battery inverter system include no need for a great land mass for installation, greater flexibility for capital investment, though not needing to invest hundreds of millions in one go, rather smaller packets of investment, with installation into a majority of existing grid connected premises being possible. However, financial viability of individual systems would need to be deemed plausible, prior to significant amounts of investment being made. Literature review and simulation of differing battery chemistries, looking for possible system performance improvements, aiming to improve system profitability, as well as full life cycle analysis of differing battery chemistries, most notably which has the lowest environmental impact at end of serviceable life, which could lead to adoption of a different battery chemistry, with a lower level of end of life environmental waste.

1.4 - Outline of research methodology

- Mathematical modelling of history data for a 150 MW battery energy storage system constraints (charge / discharge), calculated with the AMEO price history, scaled to single 5 kW system, to determine an estimated income from a theoretical standalone battery inverter system, for the 2022 calendar year.

- Extrapolate the annual income, to evaluate the profitability of a standalone battery inverter system over it's warranted (serviceable) life.

- Using HOMER Pro™ to simulate a comparison of the differing battery chemistries, with modelling based on the historic data captured from the 150 MW battery farm, determine a superior battery chemistry for the proposed purpose.

- Evaluate any performance differences between the current standard of lithium-ion batteries and any other battery chemistry deemed to be possibly viable, then ascertain through research which has a lowest level of environmental waste at the end of serviceable life, to determine the overall viability of the alternatives.

1.5-Expected outcomes

- Determine the best battery chemistry for a controlled battery inverter system, based on simulated overall system performance.

- Determine the best battery chemistry with regards to minimising environmental waste at the end of serviceable life, and evaluate any performance differences to the current standard lithium-ion battery.

- Determine the profitability of single 5 kW battery energy storage system, to ascertain the viability of a distributed system as a viable option, when compared to a single large scale installation

- Ensure the stability of batteries as to minimise / eliminate the risk of explosions and fires

- Minimise the significant amount of hazardous waste, created by end of serviceable life batteries

- Design to prevent inadvertent negative impacts to the distribution network, such as high phase voltage and phase imbalances.

1.6 - Initial Benefits/Risks/Critical Consequences Review

Initial benefits of this project include the implementation of a distributed, controllable, Battery Energy Storage System without the need for extensive land mass and significant initial investment, as well as reduced toxic environmental waste, primarily generated by end of serviceable life batteries. This will achieved by suggesting improvements through combining existing commercially available solutions, that have demonstrated proof of concept in real world situations individually, however not as a complete or combined unit. Implementation of the proposed solutions would involve a significant level of electrical, battery energy, chemical storage and fire safety risks, however there is nominal risk involved in the research side of this project, as all modelling is to be completed using computer simulation. Other risk involved with a practical implementation would include a financial risk, as there is no guarantee of financial return, especially over ten years. Consequences of failing to address the risks involved with the implantation of the proposal could include injury to persons, loss of property through fire and significant financial losses. Failure to implement the proposal will prevent the possible elimination of a significant amount of environmentally toxic waste, unstable battery chemistry resulting in continuing catastrophic failure and toxic fires, as well as a possible increases in distribution network instability.

1.7 - Project contribution

There has been significant research into Battery Energy Storage Systems, for the purpose of stabilising fluctuations in both renewable generation and load. In particular, design, construction and testing of micro- grids or pockets of greater distribution networks. Currently, the preferred option is large battery farms, that require an area of land mass, significant once off investment and a very large amount of batteries, of which full life cycle or disposal at end of serviceable life, most notably the toxic components of these batteries, does not appear to have been considered.

This project aims to determine the viability of a distributed Battey Energy Storage System, equivalent to the size of a 150 MW battery farm, market controllable in a manner similar to the battery farm, however constructed as a distributed network, negating the need for significant lass mass and large once off investment. Profitability of an individual unit will be determined from actual historic operating information and market pricing for a 150 MW battery farm, scaled to the single unit. Design considerations for a distributed Battery Energy Storage System, to prevent any inadvertent adverse stability effects on the distribution network of which they are connected, will also be discussed.

Another consideration this project will cover is the significant amount of toxic environmental waste a project of this scale could produce, with end of serviceable life batteries, using the current commercial standard lithium-ion battery. Alternative battery chemistries will be explored, with performance comparison between the current standard lithium-ion and lithium iron phosphate simulated, to determine a performance companson between the two batteries, with one of the two being cited as superior, based on both environmental and performance factors. As research has demonstrated, lithium iron phosphate batteries can be recycled at end of serviceable life, without creating any toxic waste, unlike lithium-ion and lead-acid batteries.

Chapter 2 - Literature Review

2.1 - Introduction

This chapter will review literature to determine the most efficient and effective means of implementing a Battery Energy Storage System into a distribution network, aiming to assist with reducing fluctuations in renewable energy generation. Determining the best method will need to include a number of factors such as the system's ability to respond to fluctuations, controllability of the system by network operators to allow for more effective implementation, as well as ensuring that the system does not inadvertently create any distribution network stability issues. Also being reviewed is alternatives to the current commercial standard lithium-ion battery, which can experience catastrophic failure modes.

The primary alternative being reviewed will be lithium iron phosphate batteries, as these batteries are widely commercially available, and are expected to delivery comparable performance to lithium-ion, with improved stability and safety. Environmental benefits of lithium iron phosphate compared to lithium-ion is also to be reviewed. Other plausible alternative energy sources will also be reviewed, looking for a superior environmental option, that can deliver comparable performance to the lithium based batteries. Review will begin with real world implementations of Battery Energy Storage Systems (BESS).

2.2 -Battery Energy Storage Systems

This section of literature review will be on the subject of Battery Energy Storage Systems, looking into testing of real world implementations, benefits and consequences of these systems, any knowledge gaps that need to be explored further, then use the gathered knowledge to develop a proposed design. The proposed design will be an extension of or improvement to existing systems with proven benefits, that also have limitations, inadvertently cause negative impacts or could benefit from being distributed. Will be beginning this review section with voltage-based storage control systems.

2.2.1 - Voltage-based storage control system

Use of voltage-based storage control systems, that charge the battery during low load within the battery charge acceptance limits at any given point during charging, then discharge during periods of high load, aiming to reduce stress on the distribution network of which it is connected, is becoming of increasing importance. This system has advantages over other previously researched and trialled distributed generation systems, as it has demonstrated a minimisation in the steady state voltage magnitudes, for both residential and commercial load situations. Strategic addition of this style of system, into parts of a distribution network experiencing load stresses, may defer the need for expensive network asset upgrades (Kennedy et al. 2016).

The proof of concept, such as what the research demonstrates, is of great importance to this project, especially given it specifically mentions how the system could benefit from an external feed in of information, as well as how specifics around battery chemistry were not covered, of which both topics aim to be covered by this project. Also, as this style of technology has already been demonstrated to offer both asset longevity and in turn possible financial benefits to a distribution network, this will likely improve the likelihood of adoption and implementation of the technology, once other benefits are further demonstrated.

2.2.2 - Distributed energy storage system

Investment on distributed power systems can be deferred, through the implementation of controlled distributed generation, located close to the customers, decreasing power losses and voltage drops. When accompanied by efficient energy storage solutions, balancing the disturbances of the intermittent character of renewal energy sources, enhances generation / demand being met, and voltage regulation limits being maintain, decreasing the amount of unsatisfied power demand and an unstable electricity grid supply. However, attentive planning is required for selection and sizing of energy systems, to prevent inadvertent negative impacts on power quality and voltage instability (Mena et al. 2014).

The research covers the importance of energy storage systems, and their critical part of a stable and reliable distribution network, predominately powered by distributed, renewable generators. This is important in validating this project, as research and improvements around battery energy storage systems, most notably controllable systems, will be of benefit to both distributed renewable generation and distribution networks. Other research suggests that the described load stresses, are becoming of increasing unpredictability.

2.2.3 - Effects of distributed single phase connection

With the increase in uptake of Plug-in Electric Vehicles as a result of a number of global factors, this has created another source of distribution network unbalance, due to the unplanned and random nature of vehicle charging, in conjunction with a majority of these apparatus being single phase connected, contributing to distribution unbalance. Proposed a control system, which detects the balance of voltage across the distribution three phase, then limits the load per phase consumed by the single phase Plug-In Electric Vehicle chargers, in turn limiting the voltage difference between the three phases to 2%, preventing distribution network unbalance (Haider and Muttaqi 2015).

The research is important as it strengthens the need for Battery Energy Storage Systems for grid stability, for not just fluctuations in renewable energy generation, also for unpredictable and random fluctuations in load created by the increase in Plug-in Electric Vehicles, charging from single phases of the grid. Proposition of distribution controlled single phase load control to limit imbalance, could be utilised to control distributed Battey Energy Systems, scattered across single phase electrical installations. Research into a real world application of a battery storage station, demonstrates ability to level fluctuations in both load and generation.

2.2.4 - Lithium iron phosphate based battery energy storage system

Wang et al. (2020) validates the construction of a 20MW/l0MWh, grid connected lithium iron phosphate battery storage station, to the standards of the Xing Yi regional grid, of which it is connected. The station has 10 2MW/lMWh lithium iron phosphate storage units, each consisting of 4 500kW/250kWh storage modules, connected to a 35kV (secondary) booster transformer, feeding into a 220 kV substation. All of the battery infrastructure is monitored and protected by a three-level Battery Management System. Charging and discharge testing of this station, has shown that it can reliably deliver 150 % offull rated (50 % overload) for 30 seconds, at an efficiency of 85 %, making it ideal for grid stabilisation, or leveling heavy fluctuations in both renewable generation and industrial demand.

This research is important as it demonstrates a successful real-world implementation of lithium iron phosphate battery storage, validating the other literature reviewed, as well as showing that the technology is in fact real, and not just theoretical. Performance characteristics measured within this paper, also provide a real and true indication of the potential for lithium iron phosphate batteries to reliably supply a power system, designed to counteract fluctuations in both load and renewable generation. Although the charge and discharge testing of the battery storage station has demonstrated ability to deliver greater than full rated, this practice is not recommended, as it will likely result in irreversible damage to the lithium cells. As development and deployment of battery energy storage systems has increased, so has the amount of unsafe field failures.

2.3 - Benefits and limitations of lithium iron phosphate cells

This next section of literature review will focus on comparison between lithium iron phosphate cells and existing commercial solutions including lead acid and lithium-ion, for topics such as cell safety or likelihood of unsafe failure, cell performance comparison, as well as toxic environmental waste levels at the end of serviceable life. Starting the section with review of literature on grid support energy storage system, in particular testing of system safety.

2.3.1 - Field failures of lithium ion Battery Energy Storage Systems

In recent years, there has been an increase in the development and deployment of lithium-ion based battery energy storage systems for grid support applications. With this increase, there has also been in increase in fires and explosions, as a result of field failures, with over 30 incidents reported by the Electrical Power Research Institute, over the four years up until June 2021. During 2019, FM Global performed full scale fire testing of various lithium based battery chemistries, constructed into an energy storage system, identifying that lithium iron phosphate batteries generally exhibited a lower overall hazard, compared to lithium-ion (Cozen et al. 2022).

The research demonstrates the generally lower hazard of the lithium iron phosphate cell compared to lithium-ion, as well the need to improve battery energy storage systems, given the significant number of unsafe events. This justifies the importance of researching the possibility of using lithium iron phosphate as an alternative in Battery Energy Storage Systems, from a performance and profitability point of view, with aim to improve the overall system safety. However, the lithium iron phosphate alternative, will need to demonstrate comparable performance and longevity characteristics.

2.3.2 - System performance comparison to lead acid

Research into the performance characteristics of lithium iron phosphate and lead acid batteries in energy storage units, with aim to upgrade away from lead acid batteries, has found that lithium iron phosphate batteries have improved heat management and voltage profiles (lower change in battery voltage over the dropping state of charge and after an increase in load current) as well as demonstrating faster voltage recovery after a decrease in load current. This results in an increase in overall system performance, making lithium iron phosphate batteries the superior option (Kumar et al. 2022).

This research is important, for demonstrating that lithium iron phosphate batteries are in fact a suitable replacement for where lead acid batteries are used currently. Also demonstrated, is the superior voltage recovery characteristics of the lithium iron phosphate technology, which will be greatly beneficial for operational situations where switching between charging and discharging occurs, such as responding to fluctuations in renewable generation. More in depth experimentation looking specifically at cell charging and discharging of the individual batteries furthers this.

2.3.3 - Fixed discharging and charging comparison

Experimentation using a fixed discharging and charging apparatus and parameters, comparing lead acid and lithium iron phosphate batteries has yielded that the lithium iron phosphate battery exhibits superior discharge characteristics, that is a lower change in terminal voltage until cut-off voltage is approached. This means that a larger percentage of the lithium iron phosphate battery capacity is usable, compared to the lead acid. The lithium iron phosphate battery also exhibited better charging efficiency than the lead acid (Hua & Syue 2010).

Here, a performance comparison between individual lead acid and lithium iron phosphate batteries to a more in-depth level, compared to the overall full system comparison reviewed earlier. Specific details around greater usable capacity and lower drop in terminal voltage over the discharge cycle, are characteristics that would be greatly beneficial to a power system as responding to fluctuations in renewable generation. Not only is the technology superior to lead acid batteries, it is also superior to other lithium based alternatives.

2.3.4 - Comparison to other lithium based alternatives

Comparison between various types of lithium battery compositions, of differing composite solid polymer electrolytes (CSPE), notably testing ionic conductivity, transference number, as well as cyclic, electromechanical and thermal stability, demonstrated the lithium iron phosphate cell as superior to the other lithium based alternatives. Although it did not exhibit the highest ionic conductivity out of all of the alternatives, it was stable cyclic, electromechanically and thermally, unlike the alternative with higher ionic conductivity (Lu et al. 2022).

This research is beneficial to this project, as it justifies the selection of the lithium iron phosphate technology, over the many other forms of lithium storage available, including the alternative with higher ionic conductivity. Battery cell stability is essential, to ensure the reliability of the overall power system, as well as minimise the likelihood of an unsafe situation such as inextinguishable fire, from occurring in the first place. However, lithium iron phosphate batteries do have a lower maximum operating voltage, compared to other battery alternatives.

2.3.5 -Temperature stability improvement for cell

Experimentation around improving the polyolefin separators within lithium iron phosphate cells, that currently have a low melting point of 80 degrees Celsius and shrink at high operating temperatures, has improved the separator to be stable at around 145 degrees Celsius. The disforming of the separator is the root cause of cell short circuiting and infamous lithium cell fire. Addition of a boehmite nanofiber coating to the separator, has greatly improved cell thermal stability without significantly impacting on electrochemical performance (Nag et al. 2022).

This research demonstrates that innovation to rectify the current (60 degrees Celsius) low maximum operating temperature limitation is possible, however this not been commercially adopted at this stage. Implementation of this innovation would rectify the current lithium iron phosphate cell shortfall, resulting in stability at higher operating temperatures, thus making it suitable for use in non-climate controlled applications. Other research suggests improvement to the thermal management, though another means.

2.3.6 - Thermal management improvement for cell

Research has been conducted into improving cold plate thermal management within lithium iron phosphate batteries, with aim to improve overall thermal stability. Use of a double S-channel cold plate compared to the conventional single S-channel cold plate has yielded a more uniform battery temperature, with a battery thermal management system power use reduction of over 73 %, achieved through reduced flow resistance, which in turn increases heat transfer, hence an improvement in overall thermal performance (Zuo et al. 2022).

The innovation mention in this research, provides a plausible improvement, assisting to overcome the lower operating temperature, however it has not been commercially adopted at this stage. This is important to this project, to further demonstrate that the operating temperature limitation of lithium iron phosphate cells, can be improved, thus supporting the adoption of the chemistry. What happens to the batteries at end of serviceable life also needs to be considered, not just performance during serviceable life.

2.3.7 - Recycling end of life batteries

Spent lithium iron phosphate cells can separated through the use of a cyclone separator, a low energy consumption, low cost solution with a 60 % efficiency after 7 separations, increasing to 76 % after 15 separations. This process separates the materials lithium ferrophosphate, aluminium, iron and copper, allowing the reclaimed materials to be used for other purposes. Unlike spent lithium-ion and lead acid batteries, there are no toxic materials after the reclamation process, making this technology superior over the alternatives listed, from a full life cycle perspective, in particular regarding minimisation or preferable elimination of environmental waste after the battery's serviceable life (Pang et al. 2022).

Responsible engineering includes a full life cycle analysis of any proposed product to be used as part of a project. This research offers up the viable option of a low cost, low energy consumption, material reclamation from end oflife products, creating a closed loop for product materials. Thus, proving that lithium iron phosphate is a better option environmentally, with no toxic materials at end of life, unlike the other alternatives. Other research explores possible uses for the reclaimed materials.

2.3.8 - Uses for reclaimed materials

One possible application for some of the reclaimed material include being utilised as a catalyst in initiating chain reactions, for example, being used to degrade organic pollutants from industrial wastewater. Research suggests that spent lithium iron phosphate materials are as much as 80 % more effective at degrading organic materials in an aqueous solution, compared to an existing commercially acquired catalyst, after 60 minutes (Wang et al. 2022)

The research provides a solution to a different environmental problem, offering not only a possible use for the reclaimed materials, it demonstrates superior results when compared to existing materials when used with standard practices. Once again, validating the selection of the lithium iron phosphate battery technology over the previously mentioned alternatives, for being the better option environmentally. Further comparison specifically between lithium iron phosphate, lithium-ion and lead acid batteries, will cover other differences between the technologies.

2.4 - Comparison between lithium and lead acid batteries

This section of literature review will perform comparison between lithium ion, lithium iron phosphate and lead acid batteries, focusing on the benefits and limitation of lithium iron phosphate identified in the previous section. Other comparison to be performed between the chemistries will include differences in cell charging as well as life expectancy.

2.4.1-Temperature stability comparison

Operating a lead acid battery outside of recommended ambient temperature can result in a reduction of serviceable life, or in extreme cases, bursting of the battery. The recommended maximum ambient temperature for a lead acid battery is 55 degrees Celsius, however the battery is able to operate in an ambient temperature of up to 85 degrees Celsius, for a maximum recommended duration of three hours, before negatively impacting on the battery life expectancy. Minimum operating temperature varies greatly, depending on the battery state of charge, however negative forty degrees Celsius is the recommended minimum operating temperature. (Banner, 2023).

Recommended ambient temperature range for lithium iron phosphate batteries is Oto 55 degrees Celsius. Charging below zero degrees Celsius will result in crystallising of the lithium ions within the individual cells, negatively impacting the battery capacity (Sunon, 2022). As mentioned previously (in section 2.3.5), operating lithium iron phosphate cells above the recommended maximum temperature, will result in catastrophic failure of the cell. The recommended operating temperature range for lithium iron phosphate batteries is much narrower than lead acid, as well as having little to no margin for operation above or below the recommended operating temperatures, without resulting in damage to the battery. Unlike a lead acid battery, which can operate at a temperature higher than recommended, for a fixed timeframe, without resulting in damage to the cell. Lithium-ion batteries also exhibit limitations in regards to recommended temperature operating range.

2.4.2 - Further temperature stability comparison

Temperature is a critical factor for lithium-ion batteries, as it limits battery applications, due to certain conditions resulting in adverse effects. One of the effects from operating a lithium-ion battery at low temperature or less than the generally accepted -20 degrees Celsius, include a significant reduction in the battery capacity. This occurs due to an increase in the electrolyte viscosity, as a result of the decrease in temperature, which reduces the ionic conductivity of the battery cells, increases internal cell impedance, resulting in the reduction of available battery capacity. There is also an acceptable upper temperature of 60 degrees Celsius for lithium-ion batteries, as charging and discharging generates heat internally, as a result of electrochemical reactions. Operating lithium-ion batteries at an increased ambient temperature, will accelerate the rate of degradation of the battery. When the ambient temperature exceeds recommended, it can trigger the battery's internal exothermic reactions, which in turn generate move heat, resulting in the Thermal Runaway condition, ending in fire and explosion of the battery (Ma et al. 2018).

Both lithium-ion and lithium iron phosphate have similar recommended ambient temperature ranges, much narrower than lead acid. The consequences of operating lithium-ion batteries at higher ambient temperatures are much greater than lead acid batteries, and are not able to operate at slightly higher ambient temperatures for a fixed timeframe, like lead acid batteries. There is a significant number of publicly reported events, primarily around fires started by lithium cells, as a result of lithium-ion batteries exhibiting thermal runaway. Comparing the lithium based alternatives, as previously mentioned in section 2.3.4, lithium iron phosphate is more thermally stable than lithium-ion, as such less likely to exhibit thermal runaway. Controlling the charge and discharge rates of lithium based batteries to prevent thermal runaway, is of great importance.

2.4.3 - Charging of lithium batteries

Different battery management techniques, focusing on controlling of the charging current are explored, aiming to maximise battery cycle life. Charging the battery in a low ambient temperature, can result in anode accumulation of lithium-ions, reducing battery capacity. High rates of charging and discharging can result in a thick layer forming on the surface of the electrodes, which also results in a reduction of battery capacity. Overcharging of the battery creates internal heating, that results in losing both active electrode area as well as the count of lithium-ions involved in the electrochemical reaction, both of which reduce battery capacity. Charging of the battery at high ambient temperatures can result irreversible internal damage, also reducing battery capacity. Given the significant number of factors around battery charging that can negatively impact cycle life, effective battery management can significantly improve battery cycle life (Cho et al. 2019).

The constant current-constant voltage (CC-CV) charging method, is one of the common management techniques utilised for the fast charging of lithium batteries, without greatly compromising on battery cycle life. This technique charges the battery with a constant current until the voltage reaches the maximum acceptable level, then swaps to a constant charging voltage, until the charging current drops to a pre-defined level. Unlike the other common fast charging techniques, the CC-CV charging rate alters with the change of internal battery impedance, therefore this technique does not rapidly reduce battery capacity in the same manner as the other fast charging alternatives (Cho et al. 2019).

Managing of the battery cell charging and discharging rates is important for both ensuring the safe operation of the battery, as well as maximising cycle life. Battery management is essential for lithium based batteries, to prevent the individual cells being charged or discharged in a manner that could result in thermal runaway. These type of individual battery management system are essential for lithium batteries to ensure safe operation, however are not required at all by lead acid batteries. Effective battery management, in particular controlling the charging of the lithium battery, will improve battery life cycle, which will be a factor of great importance for a Battery Energy Storage System project, where battery life cycle and subsequent capital cost, will greatly impact the overall profitability of the proposal. The cycle life expectancy of the battery chemistry will be an important factor towards the profitability of the proposal.

2.4.4 - Cycle life comparison

Cycle life comparison between lead-acid, lithium-ion as well as lithium iron phosphate batteries will be general in nature, as actual cycle life expectations of each battery is dependent on operating parameters such as ambient temperature and predominately depth of discharge. Lead-acid AGM battery is good for 500-1000 cycles typically, however that drops to as low as 250 cycles with a depth of discharge increase to 80% (PowerTech 2023a). Lithium iron phosphate battery operating at 25 degrees Celsius, with a 80% depth of discharge, have an estimated cycle life of 4,500 cycles, which drops to 3,000 cycles with an increase to 100% depth of discharge (PowerTech 2023 b). Lithium-ion battery operating at 25 degrees Celsius, at 100% depth of discharge have an estimated cycle life of 4,000 cycles (Saft 2023). Although a battery energy storage system for grid stabilisation will not be exposing the batteries to a high depth of discharge, it can be assumed with confidence that lithium-ion, will have the highest cycle life. Another factor that needs to be considered is the environmental impact of the project, especially at the end of serviceable life.

2.5 - Alternative sources of energy storage

The final section of literature review will focus on looking for plausible alternatives to lead acid and lithium based cells discussed previously, in particular, investigating the best environmental option, not necessarily the best performance option. Where a plausible alternative is found, performance comparison can be simulated, economic consequences estimated, then overall viability determined. The first alternatives investigated, result in minimal to nil environmental harm, at the end of serviceable life.

2.5.1 - Rechargeable Daniell zinc-copper cell

A proof of concept development of a rechargeable modification of the Daniell Zn-Cu based primary cell, was undertaken and subsequently proved that a rechargeable Zn-Cu based cell is possible. Further research and development such as converting into a redox flow battery, could prove to be an environmentally safer, low cost alternative for energy storage. This technology has safety and stability advantages when compared to batteries such as lithium-ion, which have potentially catastrophic failure modes, that can release toxic components (Parikipandla et al. 2017).

Although this battery technology is in proof of concept stage, and further development is required to make it suitable for use as part of a Battery Energy Storage System, it meets the project aim of looking for alternatives that reduce environmental harm at the end of the battery's serviceable life, as well as providing a more stable alternative to lithium-ion and the infamous lithium cell fire. Other research has developed and proven modelling for a single-flow zinc based battery.

2.5.2 - Single flow zinc-nickel battery

Joint State of Charge and State of Health estimation methods were developed for a single-flow zinc-nickel battery. Advantages of this battery chemistry include low cost and nontoxicity, however inherently exhibit poor cyclic performance, due to zinc deposition formation. The developed adaptive method was tested and is able to accurately estimate any cell capacity degradation, which could be utilised by a Battery Management System to recondition the cell, helping to extend the battery's serviceable life (Li et al. 2019).

This research offers a plausible improvement to zinc based single-flow batteries, which could negate inherit limitations of zinc alkaline batteries and extend their serviceable life. The development is important to this project, as it reinforces that zinc-nickel single flow batteries are not yet a superior option for a Battery Energy Storage System, when compared to lithium batteries based on cyclic performance, despite being the best option environmentally. A review of zinc-ion batteries over the past five years, discusses other variants of zinc based batteries.

2.5.3 - Various zinc-ion batteries

This review looks into four areas of zinc-ion batteries including the zinc anode, cathode material, separator and electrolyte, in particular research completed over the last five years and how this has improved overall performance. There has been a significant surge in both the amount of research published around zinc-ion batteries, as well as patents granted over the last five years. Advantages of zinc-ion batteries include no need for sophisticated manufacturing facilities, resulting in a 3-5 times lower fabrication cost, environment-friendliness and high safety compared to lithium-ion batteries. However, rechargeable zinc-ion batteries are not able to compete with lithium-ion nor lead-acid batteries, in terms of performance (Mallick & Retna Raj 2021).

The review extends investigation of plausible alternatives to include all forms of zinc-ion battery, which is important for this project, aiming to find a more environmentally friendly option to the current standard of lithium-ion batteries. Unfortunately, zinc-ion despite being a growth area ofresearch and development over the past five years and being the superior option environmentally, is unable to compete performance wise with the existing options including lithium-ion and lead-acid. And now for something completely different, research that suggests repurposing end of serviceable life Electric Vehicle batteries, for use in a Battery Energy Storage System.

2.5.4 - Use of retired Electric Vehicle batteries

Given the availability of retired Electric Vehicle batteries is expected to reach 200 GWh per year by 2030, some of which might have 80% available capacity, these batteries could be repurposed for a second-use battery energy storage system (2-BESS). Challenges with this proposal include getting the second-use batteries of differing State of Health levels and reduced capacity due to varying degradation, to work together in a single system. This can be achieved through use of the 2 layer, Lite-Sparse Hierarchical Power Processing architecture, which can achieve an optimal 93.6% battery power utilisation (Cui et al. 2022).

The research demonstrates that used Electric Vehicle batteries, of which there will be a great supply of in the future, could be utilised to form a second-use battery energy storage system. In regards to this project, the research proposes prolonging the lithium-ion batteries serviceable life into a second life, which meets the project aim of minimising environmental waste, however does not solve the issue of toxic waste at the end of the second-life. Utilisation of second-life Electric Vehicle batteries rather than new batteries to form Battey Energy Storage Systems for the purpose of grid stabilisation, would reduce the global number of batteries required and subsequently becoming waste at the end of serviceable life, thus reducing the level of environmental harm for a project of this scale.

Chapter 3 - Methodology for Battery Energy Storage System Design

3.1 - Energy System Design

The distributed, grid connected, controllable Battery Energy Storage System design, will be proposing improvements to existing manufacturer processes and design, based on research conducted around distributed generation and both the positive and negative effects it has on the distribution network, of which it is connected. Connection of a Battery Energy Storage System to a distribution network, in both residential and commercial load situations, has shown to reduce distribution voltage magnitudes for both high and low loading (Kennedy et al. 2016, p.282). Controlled distributed generation which includes battery storage, located close to the customers, has lower power loses and voltage drops compared to centralised power supplies, which enhances customer power and voltage profiles, reduces unsatisfied power demand, resulting in the possible deferral of the requirement for significant investment into the distribution power system (Mena et al. 2014, p.779). Despite the benefits of a controllable, distributed, battery energy storage system, not all of the effects on the network are positive.

Considerations need to be made in regard to maintaining balance of the three phase distribution network, to prevent inadvertent negative impacts on consumer power quality. With the recent global uptake of Plug-in Electric Vehicles, it is expected that they will be unevenly connected to different phases, resulting in unbalancing of the distribution network (Haider and Muttaqi 2015, p.282). An unevenly connected distributed Battery Energy Storage System or generation system, would result in similar unbalancing of the distribution network. The distributed generation system installed near to consumer load would reduce voltage fluctuations for the phase of which it is connected, however it would likely reduce power quality for any three phase connected consumers, due to phase imbalance. This thesis proposes a solution for a distributed generation system, installed near to consumer load, that negates any possible phase imbalance issues that could arise from uneven connection into different phases, utilising commercially available products.

3.2 - Commercially available solution

Commercially available, controllable Battey Energy Storage System, containing a lithium-ion battery pack are manufactured and distributed by Tesla. The Tesla Powerwall™ is a 5 kW, single phase connected battery system, designed for residential and commercial consumers (Tesla 2023a, Appendix B). These units are controllable using Tesla Energy Software, whose customers include Energy Market Traders and is the same software used to control the Tesla Megapack™ (Tesla 2023 b), which make up the 1S0MW Homsdale Power Reserve (Neoen 2023a). Combining of these technologies creates the Tesla Energy Plan™, that is currently available in limited parts of Australia and offers an additional 5 year warranty on the connected Powerwall **unit** (Tesla 2023c). This plan is based on the Tesla Virtual Power Plant™, which was originally trialled in California during 2021, to assist with stabilising the Californian power grid using clean energy sources (Tesla 2023d). Both of these initiatives are based on the consumer also having a suitably sized solar array to charge the storage battery, however this thesis will be solely focusing on the controllable, distributed, battery energy storage component. The proposed design will be an extension to the standard commercial installation.

3.3 - Proposed design

The proposed design is a package consisting of three Tesla Powerwall™ 5 kW single phase units, connected one per phase, all connected to a dedicated ethernet router with open gateway access, to allow for the remote controllable energy software to operate, without the reliance on the customer's internet connection. Advantages of a dedicated communications link include reducing the likelihood of inadvertent configuration change, as well as the option to convert the open gateway link to an extension of a dedicated network, where the power operator has provision.

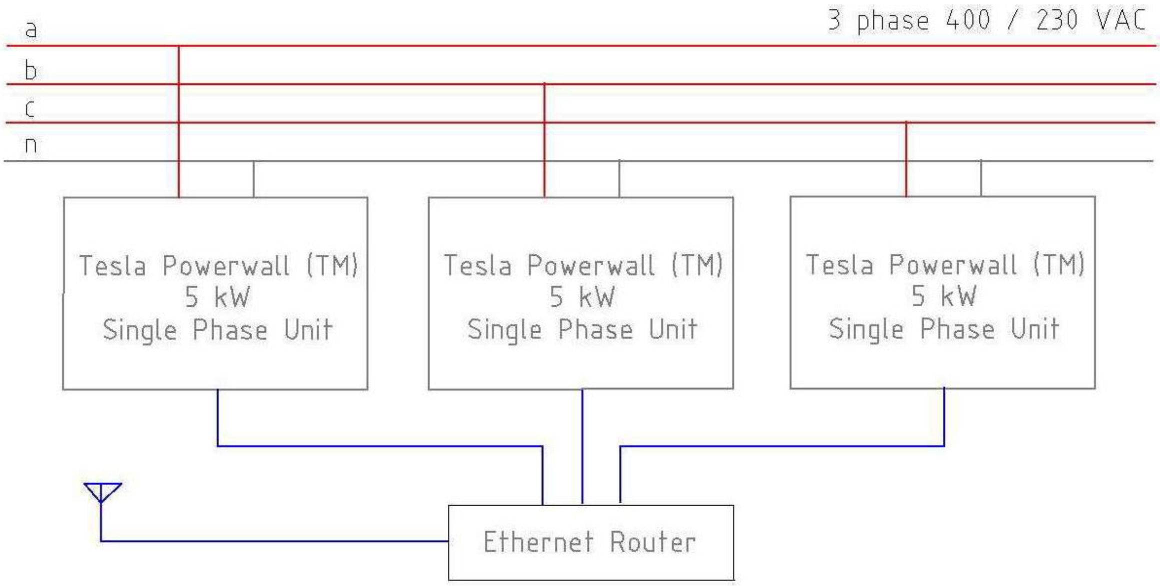


Figure 3.1 - Overview connection diagram for proposed design

Advantages of the proposed design compared to a single commercially available unit, in addition to the previously mentioned dedicated communication link, include preventing any three phase distribution imbalance issue that could arise from the installation of a distributed generation or storage system on only one of the phases. This is whilst achieving a controllable, distributable Battery Energy Storage System, connected near consumers to minimise load losses, that can be utilised to counteract fluctuations in renewable generation. Controllability of the proposed design could be achieved using existing network control software packages, in a similar manner to how battery farms are currently remote controlled. Calculation around the total number of units needed to achieve a distributed total storage of 150 MW will be required, as it will not be as simple as 30,000 of the 5 kW units or 10,000 installations to achieve the targeted total.

3.4 - Calculations for distributed 150 MW system

Given three 5 kW single phase units, connected one per phase does not equate to a maximum rated installation output of 15 kW, rather equating to;

$$\sqrt{3} \cdot 5 = 8.66 kW. \qquad 3.4.1$$

This means that when scaling from actual figures for the 150 MW battery farm, to determine an installation figure such as dis/charge rates;

$$\sqrt{3} \cdot \frac{150 \ MW}{30\ 000} = 8.66 \ kW. \qquad 3.4.2$$

Finally, to achieve a total distributed system rating of 150 MW, given each installation is 8.66 kW, the total number of required installations will be;

$$\frac{150\ 000}{8.66} \quad 17321. \qquad 3.4.3$$

These equations will be used to scale actual operating figures for the 150MW Homsdale Battey Farm, to determine an estimated annual income for the proposed installation. This figure will then be used to determine profitability of the proposal. Before attempting to determine profitability, an estimation of cost will need to be determined.

Chapter 4 - Lithium Cell Comparison Using HOMER Pro™

4.1 - Simulation Schematics

Both schematics contain scaled discharging figures that were extracted from actual operating figures using MATLAB®, then modelled as 'Electric Load', connected to the AC Bus. Zero figures were set as 1×10^{-4}, to eliminate the zero load warning in HOMER Pro™. Scaled charging figures were extracted from actual operating figures using MATLAB®, then modelled as 'PV power output modelled in PVsyst', connected to the AC Bus. A 8.66 kW Converter has been placed between the AC and DC buses, to simulate the three phase, 5 kW individual units as a single combined unit. The DC buses both consist of three, batteries of differing chemistries, totalling 10 kWh +2% -1%.

For the lithium-ion schematic shown in figure 4.1, three strings of 3.3 kWh LGChem RESU battery model have been chosen, as LG is one of the suppliers of lithium-ion batteries to Tesla™, with three strings chosen to obtain a battery capacity as close as possible to 10 kWh, with the three batteries to represent each of the individual units, connected one per phase. The lithium iron phosphate schematic shown in figure 4.2, consists of three batteries, each containing two strings of 5.1 kWh Li.ONESS 51.2V batteries, as this was the only lithium iron phosphate battery model in the evaluation software package, with two per string to achieve an individual battery capacity as close as possible to 10 kWh.

An individual battery capacity of 10 kWh was chosen, as multiples of strings of 3.3 kWh and 5.1 kWh batteries can achieve this figure with nominal difference in total capacity between schematics. This is important to improve the accuracy of performance characteristics between the schematics, as the greater the difference in capacity between schematics, the less accurate the comparison. Although a total capacity of 15 kWh would have been closer to the rated 13.5 kWh of the proposed Powerwall 2 unit, the difference in capacity between the schematics would have been approximately 7%, or over twice the 3% achieved using 10 kWh individual battery capacity. Comparison of the simulation results for both of the schematics, will demonstrate comparable testing parameters for both, as well as performance differences between the two battery chemistries.

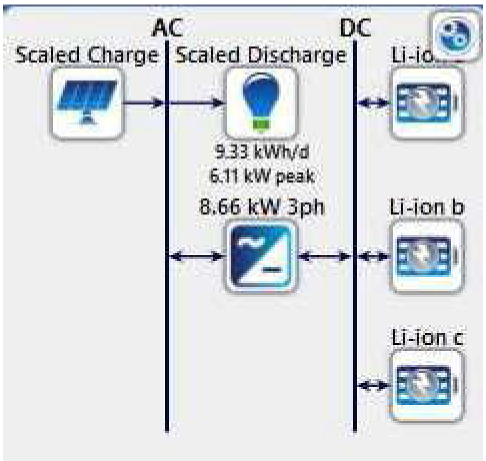


Figure 4.1 - Lithium-ion HOMER Pro™ Schematic

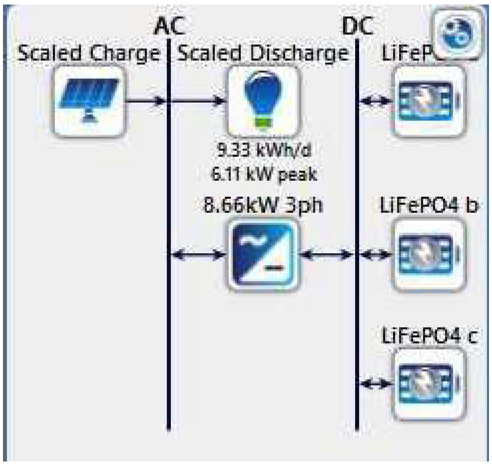


Figure 4.2 - LiFePO4 HOMER Pro™ Schematic

4.2 - Simulation Electrical Power Comparison

Comparison of the Total Electrical Load Served as well as Battey Input Power Monthly Averages for the separate simulations for lithium-ion and lithium iron phosphate batteries, will demonstrate the level of consistency of the scaled charge and discharge control, across the separate simulations. Given the nominal to no difference between both simulations, for Input Power (Figures 4.3 & 4.4) as well as Total Electrical Load Served (Figures 4.5 & 4.6) Monthly Averages, it can be seen that the scaled charge and discharge controls, is consistent across both simulations. This means that any differences in performance characteristics found between the simulations, can be confidently attributed to the difference in battery chemistries, meeting the aim of determining performance differences between lithium-ion and in this case, lithium iron phosphate batteries.

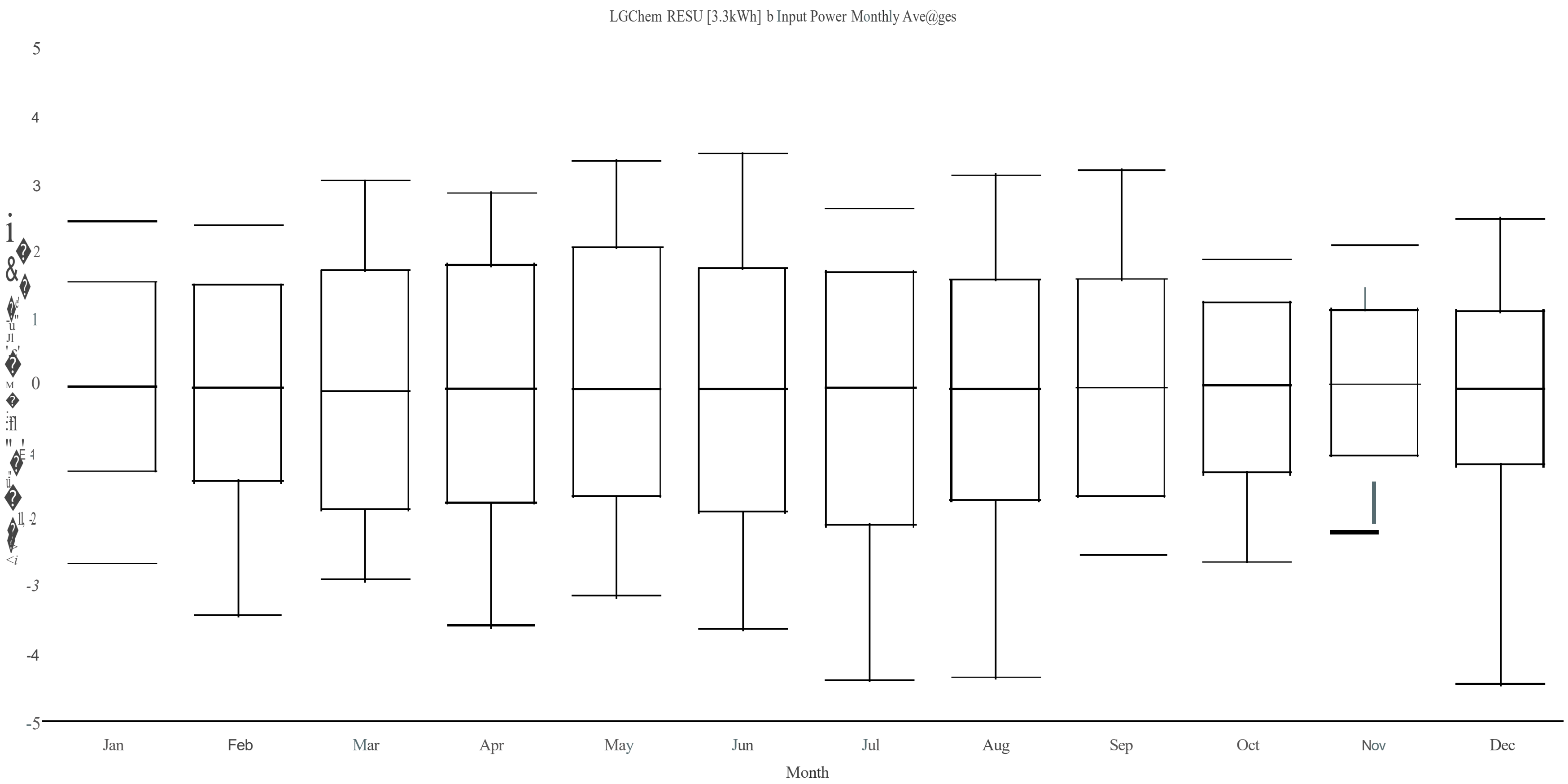


Figure 4.3 - HOMER Pro™ Simulation, Lithium-ion Input Power Monthly Averages

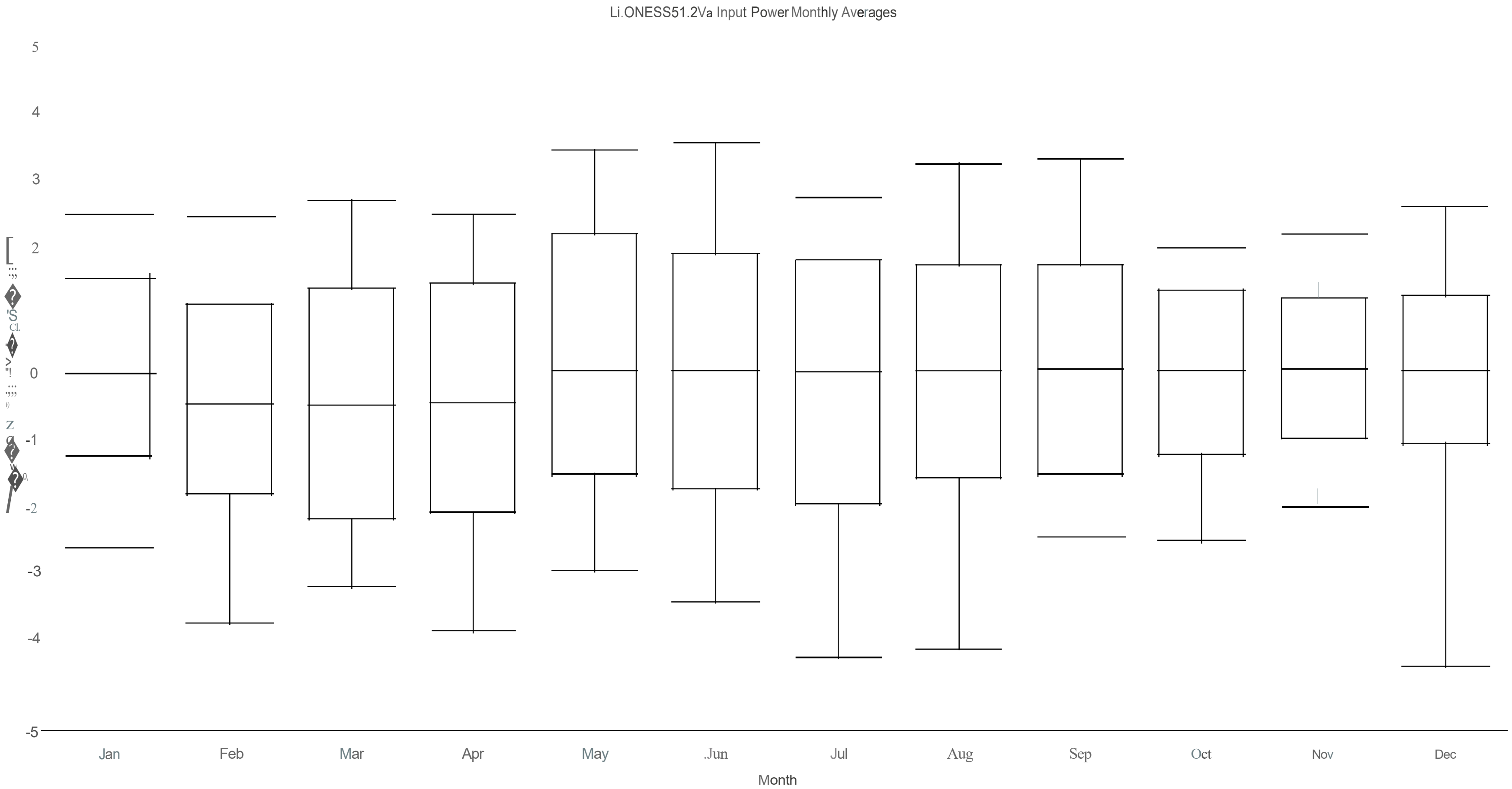


Figure 4.4-HOMER Pro™ Simulation, LiFeP04 Input Power Monthly Averages

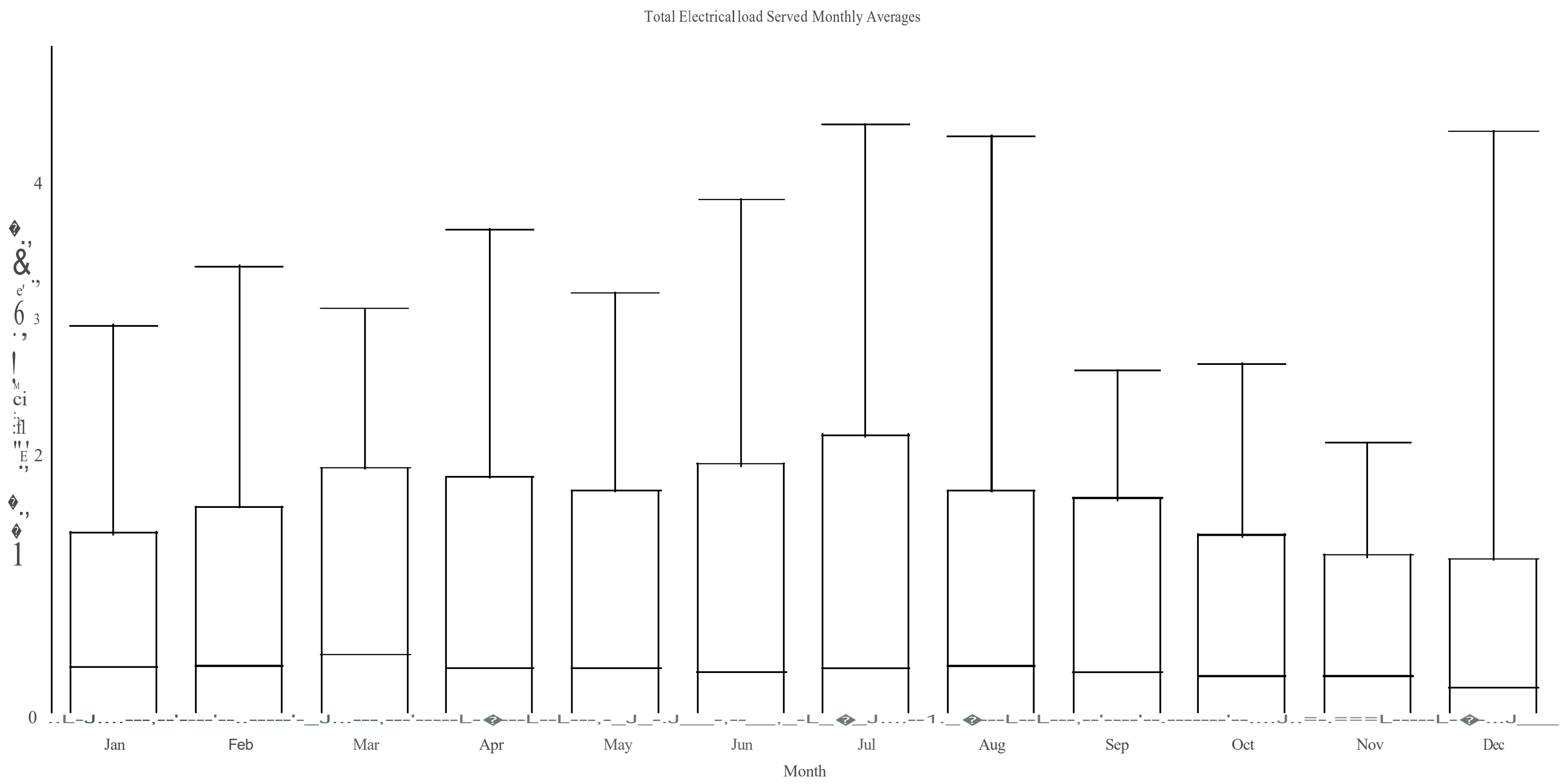


Figure 4.5 - HOMER Pro™ Simulation, Lithium-ion Electrical Load Monthly Averages

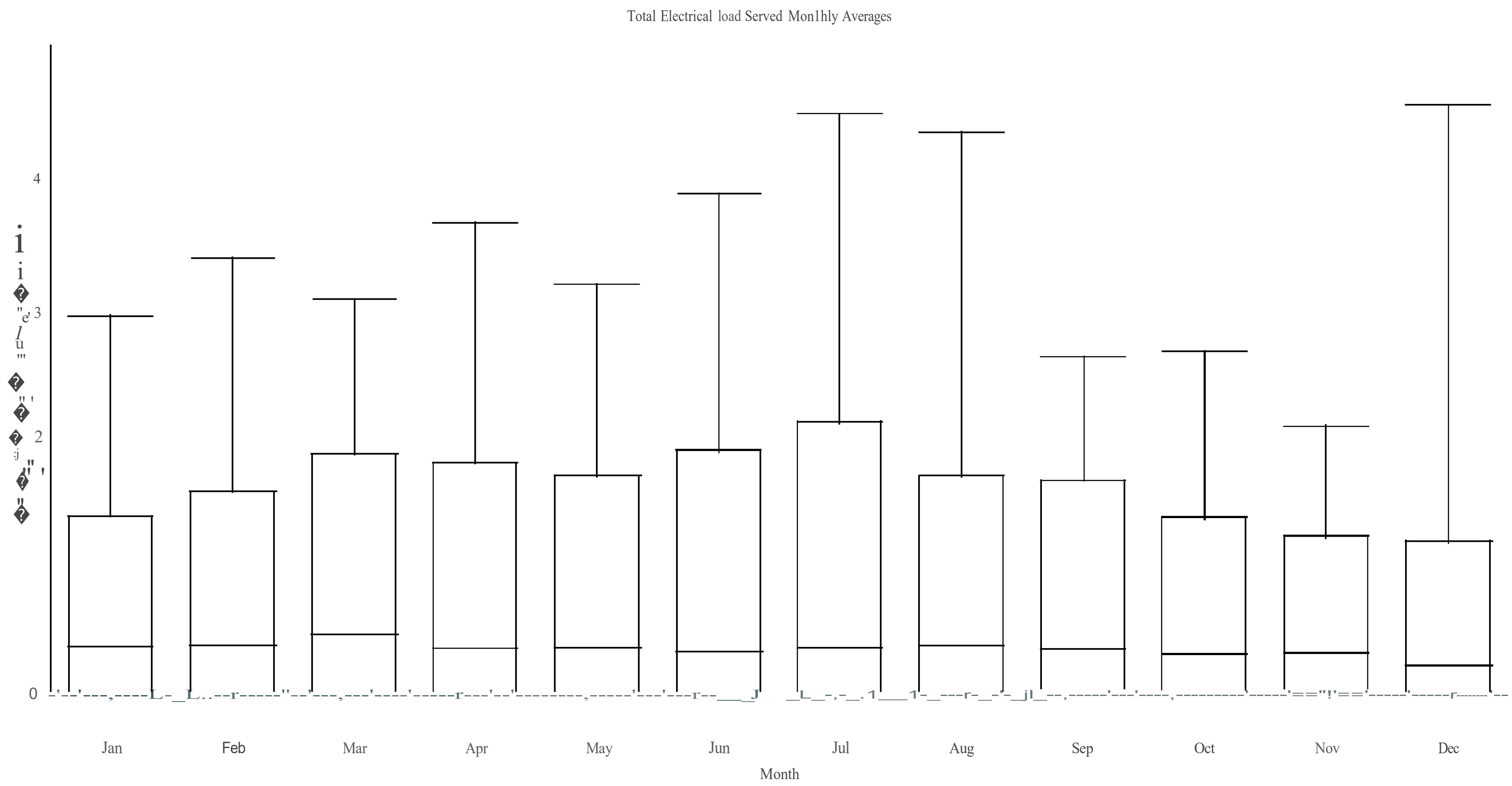


Figure 4.6- HOMER Pro™ Simulation, LiFeP04 Electrical Load Monthly Averages

4.3 - State of Charge Comparison

Shown below in figures 4.7 and 4.8, are State of Charge Monthly Averages simulation results using HOMER Pro™, with modelling based on scaled actual history charge and discharge figures from the Hornsdale 150 MW Power Reserve. These figures show that lithium iron phosphate exhibits a greater average range in state of charge percentage compared to lithium-ion, as well as maintain a significantly higher average state of charge over the course of the year, even when taking into account the 3% difference in storage capacity between the two simulation models. During December, simulation results shows lithium-ion with an average state of charge around 20%, whereas lithium iron phosphate is double that at around 40%, despite the two different chemistries operating with identical charge and discharge parameters.

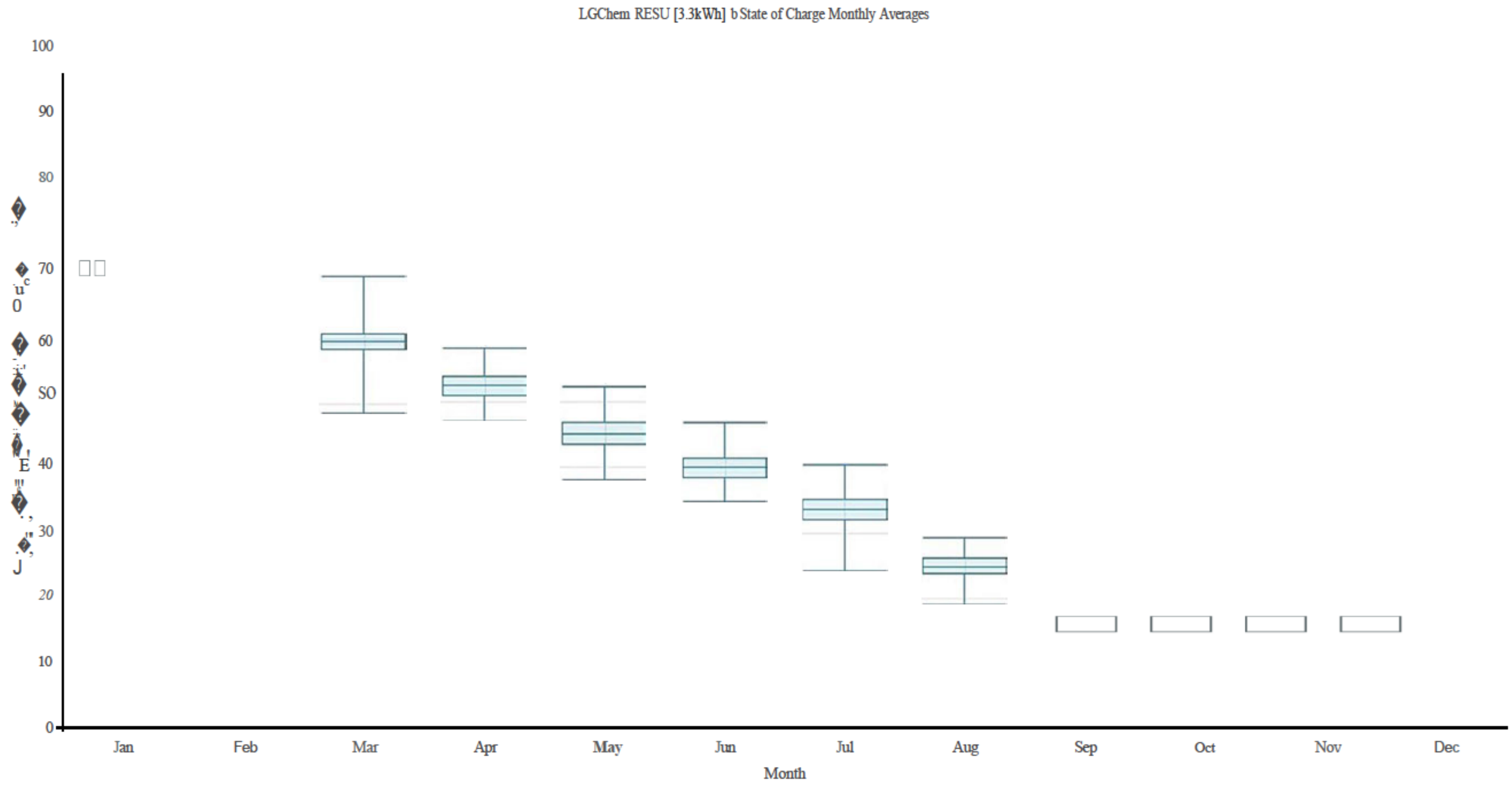


Figure 4.7-HOMER Pro™ Simulation, Lithium-ion State of Charge Monthly Averages

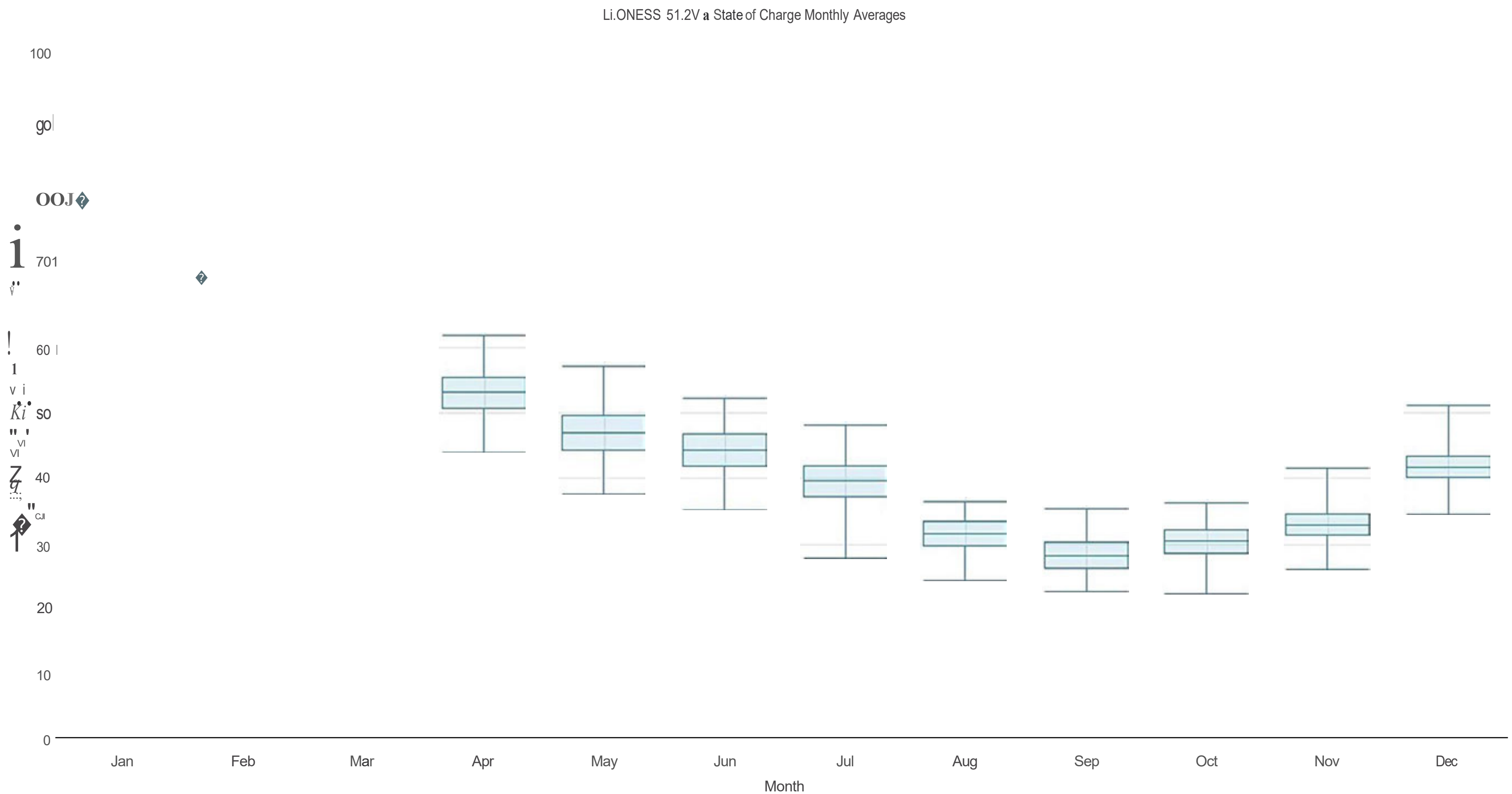


Figure 4.8-HOMER Pro™ Simulation, LiFePO4State of Charge Monthly Averages

4.4-Maximum Charge and Discharge Power Comparison

Despite both schematics demonstrating near identical average power input and output, as well as total electrical load served, there is a significant difference in maximum discharge power between lithium-ion and lithium iron phosphate. Lithium-ion exhibited a maximum discharge power, monthly average for the year in January, of over 130 kW, which is shown in Figure 4.9. Whereas lithium iron phosphate only exhibited a maximum for the year of less than 80 kW, also in January, shown in Figure 4.10. This is also reflected in maximum charge power averages, with lithium-ion exhibiting a maximum of just over 170 kW in October, shown in Figure 4.11, with lithium iron phosphate only exhibiting a maximum of just over 90 kW, also in October, shown in Figure 4.12.

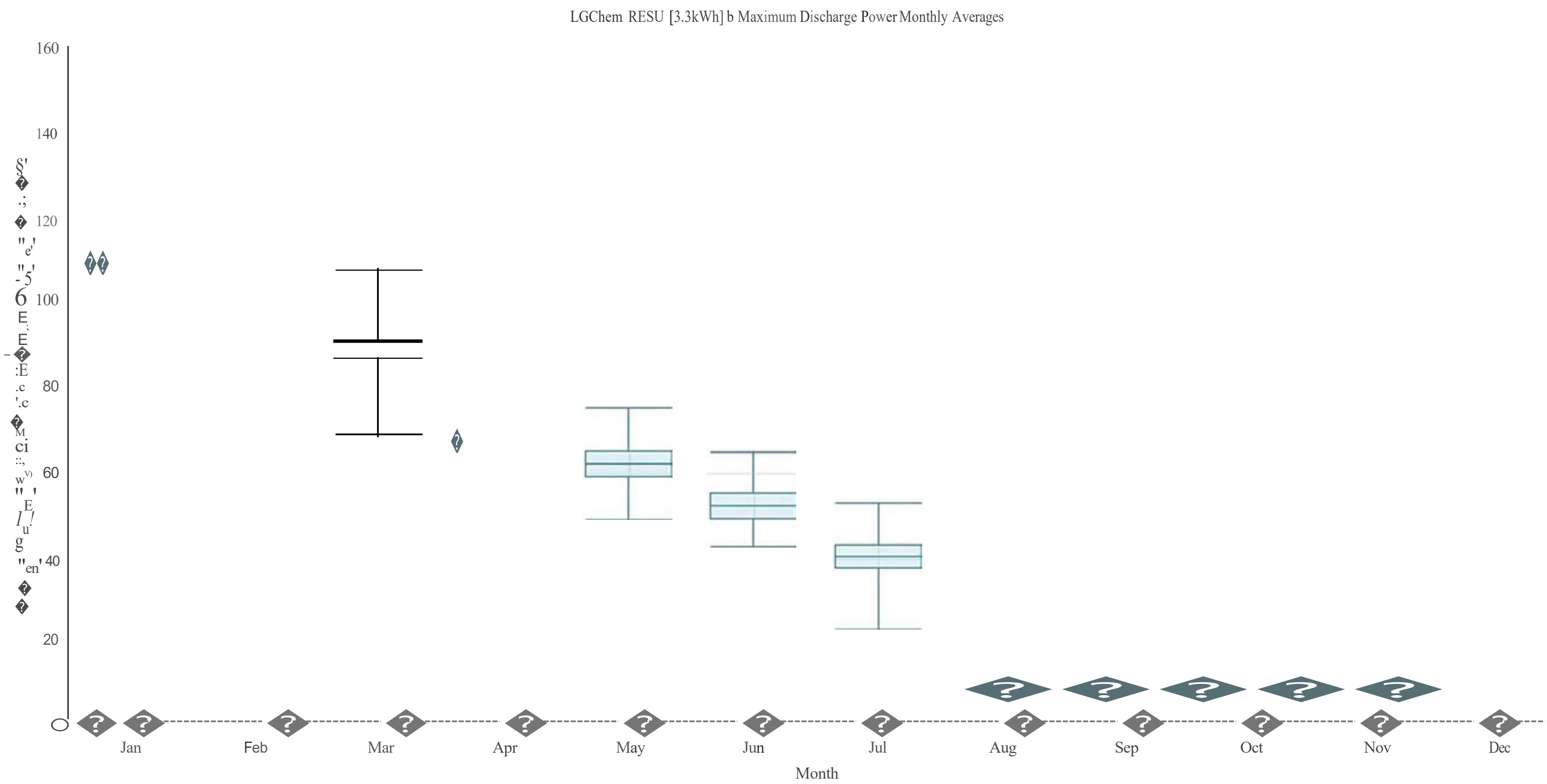


Figure 4.9- HOMER Pro™ Simulation, Lithium-ion Maximum Discharge Power Averages

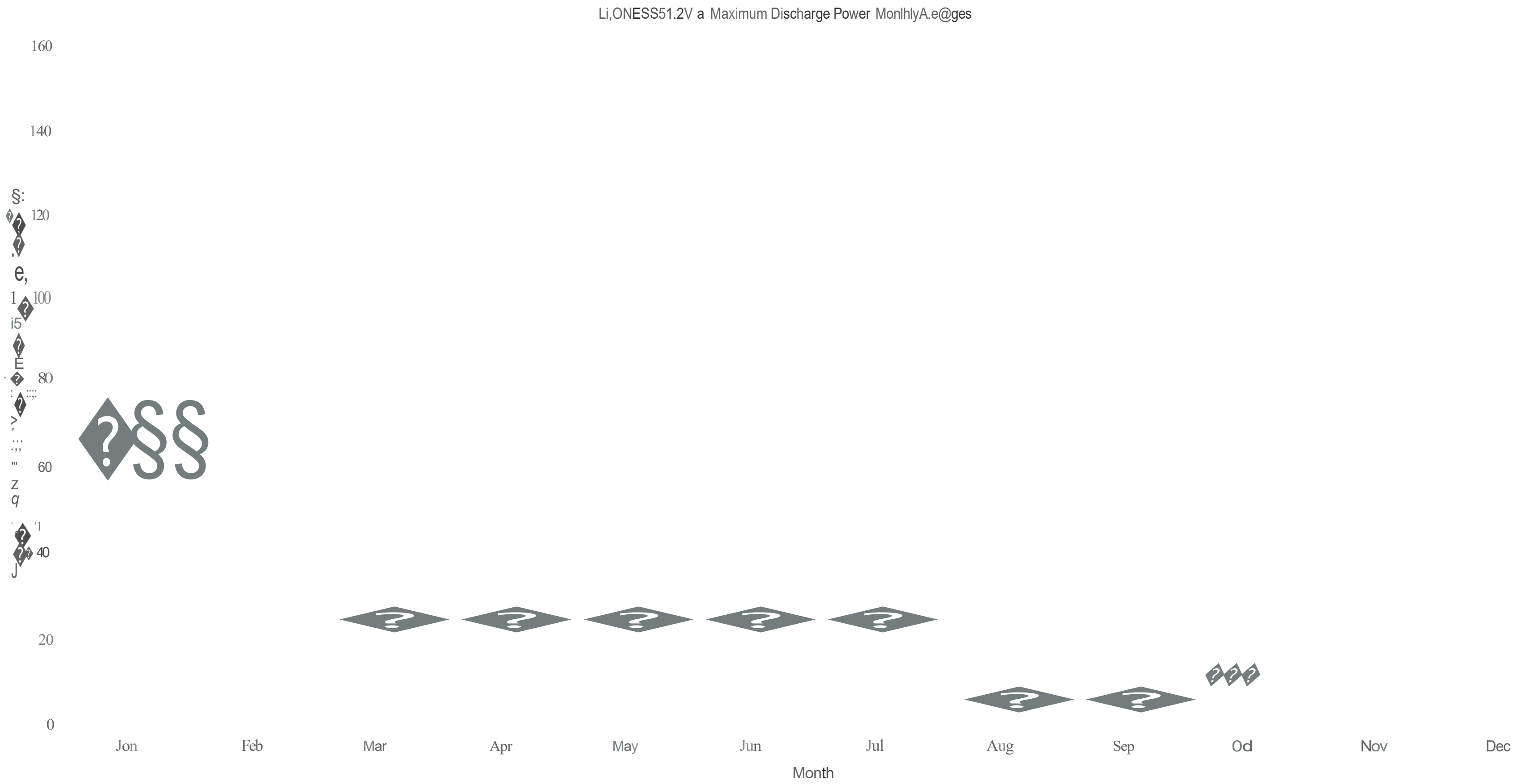


Figure 4.10-HOMER Pro™ Simulation, LiFePO4 Maximum Discharge Power Averages

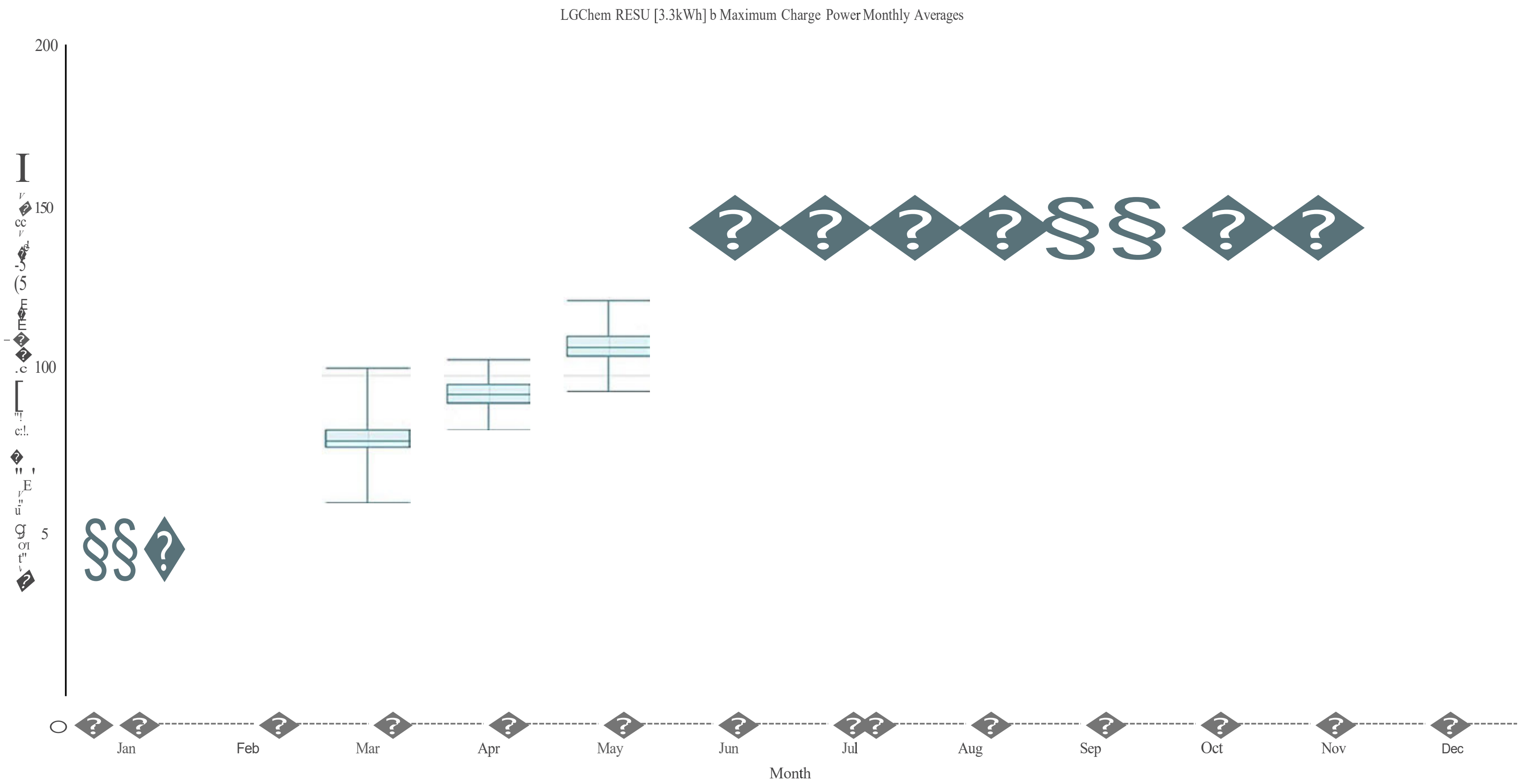


Figure 4.11 - HOMER ProTM Simulation, Lithium-ion Maximum Charge Power Averages

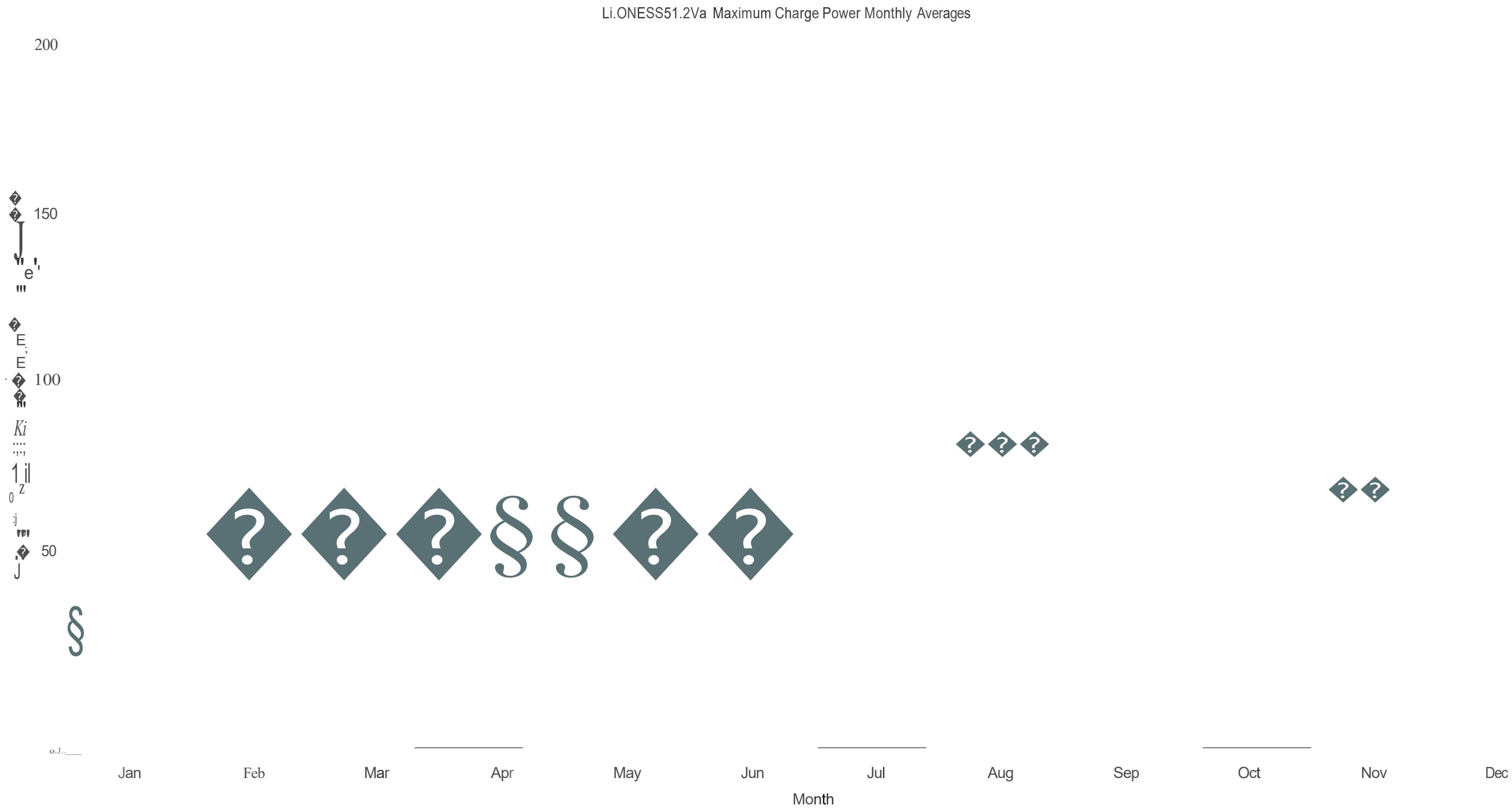


Figure 4.12 - HOMER Pro™ Simulation, LiFeP04 Maximum Charge Power Averages

Chapter 5 - Benefits, Consequences, Risks and Criticality

5.1 - Estimation of cost

Given the installation is purely hypothetical, with exact details such as conductor size, cable support and electrical enclosure requirements not able to be determined, a universal cost estimate figure utilised by industrial electrical estimators for a generic main switchboard including distribution network connection, will be included. This figure was learnt through performing industrial electrical estimator duties earlier in this year and has previously proven itself as not being an underestimate, however not being an excessive overestimation either. It allows for a range of unknowns such as electrical installation earth continuity non-conformance, replacement of main switchboard components to meet or exceed current Australian Standards and distribution network requirements, regardless of the age and condition of the current electrical installation, all of which contribute to overall installation cost.

Qty	**Component**	**Line / Unit Cost**	**Total Cost**
3	Tesla Powerwall™ 2	$11,790.00 (Springers Solar 2023)	$35,370
1	Dual Sim, Dual Band 4G Gigabit Router	$ 739.20 (Comset 2023)	$36,110
	Unit installation including Distribution Network connection, components and labour	$ 5,000.00	$41,110

Table 5.1 - Estimated cost per installation of three units, one per phase.

Given the estimated cost per installation is $41,110, as previously calculated 17,321 installations will be required to achieve a distributed system rating of 150MW, this equates to a total project cost of $712 million. This figure is significantly more than the project cost for the 150MW battery farm, which is approximately
$160 million, €56 million for the initial 1OOMW battery farm (Neon 2019) which converted to approximately $90 million, plus the $71 million for the SOMW expansion (Australian Renewable Energy Agency 2020). To be considered commercially profitable, the project cost would need to be generated as income within the first five years. For the proposed design, this equates to an estimated annual return of around $8,500. Using MATLAB®, actual operating figures for the 1SOMW Hornsdale Battery Farm during 2022, will be scaled to determine an estimated annual return.

5.2 - Estimation of profit

Actual operating figures for the l 50MW Hornsdale Battery Farm were obtained from the Hornsdale Power Reserve website (Neoen 2023). Using the Fixed interval of from 01/01/2022 00:01 to 31/12/2022 23:59, a csv file of actual operating figures was populated, then downloaded. This csv file was imported into MATLAB® using code 'importCSV.m', shown in Appendix C.1. Initially, the code 'BESS_Profitability.m' was run without scaling, that is variables 'MW_TO_5kW' and 'MWh_TO_kWh' were set to l, returning values of estimated profit for the 150MW battery farm. Secondly, the code was run again with variables changed to match equation 3.4.2, with a factor of 1,000 applied to both variables, converting the units from MW to kW. The outputted values of the code are summarised in table 4.2 below.

Estimated Profit	**1 year**	**10 years**	**15 years**
150 MW battery farm	$ 64,160,304	$641,603,036	$ 962,404,554
Proposed design	$ 3,704	$ 37,043	$ 55,564

Table 5.2 - Estimated profit, based on 2022 actual operating figures.

Estimation of the 150MW battery farm annual profit was run as a benchmark to demonstrate that the calculated values are within an accurate range. Official and exact figures for 2022 annual profit are difficult to obtain, however multiple unofficial sources are reporting that the Hornsdale Power Reserve has returned a profit, that is generated a total revenue greater than the total project cost of approximately $160 million, in just over two and half years. This would mean that the estimated annual income of $64 million is in fact within an accurate range. Manual calculations for the first hour of scaled operation are shown in Appendix C.3, of which the manually calculated figure of 0.1109 matches the returned code variable 'hourOneProfit', which demonstrates that the scaled equations are operating as expected. Given there is confidence in the calculated figures, a profitability conclusion can be made.

5.3 - Conclusion of profitability

In conclusion, the proposed design is not commercially profitable, as it does not return the capital investment cost within five years. The proposed design is also not profitable within the standard ten year warranty and assumed serviceable life for the Tesla Powerwall™ units. However, with the units being connected to the Tesla Power Plant™, claiming the additional five year warranty (Tesla 2023c) and assumed extended serviceable life, the proposed design will return the initial cost in approximately eleven years and one month, delivering a net profit of approximately $14,400 or 35 % of the initial cost, over the fifteen years. This is based on the assumption that the units will be able to operate at the scaled 2022 operating figures during year fifteen of unit operation.

In the absence of operational degradation curves or figures for the Powerwall™ units, as they are not stipulated by the manufacturer in the unit datasheet, the assumption of 80% available capacity at the end of serviceable life or during the fifteenth year of operation, similar to that of end of serviceable life Plug-in Electric Vehicle batteries (Cui et al. 2022), is being made. Using MATLAB™, the maximum value of the scaled data, indicate a maximum installation discharge rate of 6.11 kW or 71% of overall capacity, which would still be achievable in the fifteenth year, even with worst case battery degradation. Another factor to be considered is the expected change in lithium battery pricing going into the future.

Given current projects for lithium supply and demand are projecting a worldwide shortage in the upcoming years, this will not be favourable for the proposal's profitability. A shortage of raw material will almost certainly result **in an** increase in unit manufacturing cost, decreasing the profitability of the proposal. As the current estimated annual profit return is estimated at 2.33% over 15 years, this does not allow for a significant increase in manufacturing cost, before the proposal becomes not profitable at all. On the flipside, well into the future when supply manufacturing meets or exceeds consumer demand, manufacturing costs will almost certainly reduce, in turn increasing the profitability of the proposal. Battery simulation comparison between lithium-ion and lithium iron phosphate has demonstrated some expected figures.

5.4-Battery Simulation Comparison

Battery simulation comparison between two separate 10 kW battery schematics, one based on lithium-ion, the other based on lithium iron phosphate has demonstrated that lithium-ion battery has a slower rate of storage depletion, as show in Table 5.3 below.

	Lithium ion (kWh/yr)	**Lithium iron phosphate (kWh/yr)**
Storage Depletion	-35.2	-48.5
Losses	-39.8	-53.1
Annual Throughput	2,296	2,261

Table 5.3 - HOMER Pro™ Battery Comparison Simulation Results

The result is expected, based on literature review which demonstrated that lithium-ion has a higher cycle life expectancy, hence a slower rate of battery degradation. Simulation has demonstrated the lithium iron phosphate has a 37% higher rate of storage depletion or battery degradation per year, compared to lithium-ion. This would equate to a reduction in estimated serviceable life from 15 years for the current proposal, to 9 years and 5 months. Despite this, lithium iron phosphate simulates a higher average state of charge, as well as significantly lower maximum charge and discharge power averages. Indicating that lithium-iron phosphate is capable of delivering improved performance when compared to lithium-ion, however over a much shorter life expectancy.

Chapter 6 - Conclusions

6.1 - Aims, Objectives and Research Findings

In conclusion, modelling of actual history operating parameters for the Hornsdale 150 MW Power Reserve, scaled to a single proposed installation consisting of three 5 kW storage systems connected one per phase, ascertained that the proposed design would not be profitable within the standard 10 year manufacturer warranty. It would however be profitable within the extended 15 year warranty, which is available to individual units used exclusively in grid support mode, taking just over 11 years to recover estimated installation costs, return a profit of 35 % over the fifteen years. Further modelling was performed to compare alternate lithium based battery chemistries.

HOMER Pro™ modelling was performed between lithium-ion and lithium iron phosphate based battery energy storage systems, operating with the above mentioned scaled parameters. Lithium iron phosphate was chosen as literature review indicated that it is a superior option environmentally, compared to both lead acid and lithium-ion and is capable of delivering comparable performance to both of the alternative chemistries. Modelling showed that lithium-ion has a lower rate of storage depletion as well as losses, however lithium iron phosphate exhibits a much higher average state of charge over the course of the year, being twice that of lithium-ion during December, demonstrating that lithium iron phosphate is able to provide similar or better performance. However, with a 37% higher storage depletion rate compared to lithium-ion, it is not able to provide similar life cycle characteristics, although it is the better option environmentally at the end of serviceable life.

Environmental benefits of lithium iron phosphate include that there is no toxic materials after the material reclamation process, conducted at the end of battery's serviceable life, unlike both lead acid and lithium-1on. Other benefits include being able to utilise the reclaimed materials for purposes such as decontamination of industrial wastewater, with the reclaimed materials demonstrating supenor performance to currently utilised catalysts. Despite all of these factors, including improved performance over a shorter timeframe and environmental benefits that could be obtained through a change from lithium-ion battery chemistry, the benefits do not equate to an increase in profitability.

6.2 - Summary of learning from research project

Having started with a basic understanding of the national energy market and how fluctuations in renewable generation makes it difficult to provide stable power to the distribution networks, now having that knowledge extended to the importance of energy storage systems, the need to position them as close as possible to consumers to minimise distribution losses, as well as how profitable a large scale storage facility can be that reliably provides a controllable means of energy storage to the national market operator.

Knowledge has also been gained around specific dangers associated with lithium based batteries, in particular when used in large scale battery energy storage systems, as well as operating limitations for all kinds of batteries, most notably at lower (sub zero) temperatures, which is something that is not really covered during advanced trade training of standalone battery systems, especially in Queensland. Other knowledge gained includes the benefits and limitations of lithium iron phosphate when compared to both lead acid and lithium-ion, despite being superior environmentally, the longevity and in tum profitability is not there.

Having very limited prior knowledge of zinc based batteries, literature review has taught a lot around the potential for zinc based batteries, given the ready availably of the core materials, environmentally safe disposal, however they are not yet able to offer comparable cyclic performance nor size to power ratio. Given the amount ofresearch being conducted worldwide into zinc based batteries, attempting to create a comparable alternative, it should only be a matter of time.

Appendix A - Project Specification

For: Shane DALE

Title: Distributed, grid connected, controllable battery energy storage system, to assist with counteracting renewable generation fluctuations.

Major: Electrical and Electronics

Supervisors: Andreas Helwig

Enrollment: ENG4111-EXT Sl, 2023
ENG4l 12-EXT S2, 2023

Project Aim: To investigate the profitability and viability of a controlled, distributed Battery Energy Storage System, consisting of an individual 5 kW unit, similar to a 150 MW battery farm, as well as the possibility of a more environmentally friendly alternative battery chemistry, to the current standard of Lithium-Ion.

A.1 - Programme: Version 1, 11th March 2023

- Using MATLAB, perform mathematical modelling of historic controls (charge/ discharge) data for a 150 MW battery farm (Homsdale, SA for 2022), scaled to single 5 kW system.

2 - Using MATLAB, using the scaled controls data, calculated with the AMEO price history, determine an estimated income for a theoretical standalone battery inverter system, for the 2022 calendar year.

3 - Extrapolate the estimated annual income, to evaluate the profitability of a standalone battery inverter system over it's warranted (serviceable) life.

4 - Using HOMER Pro, simulate a comparison of the differing battery chemistries, with modelling based on the historic data captured from the 150 MW battery farm, to determine a superior battery chemistry for the proposed purpose.

5 - Evaluate any performance differences between the current standard of lithium-ion batteries and the lithium iron phosphate alternative, to determine the overall viability of lithium iron phosphate.

6 - Using part of the literature review, determine which of the battery chemistries have the lowest level of environmental waste at the end of serviceable life. Noting any performance differences between the battery chemistries, develop findings to support and discredit a change away from the current standard of lithium-ion.

Jf time and resource permit:

7 - Evaluate performance differences between lithium-ion, lithium iron phosphate and any other battery chemistry deemed through literature review, to be plausibly viable.

A.2 - ENG4111/4112 - Project Plan - rev 1 (13 Mar 2023)

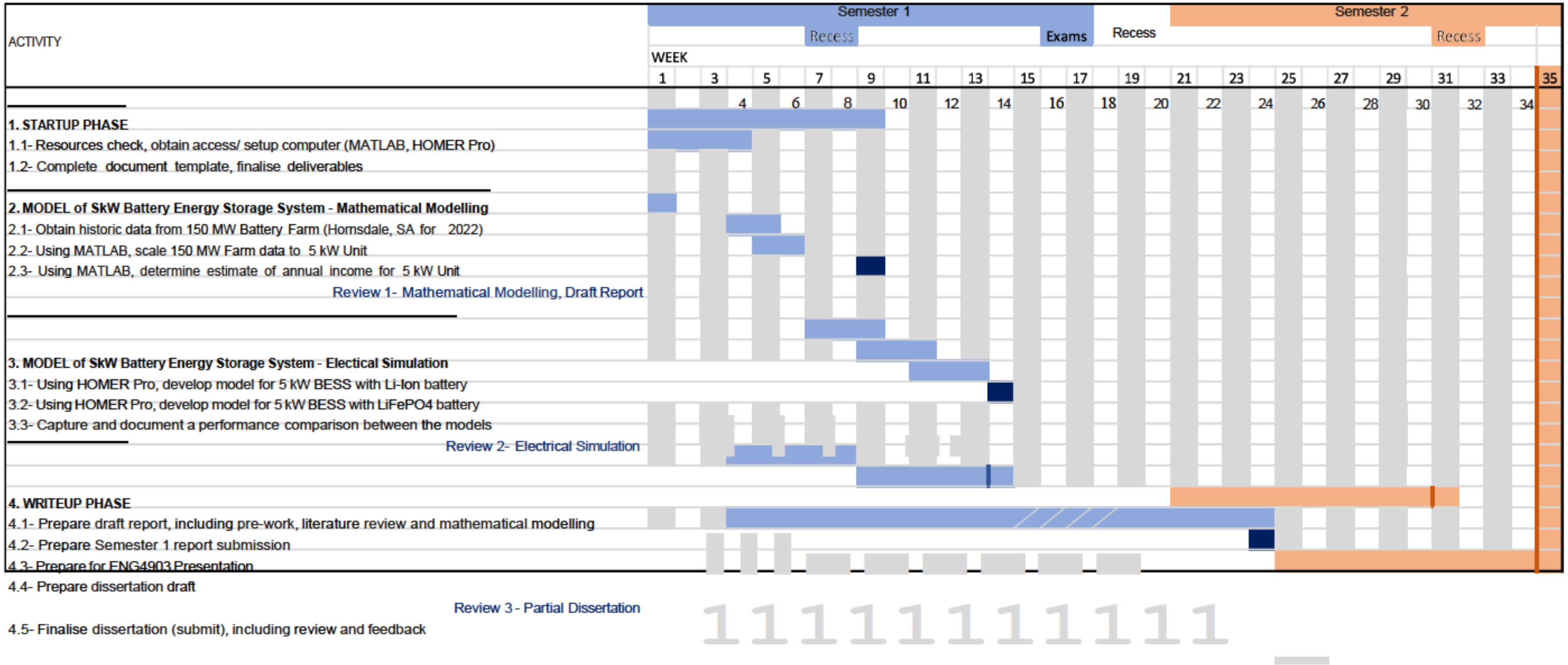


Figure A.1 - Project Plan

A.3 - Communication

Communication will be predominately via email, with latest progress drafts forwarded, containing 'Track Changes' to highlight changes from the previous draft.

Queries will be initially sent via email, however if a more complex discussion is required, telephone/ online meeting will be organised as required.

Progress update emails will occur at intervals of no greater than the Review weeks stipulated above (around 5 working weeks), however sections will be forwarded on as soon as they are completed.

Closer to week 30, will aim to book in a face-to-face discussion, for either late week 30 or during week 31 (Semester 2, 2023 week 10 or 11), depending on availability, whilst in Toowoomba for ENG4903.

A.4-ENG4111/4112 -Project Resources- rev 1 (13 Mar 2023)

Purchase equipment or raw material

There will be no need to purchase equipment or raw material.

Access to specific laboratory or workshop facilities

Will require access to USQ licence and/or remote access for HOMER Pro.

Training for HOMER Pro will also be required, which is offered by the software distributor via a YouTube channel. Instructor led training is also available for a fee. Will need to look into USQ available resources for software training, whilst attempting to get access to the software.

Already have access to a USQ licenced MATLAB, installed for another subject. Training to complete the required data import and then calculation output, is also provided by another subject.

Particular data sets or documents

Have already obtained a csv download of the Hornsdale, SA 150MW Battery Farm historic operating data for 2022, which also contains the AEMO pricing for each 5 minute of time. This was downloaded directly from Hornsdale Battery Farm website.

Access to a site that may only be available at certain times

No site access will be required.

Consider contingencies if there is a problem

If HOMER Pro access is not available / obtainable through USQ, or am unable to perform the comparison between battery chemistries as planned, will need to either look for an alternative software package and/or obtain an individual software licence.

Appendix B -Tesla Powerwall Datasheet

Sourced: Tesla 2023, *Powerwall,* Datasheet, viewed 18th Mar 2023, <https://www.tesla.com/sites/default/files/pdfs/powerwall/Powerwallo/o202_AC_Datasheet_en_AU.pdt>.

POWERWALL

Tesla Powerwall is a fully-integrated AC battery system for residential or light commercial use. Its rechargeable lithium-ion battery pack provides energy storage for solar self-consumption, time-based control, and backup.

Powerwall's electrical interface provides a simple connection to any home or building. Its revolutionary compact design achieves market-leading energy density and is easy to install, enabling owners to quickly realize the benefits of reliable, clean power.

PERFORMANCE SPECIFICATIONS

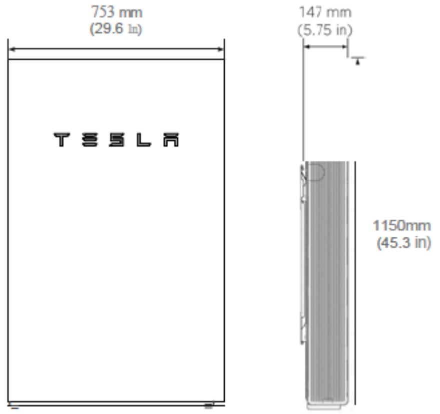
AC Voltage (Nominal)	230 V
Feed-In Type	Single Phase
Grid Frequency	50 Hz
Total Energy'	14kWh
Usable Energy'	13.5 kWh
Real Power, max continuous[2]	5 kW (charge and discharge)
Apparent Power, max continuous	5 kVA (charge and discharge)
Maximum Supply Fault Current	10 kA
Maximum Output Fault Current	32 A
Power Factor Output Range	+/- 1.0 adJustable
Internal Battery DC Voltage	50 V
Round Trip Efficiency [1,3]	90%
Warranty	10 years

[7]Values provided for 25°C, 3.3 kW charge/discharge power.
[2]1n Backup mode, grid charge power is limited to 3.3 kW.
[3]AC to battery to AC. at beginning of life.

MECHANICAL SPECIFICATIONS

Dimensions[1]	1150 mm x 753 mm x 147 mm
Weight	114 kg
Mounting options	Floor or wall mount

[1]Dimensions and weight differ slightly if manufactured before March 207 9. Contact Tesla for additional information.



COMPLIANCE INFORMATION

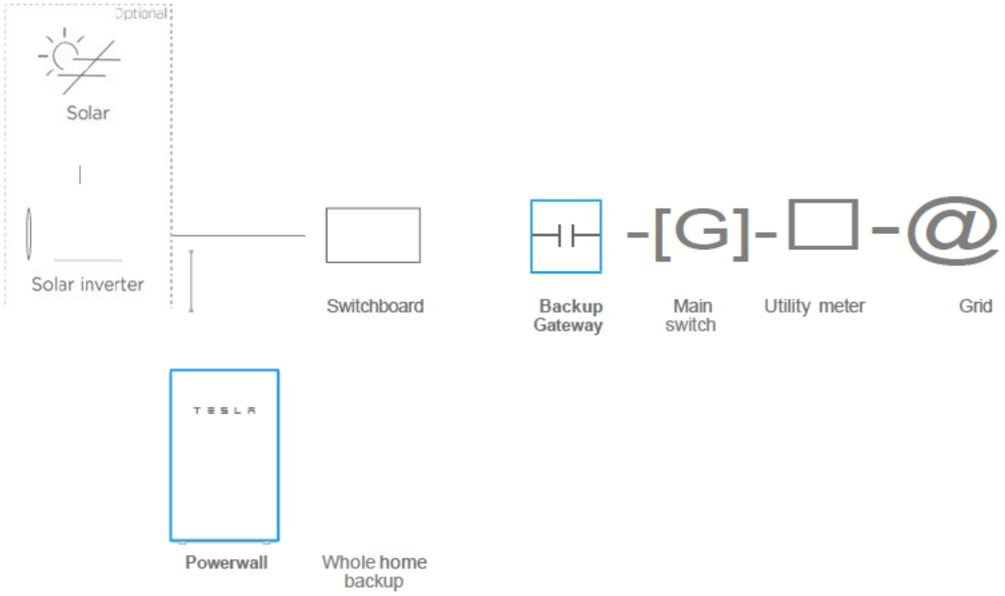
Certifications	IEC 62109-1, IEC 62109-2, IEC 62619, UN 38.3
Grid Connection	Worldwide Compatibility
Emissions	IEC 61000-6-1, IEC 61000-6-3
Environmental	RoHS Directive 2011/65/EU, WEEE Directive 2012/19/EU, Battery Directive 2006/66/EC, REACH Regulation
Seismic	AC156, IEEE 693-2005 (high)

ENVIRONMENTAL SPECIFICATIONS

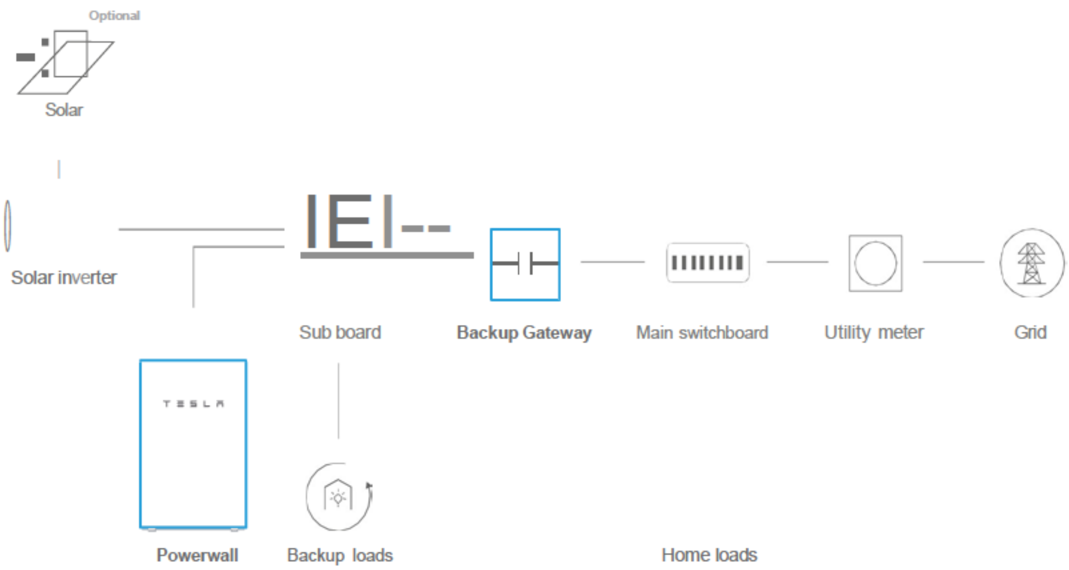
Operating Temperature	-20°C to 50°C
Recommended Temperature	0°C to 30°C
Operating Humidity (RH)	Up to 100%, condensing
Storage Conditions	-20°C to 30°C Up to 95% RH, non-condensing State of Energy (SoE): 25% initial
Maximum Elevation	3000 m
Environment	Indoor and outdoor rated
Ingress Rating	IP67 (Battery & Power Electronics) IP56 (Wiring Compartment)
Wet Location Rating	Yes
Noise Level @ 1m	< 40 dBA at 30°C

TYPICAL SYSTEM LAYOUTS

WHOLE HOME BACKUP



PARTIAL HOME BACKUP



Appendix C - MATLAB® Code and Mathcad® Calculations

C.1 - importCSV.m

```
%% Import data from CSV file - importCSV.m -
% Script for importing data from the following CSV file:
%
%    filename: ./Ez2viewAustralia - Hornsdale 150MW Battery in SA (Download) -
28th Jan 2023, 18 14 OTC+10.csv
%
% Auto-generated by MATLAB on 25-Mar-2023 07:57:02
%
% Created by Shane DALE [redacted] - March 2023

%% Set up the Import Options and import the data
opts= delimitedTextimportOptions("NumVariables", 6);

% Specify range and delimiter
opts.DataLines   [2, Inf];
opts.Delimiter=",";

% Specify column names and types
opts.VariableNames = ["Var1", "Var2", "PriceFCASRegulationLowerMWh",
"PriceFCASRegulationRaiseMWh", "BatteryDischargingMW", "BatteryChargingMW"];
opts.SelectedVariableNames = ["PriceFCASRegulationLowerMWh",
"PriceFCASRegulationRaiseMWh", "BatteryDischargingMW", "BatteryChargingMW"];
opts.VariableTypes = ["string", "string", "double", "double", "double",
"double"];

% Specify file level properties
opts.ExtraColumnsRule = "ignore";
opts.EmptyLineRule = "read";

% Specify variable properties
opts   setvaropts(opts, ["Var1", "Var2"], "WhitespaceRule", "preserve");
opts = setvaropts(opts, ["Var1", "Var2"], "EmptyFieldRule", "auto");

% Import the data
Hornsdale150MWBattery2022 = readtable("./Ez2viewAustralia - Hornsdale 150MW
Battery in SA (Download) - 28th Jan 2023, 18 14 OTC+10.csv", opts);

%% Convert to output type
Hornsdale150MWBattery2022 = table2array(Hornsdale150MWBattery2022);

%% Clear temporary variables
clear opts
```

C.2 - BESS_Profitability.m

```
%% Determine profitability of 3 phase 5kWh units - BESS Profitability.m -
%
% Script to scale raw historical data from the Hornsdale 150MW battery farm
%  to a 3 phase connected 5kWh 'individual unit', to determine an annual
%  income estimate of the 'individual unit' for the year 2022.
%
% Created by Shane DALE [redacted] - March 2023


%% clear the Display and Workspace
clc
clear

% import raw historical data
importCSV

% define scale constants
MW_TO_SkW = ((sqrt(3) * (1 / 30000)) * 1000);
MWh_TO_kWh = (1 / 1000);

% commented out, used to determine estimate for actual 150MW battery farm
%MW_TO_5kW = 1;
%MWh_TO_kWh = 1;

%% array and variable to calculate nett dis/charge and profit for hour one
hourOneTest = NaN(12,2);
hourOneProfit = 0;


% raw data in 5 minute increments, 12 for hour one
for N = 1:12
    % nett dis/charge for 5 minute increment
    hourOneTest(N,1) = ((Hornsdale150MWBattery2022(N,3) + ...
        Hornsdale150MWBattery2022(N,4)) * MW_TO_SkW);

    % nett profit for 5 minute increment
    hourOneTest(N,2) = (((Hornsdale150MWBattery2022(N,3) * MW_TO_5kW) *
        (Hornsdale150MWBattery2022(N,2) * MWh_TO_kWh)) -
        ((Hornsdale150MWBattery2022(N,4) * MW_TO_SkW) * ...
        (Hornsdale150MWBattery2022(N,1) * MWh_TO_kWh)));

    % add nett profit to rolling total
    hourOneProfit = hourOneProfit + hourOneTest(N,2);
end


%% array and variable to calculate nett dis/charge and profit for the year
BESS_SkW = NaN(length(Hornsdale150MWBattery2022),2);
annualProfit = 0;

% raw data in 5 minute increments, 12 for hour one
for N = 1:length(Hornsdale150MWBattery2022)
    % nett dis/charge for 5 minute increment
    BESS_SkW(N,1) = ((Hornsdale150MWBattery2022(N,3) +
        Hornsdale150MWBattery2022(N,4)) * MW_TO_SkW);

    % nett profit for 5 minute increment
```

```
    BESS_5kW(N,2) = (((Hornsdale150MWBattery2022(N,3) * MW_TO_5kW) *
        (Hornsdale150MWBattery2022(N,2) * MWh_TO_kWh)) - ...
        ((Hornsdale150MWBattery2022(N,4) * MW_TO_5kW) * ...
        (Hornsdale150MWBattery2022(N,1) * MWh_TO_kWh)));

    % add nett profit to rolling total
    annualProfit = annualProfit + BESS_5kW(N,2);
end


%% display result to command window
str = sprintf('%.0f',annualProfit);
str5 = sprintf('%.0f',(annualProfit * 5));
str10   sprintf('%.0f',(annualProfit * 10));
str15 = sprintf('%.0f',(annualProfit * 15));

% add comma separators to strings
str = regexprep(str,'\d{1,3)(?=(\d{3})+\>)','$&, ');
str5 = regexprep(str5,'\d{1,3}(?=(\d{3})+\>)','$&, ');
str10   regexprep(str10,'\d{1,3}(?=(\d{3})+\>)','$&, ');
str15 = regexprep(str15,'\d{1,3)(?=(\d{3})+\>)','$&, ');

% output strings
disp("Estimated annual profit is       $ " + str)
disp("Estimated profit over  5 years is $" + str5)
disp("Estimated profit over 10 years is $" + str10)
disp("Estimated profit over 15 years is $" + str15)
```

C.3 - Matchcad calculation for first hour of scaled raw data

C.3.1 - Source Data

$$lowerMWh := \begin{pmatrix} 7.5 \\ 9 \\ 9 \\ 7.5 \\ 10.88 \\ 9 \\ 7.5 \\ 9 \\ 7.5 \\ 9 \\ 10.49 \\ 7.5 \end{pmatrix} \qquad raiseMWh := \begin{pmatrix} 19.94 \\ 19.94 \\ 19.94 \\ 19.94 \\ 19.94 \\ 24.79 \\ 19.94 \\ 19.94 \\ 19.94 \\ 24.79 \\ 24.79 \\ 24.79 \end{pmatrix}$$

$$dischargeMW := \begin{pmatrix} 0 \\ 19.7 \\ 1.5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 29.9 \\ 8.9 \\ 0.9 \end{pmatrix}$$

$$chargeMW := \begin{pmatrix} -15.2 \\ 0 \\ 0 \\ -6.2 \\ -5.2 \\ -17.5 \\ -2.2 \\ 0 \\ 0 \\ 0 \\ -27.1 \\ -3.5 \end{pmatrix}$$

C.3.2 - 150MW raw data scaled to 3 phase 5kW units

$$powerkWh := \frac{powerMWh}{1000} = \begin{pmatrix} 0.0081 \\ 0.0090 \\ 0.0090 \\ 0.0075 \\ 0.0109 \\ 0.0090 \\ 0.0075 \\ 0.0090 \\ 0.0075 \\ 0.0090 \\ \text{[illegible]} \\ \text{[illegible]} \end{pmatrix} \qquad raisekWh := \frac{raiseMWh}{1000} = \begin{pmatrix} 0.0199 \\ 0.0199 \\ 0.0199 \\ 0.0199 \\ 0.0199 \\ 0.0248 \\ 0.0199 \\ 0.0199 \\ 0.0199 \\ 0.0248 \\ 0.0248 \\ \text{[illegible]} \end{pmatrix}$$

$$dischargekW := \left(\frac{\sqrt{3}\cdot(dischargeMW)}{30000}\right)\cdot 1000 = \begin{pmatrix} 0.0000 \\ 1.1374 \\ 0.0866 \\ 0.0000 \\ 0.0000 \\ 0.0000 \\ 0.0000 \\ 1.7263 \\ 0.5138 \\ 0.0520 \\ 0.0000 \\ 0.0000 \end{pmatrix}$$

$$chargekW := \left(\frac{\sqrt{3}\cdot(chargeMW)}{30000}\right)\cdot 1000 = \begin{pmatrix} -0.8776 \\ 0.0000 \\ 0.0000 \\ -0.3580 \\ -0.3002 \\ -1.0104 \\ -0.1270 \\ 0.0000 \\ 0.0000 \\ 0.0000 \\ -1.5646 \\ -0.2021 \end{pmatrix}$$

$$hourOneProfit := (dischargekW \cdot raisekWh)_1 - (chargekW \cdot powerkWh) = 0.1109$$

Appendix **D** - Risk Assessment

University of Southern Queensland **Offline Version**

USQ Safety Risk Management System

Note: This is the offline version of the Safety Risk Management System (SRMS) Risk Management Plan (RMP) and is only to be used for planning and drafting sessions, and when working in remote areas or on field activities. It must be transferred to the online SRMS at the first opportunity.

Safety Risk Management Plan - Offline Version			
Assessment Title:	Research Proposal Risk Assessment	Assessment Date:	**8/05/2023**
Workplace (Division/Faculty/Section):	Engineering	Review Date:(5 Years Max)	**8/05/2024**
Context			
Description:			
What is the task/event/purchase/project/procedure?	Research Project		
Why is it being conducted?	Assessment Requirement		
Where is it being conducted?	Offsite		
Course code (if applicable)	**ENG4111 & ENG4112**	Chemical name (if applicable)	**UN 3480**
What other nominal conditions?			
Personnel involved	Licenced Electrical Fitter Mechanic, with Advanced Trade Certification in Standalone Power Systems		
Equipment	Lithium-ion and Lithium iron phosphate batteries, commercially acquired grid connected battery storage system		
Environment	Commercially acquired IP rated equipment or non-rated equipment installed in IP rated enclosures		
Other	Hazardous voltages up to 400 VAC, residential level radio frequency transmission		
Briefly explain the procedure/process	Design, construction and testing of a distributed, grid connected, controllable Battery Energy Storage System		
Assessment Team -who is conducting the assessment?			
Assessor(s)	Shane Dale		
Others consulted:	Andreas Helwig		

Eg 1. Enter Consequence

Eg2.Enter Probability

Probability	Insignificant No Injury 0-$5K	Minor First Aid $5K-$50K	Moderate Med Treatment $50K-$100K	Major Serious Injuries $100K.$250K	Catastrophic Death More thc11 $250K
	M	H	E	E	E
Likely 1in100	M		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	

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

Step 1 (cont)	Step 2	Step 2a	Step 2b	Step 3			Step 4				
Hazards: From step 1 or more if identified	*The Risk:* What can happen if exposed to the hazard without existing controls in place?	*Consequence:* What is the harm that can be caused by the hazard without existing controls in place?	*Existing Controls:* What are the existing controls that are already in place?	*Risk Assessment:* Consequence x Probability= Risk Level			*Additional controls:* Enter additional controls if required to reduce the risk level	*Risk assessment with additional controls:*			
				Probability	Risk Level	ALARP? Yes/no		Consequence	Probability	Risk Level	ALARP? Yes/no
Example											
Working in temperatures over 35° C	Heat stress/heat stroke/exhaustion leading to serious personal injury/death	catastrophic	Regular breaks, chilled water available, loose clothing, fatigue management policy.	possible	high	No	temporary shade shelters, essential tasks only, close supervision, buddy system	catastrophic	unlikely	mod	Yes
Unsafe design **and/or** installation	Catastrophic failure of components, most notably the Lithium battery	Major	**All works to be performed by** licenced, certified personnel only, to all relevant standards	**Unlikely**	Moderate	No	Physical separation of the components under test to untrained persons	Minor	Unlikely	Low	Yes
Catastrophic failure of the lithium battery	Extremely hot fire blast, release of dangerous gases	Catastrophic	Physical separation of the test area, installation within a suitable fire rated enclosure made from 3mm thick carton or stainless steel	**Unlikely**	Moderate	**No**	Development of emergency procedures to ensure evacuation of and exclusion zone around test area	Minor	Unlikely	Low	Yes
Live electrical parts	Electric shock received during installation and/or testing	Moderate	**All works to be performed by** licenced, certified personnel only, following all relevant Safe Work Australia Model Codes of Practice, notably Managing electrical risks in the workplace	**Unlikely**	Moderate	Yes	Majority of the post-installation testing will not require live electrical testing, as the components will log the required information	Moderate	Rare	Low	Yes
Manual handling	Strain/ Crush injuries occurring during the installation phase	Minor	Follow Model Code of Practice for Hazardous manual tasks, for safe handling of heavy items	Possible	Moderate	No	Use of lifting/ carrying handle and tray supplied with battery	Minor	Unlikely	Low	Yes

Step 1 (cont)	Step 2	Step 2a	Step 2b	Step 3			Step 4				
Hazards: From step 1 or more if identified	*The Risk:* What can happen if exposed to the hazard without existing controls in place?	*Consequence:* What is the harm that can be caused by the hazard without existing controls in place?	*Existing Controls:* What are the existing controls that are already in place?	*Risk Assessment:* Consequence x Probability= Risk Level			*Additional controls:* Enter additional controls if required to reduce the risk level	*Risk assessment with additional controls:*			
				Probability	**Risk Level**	**ALARP? Yes/no**		**Consequence**	**Probability**	**Risk Level**	**ALARP? Yes/no**
Example											
Working in temperatures over 35° C	Heat stress/heat stroke/exhaustion leading to serious personal injury/death	catastrophic	Regular breaks, chilled water available, loose clothing, fatigue management policy.	possible	high	No	temporary shade shelters, essential tasks only, close supervision, buddy system	catastrophic	unlikely	mod	Yes
Inclement weather	Exposure to high UV, **extreme heat or cold,** rain, storms etc.	Insignificant	Avoid working in inclement weather, follow heat stress management and sun smart strategies	Almost Certain	Moderate	Yes	Use of weatherproof **enclosures to prevent** component exposure to inclement weather	Minor	Unlikely	Low	Yes
Ignition sources	**Mixing of** incompatible dangerous good within the dedicated test area	Major	No other class of dangerous goods or ignition sources are to be stored in and/or around the dedicated test area	**Unlikely**	Moderate	No	Securing of the test area through use of physical barriers and padlock, appropriate dangerous goods signage	Minor	Unlikely	Low	Yes

Step 5 - Action Plan (for controls not already in place)

Additional controls:	*Resources:*	*Persons responsible:*	*Proposed implementation date:*
Physical separation of the components under test to untrained persons	Physical barriers, test area located away from general access areas, use of specialist tools to limit access	Installer	Click here to enter a date.
Majority of the post-installation testing will not require live electrical testing, as the components will log the required information	Electrical warning signage compliant with all relevant standards	installer	Click here to enter a date.
Use of lifting/ carrying handle and tray supplied with battery	Additional resources supplied with battery	Installer	Click here to enter a date.
Use of weatherproof enclosures to prevent component exposure to inclement weather	Commercially acquired weatherproof enclosures	Installer	Click here to enter a date.
Securing of the test area through use of physical barriers and padlock, appropriate dangerous goods signage	Physical barriers and padlock, suitable dangerous goods signage for UN 3480 items.	Installer	Click here to enter a date.
Development of emergency procedures to ensure evacuation of and exclusion zone around test area	Awareness training for those working around or in the test area to the additional dangers	1nstaller / Site Health and Safety Committee	Click here to enter a date.

Step 6 - Approval

Drafter's name:	Shane Dale	Draft date:	8/05/2023
Drafter's comments:	Actual installation of the proposed design is not intended to be completed as part of this research project		
Approver's name:		Approver's title/position:	
Approver's comments:			
I am satisfied that the risks are as low as reasonably practicable and that the resources required will be provided.			
Approver's signature:		Approval date:	Click here to enter a date.

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