University of Southern Queensland

Faculty of Health, Engineering & Sciences

An Environmental Controls Analysis for a Vanadium Redox Flow Battery (VRFB)

A dissertation submitted by

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ABSTRACT

The outlook on electricity system on the global scale in recent years has reflected the changing societal viewpoints towards environmental sustainability. In turn, electrical distribution companies such as Ergon Energy or Energex (with parent company Energy Queensland) have adapted their network structure and responses to safely and successfully harness these technologies successfully. Renewables are a main driver for the change on the grid but introduce complexities such as a lack of system inertia. Issues such as this can be addressed by technologies such as batteries. They are thus vital for ongoing operation of the everchanging network structure, and limitations need to be considered. One such battery solution is the recent operational emergence of the Vanadium Redox Flow Battery (VRFB).

Emerging technologies can, however, introduce new problems to solve and with sustainability as a point of issue, the environmental impact of these technologies needs to be understood more effectively. Thus, the project aim is to conclude what are the major driving elements for a Vanadium Redox Flow Battery's impact on the environment. This is to inform the development of an environmental controls framework that addresses risk management processes through business controls. The framework provides a logical and streamlined approach towards the assessment of all projects in an environmental capacity, whilst focusing on the current issue of the VRFB. This has been achieved through investigative analysis of:

- Clarifying site conditions such as climatic, legal and other operating limitations by investigating Energy Queensland circumstances.
- Identification of potential unknown relationships through a quantified literature analysis.
- Reliability assessments of individual components using probability to assess what conditions significantly affect system reliability.
- Risk Analysis with industry feedback to best inform a draft decision risk matrix to populate the draft controls framework.

Upon completion of these tasks, the environmental controls framework draft was completed to provide simplicity and scalability through implementation. The findings have found a link between climatic concepts and operational implications but have also led towards next steps of business integration.

Limitations are found with minimal exposure to industry values through lack of resources as well as with time affecting the analysis outcomes, such as a series of life cycle assessments unable to be undertaken. The overall understanding of VRFB's in an operational capacity is relatively unknown and as such can find limitations in consistent literature outcomes. This means that obtaining more understanding of best use cases will be a matter of using the technology and adapting developed policies around new findings, where the environmental controls framework will assist in providing that flexibility.

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CERTIFICATION OF DISSERTATION

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.

Luke Brandt

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06/11/2024

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Luke Brandt

University Of Southern Queensland (UniSQ)

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NOMENCLATURE

Definitions

Bunding	-	Chemical containment for leaks to ensure no leakage to external elements causing damage, injury or death.
Compound	-	An area bounded by natural containers or a bund, and sufficiently impervious to retain any fire water, spillage or leakage inclusive of the floor.
Cradle-to-Gate	-	The lifecycle of a product extending from raw material acquisition from to when the final product is developed before being utilised in field operation.
Cradle-to-Grave	-	The lifecycle of a product extending from raw material acquisition to disposal. Note: Some of the product may be reusable or recyclable and these instances are referred to as Cradle-to-Cradle. This is not a consistent term for VRFB usage and will not be used further.
Current Density	-	Implies an electrochemical reaction, where a high density indicates a faster reaction and vice versa

Abbreviations

AS/NZS	-	Australian Standards and New Zealand Standards.
BESS	-	Battery Energy Storage Systems
BMS	-	Battery Management System
CRD	-	Component Research Database
EFA	-	Exploratory Factor Analysis
EQL	-	Energy Queensland (Queensland Parent Company for Queensland Electrical Distribution Utilities)
FRP/ GRP	-	Fibre Reinforced Polyethylene/ Glass Reinforced Polyethylene
GHS	-	Globally Harmonized System of Classification and Labelling of Chemicals
GIS	-	Geographic information Systems
HCA	-	Hierarchical Clustering Analysis
HER	-	Hydrogen Evolution Reaction
HV	-	High Voltage
ICE	-	Internal Combustion Engine
ISO	-	International Organisation for Standards
Kh	-	Kilohours (1000 hours)
Km	-	Kilometres
LCA	-	Life Cycle Assessment
LGA	-	Local Government Area
LV	-	Low Voltage
MTTF	-	Mean Time To Failure
OEM	-	Original Equipment Manufacturer
ONAF	-	Oil Natural Air Forced
ONAN	-	Oil Natural Air Natural
PE	-	Polyethylene
PGA	-	Peak Ground Acceleration
PP	-	Polypropylene
PVC	-	Polyvinyl Chloride
REZ	-	Renewable Energy Zone
RH	-	Relative Humidity
SDG	-	Sustainable Development Goals
UniSQ	-	The University of Southern Queensland
VRFB	-	Vanadium Redox Flow Battery
WMS	-	Web Map Service

1.0 INTRODUCTION AND CONSULATION

1.1 Background

Ensuring effective project implementation can be a troublesome endeavour with numerous major elements such as financial, environmental, societal, legal and more needing to be considered for implementation. Exposure of renewables in the energy grid is growing, and other technologies are needed to help complement and maintain stable electrical supply with the conditions reliant generation source (Liu et al., 2023). To this end, Energy Queensland (EQL) has begun implementing Battery Energy Storage Systems (BESS) on a wide scale basis and are expanding from initially only Lithium-Ion utility scale installations. Recent expansions include smaller ‘Neighbourhood’ scale batteries as well as other battery technologies which evidently has required effective project management (Mick de Brenni & Lance McCallum, 2023). Another recent expansion is another battery type called the Vanadium Redox Flow Battery (VRFB) which is currently undergoing final stages of commissioning. Its’ usage complements similar Vanadium development in Queensland; where mining, a manufacturing facility and additional VRFB research locations are prevalent. The following figure shows general locations of these developments.

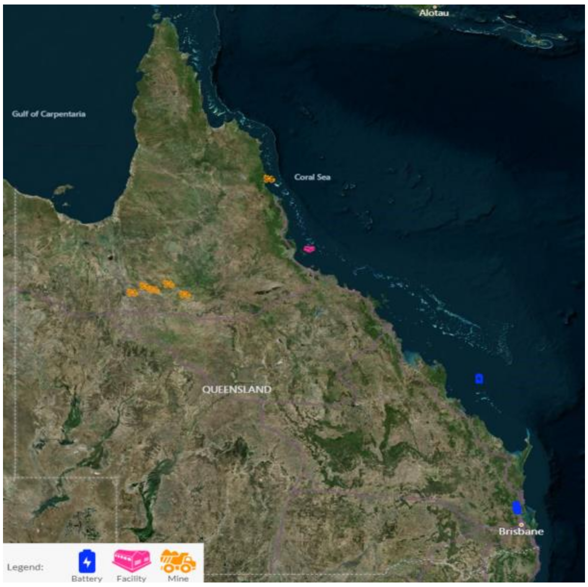

Figure 1-1: General Locations of Vanadium Resources and Developments in Queensland (Vanitec, 2024)

1.1.1 Working Principle

Vanadium Redox Flow batteries (VRFB's) were designed by Maria Skyllas-Kazacos with the University of New South Wales (UNSW) in 1986 (Skyllas-Kazacos et al., 1986). They are a chemical energy storage solution made of four main components to achieve power conversion to the grid that interact as below:

- The fluid circulation system is made up of two pumps, two tanks with electrolyte (catholyte and anolyte), plumbing components such as pipes and valves, and also sensors (British Standards Institution, 2020).
- Cells to create power: Consists of multiple components including electrodes for the positive and negative half cells respectively, an ion exchange membrane to separate the vanadium electrolyte ions and bipolar plates all arranged to achieve as a cell stack capable of power generation (Gautam & Kumar, 2022).
  The fluid is pumped in this cell arrangement according to half-cell polarity, and the cells can be arranged as a stack to combine power output from each cell. This cell stack is then finalised with current collector plates on the outside of the cell to ensure the chemical reaction is harnessed for electrical generation throughout the whole Cell Stack.
- A Battery Management System (BMS) which ensures effective battery operation in monitoring, protection, and communication purposes. It ensures optimal output under current battery operating conditions and as such is a major component to ensure reliability, longevity and safe operation of the battery.
- Battery Support System: Auxiliary components of the VRFB including but not limited to the heat exchanger and ventilation systems. It can be summarised any component that does not directly contribute to power conversion but is essential to safe and reliable operation.

The interaction of these parts can be explained as two sides to the battery cell stack which are the positive and the negative half cells consisting of positive and negative electrolyte. They both consist of a pump which circulates the vanadium electrolyte around each side of an Ion exchange membrane. This ion exchange membrane ideally allows hydrogen transfer only, however vanadium ion exchange can occur leading to reactions without electrical generation (Trovò & Guarnieri, 2020b). This chemical to electrical conversion process is made possible by the disparity of electrons between electrolyte in each tank. With hydrogen ion crossover, this promotes the flow of electrons through electrodes and into an AC/DC converter that feeds electricity back into the grid.

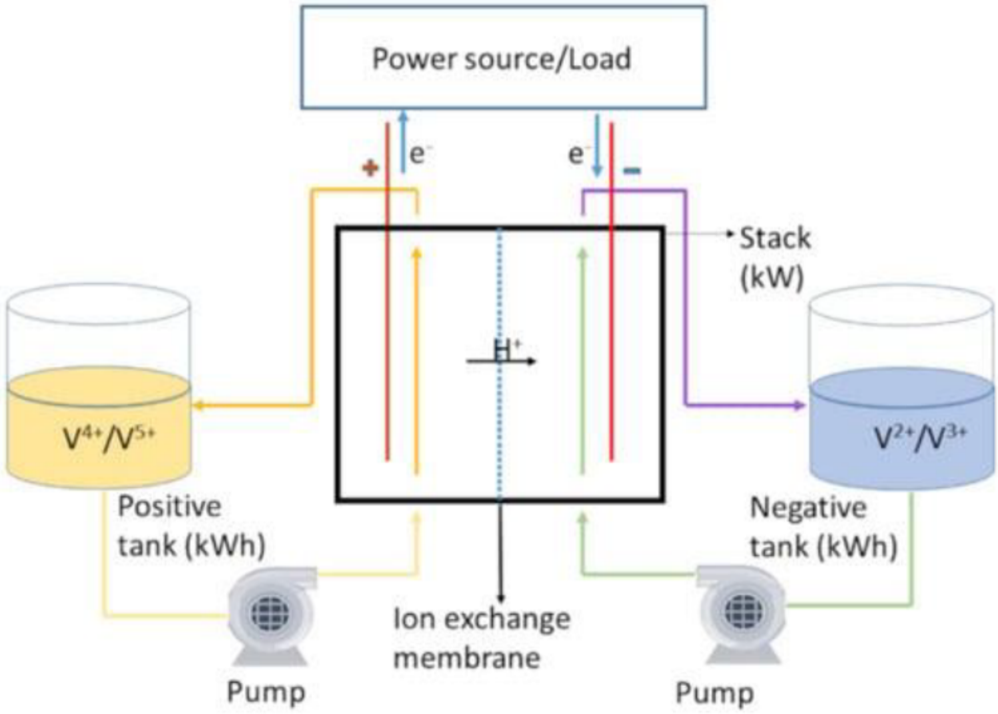

Figure 1-2: Vanadium Redox Flow Operation (Ghimire et al., 2021)

The chemical-electrical exchange can be summarised as below:

- Upon charging, current flows from the positive to the negative electrode meaning the positive electrolyte solution (Catholyte) loses an electron.
- Upon discharging, current flows from the negative to positive electrodes meaning the negative electrolyte solution (Anolyte) loses an electron.
- This is the redox reaction process, and each half reaction can be represented as:

Table 1-1: Redox Reactions and Cell Voltage

Redox Reactions	**Charging**	**Potentials (E°) (Jessie A. Key & Ball, 2014)**	**Discharging**
Positive Electrolyte	Oxidation: $V^{4+} - e^{-} \rightarrow V^{5+}$ (1.1)	1.000 V	Reduction: $V^{5+} + e^{-} \rightarrow V^{4+}$ (1.2)
Negative Electrolyte	Reduction: $V^{3+} + e^{-} \rightarrow V^{2+}$ (1.3)	-0.255 V	Oxidation: $V^{2+} - e^{-} \rightarrow V^{3+}$ (1.4)

The reversible redox reaction means that in one direction, there is an exothermic reaction. The direction for spontaneous exothermic reactions can be determined through comparison of reaction potentials, which is performed below on a cathode to anode directional basis.

$$\boldsymbol{E}^{\circ}_{\boldsymbol{cell}} = E^{\circ}_{cathode} - E^{\circ}_{anode} \tag{1.5}$$

$$\boldsymbol{E}^{\circ}_{\boldsymbol{cell}} = 1 - (-0.26)\ V = 1.26\ V\ in\ forward\ direction$$

Evidently this means that in the discharge direction, the reaction is spontaneous and thus exothermic, meaning it is producing heat whilst undergoing the change. Reversible redox reactions experience exothermic during discharge in this instance and thus are endothermic and non-spontaneous during the charging period. Meaning that the cell stack would be cooler than ambient temperature during the charging period.

One consideration for an oxidation process, there is the potential for byproduct dissolved oxygen to occur. Under storage conditions for chemicals, inert gas is often utilised to extend the life of the chemical as well as prevent oxidation from occurring in the chemical. To a fuel cell with a long life, using an inert gas such as nitrogen for this purpose could be expected. Fuel cells such as the Polymer Electrolyte Membrane (PEM) use the blanketing technique for this purpose (Meyer et al., 2016). Other techniques commonly used alongside blanketing is pressurised purging and venting, which allows certain contaminants to be picked up and vented to atmosphere as performed on a VRFB (Puleston et al., 2024) and discussed (Bhattarai et al., 2019). The use of inert gas for purification purposes is established for fuel cell usage and is a safe assumption as a control implemented in the current system design.

The inherent behaviour of this sealed system is that the lifecycle of the battery is not limited by the electrolyte but rather other components of the system such as pumps as well as electrode quality and their operating efficiencies. There are exceptions to this such as operating conditions to be covered further in this study. An electrolyte run in optimal conditions can achieve a large cycle life of 270000 charge-discharge cycles with minimal loss to system efficiency over the course of its' life (Minke et al., 2017). Evidently, practical system usage is a limitation to the theoretical limits, but some work has been undertaken investigating this. The modelling of the VRFB in both generation (Lei et al., 2021) and costing capacities has been explored (Minke et al., 2017), meaning that the technology is well researched and requires effective grid integration to flourish.

Thermal considerations need to be made when designing and placing the battery for the location required, and generally VRFB batteries' perform better than lithium ion under temperature variation due to the electrolytes storage in larger volumes. This behaviour means not only does the electrolyte carry the chemical vanadium solution for energy generation, it also acts as coolant (Rho et al., 2022). However, liquid cooled systems or heat exchangers as implemented in the EQL capacity can still be implemented which provides further cooling capability to reduce the probability of crystallisation or precipitates occurring in the electrolyte.

Another important consideration is capacity scalability, where a single cell stack could still be used however an increase of tank size (and electrolyte volume) means the increase in overall capacity allowing more flexibility towards energy reserves (Lourenssen et al., 2019). This separation of Power output (Voltage and current produced through the cell stack) and the capacity of the system (Aqueous capacity of tanks) provides a unique solution and dynamic solution for an energy entity to consider when designing BESS for a location.

1.2 Operational Comparison with other Battery Technologies

As previously mentioned, there are other chemical battery technologies present, so verification of technology is important to cover. The most common chemical battery technologies used for electrical grid scale purposes are:

- Lithium - Ion: Energy Queensland has utilised lithium ion batteries in both pole and pad mounted capacities (*Battery Types*).
- Sodium - Ion: Not currently widely used in utility scale services, however, is being proposed as an alternative to lithium ion. Some characteristics in comparison to lithium ion is heavier cells, lower energy density, faster charging capabilities and cheaper production costs due to more readily available materials (Kim).
- VRFB: Utilities in Japan have seen benefit in the production and use of these batteries, currently being trialled by Energy Queensland.

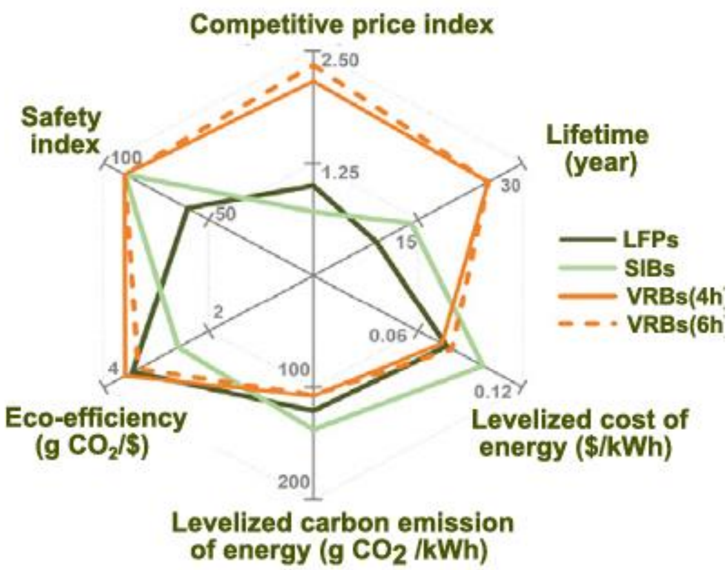

Figure 1-3: Basic Comparison on chemical battery make-up (Bai & Song, 2023)

Whilst VRFB faces constraints in both higher upfront capital cost and lesser system efficiency than the other technologies, long term usage indicates that less maintenance and less degradation would lead to more cost efficient energy generation and consumption (J. Li et al., 2024). High levels of safety during containment are also prevalent as the electrolyte is non-combustible, however still faces some health risks such as fertility issues or burns upon contact.

There are some major benefits to the implementation of VRFB, where lifecycle and safety can flourish however it faces some negatives in energy density when compared to Lithium Ion. Observing the above graph, to achieve a similar energy output roughly ten times the mass of electrolyte solution is required. This translates into a larger footprint and thus larger land and containment facilities. The main takeaway from this is the inherent benefits of providing diversification in energy storage solutions.

A further summary of operational characteristics is seen below for different types of batteries and unleaded petrol to gain an appreciation of the differences between chemical makeups. Note that the identified characteristics can change between manufacturers and the values tabulated are typical values seen in industry.

Table 1-2: Common Energy Solution Comparisons

Type	Calorific Value (MJ/kg)	Gravimetric Energy Density (Wh/kg)	Typical Operational Efficiency	Operational Lifetime	Notes	References
Lithium Ion	-	200-300	65% - 90%	• 10 - 15 Years • ~ 3000 Cycles	High Energy Density compared to Vanadium	(da Silva Lima et al., 2021)
Unleaded Petroleum	46	12,777	30% - 40%	• ~150000 km to 300000 km • ~11000 km/ year • 13.6 to 27.3 Years	Typical efficiency is derived from an Internal Combustion Engine (ICE).	(Wan Ghazali et al., 2015) (Roberts et al., 2014) (Weymar & Finkbeiner, 2016)
Vanadium	-	25 -35	70% -80%	• 5 - 20+ Years • ~ 29200 Cycles	Improvements in electrolyte can improve energy density	(Poullikkas, 2013) (likit-anurak et al., 2017)
Zinc-Bromide	-	34.4 - 54	75.9%	• 2000 cycles	Requires Cleaning due to scale build up	(Poullikkas, 2013)

1.3 Consultation and Expected Outcomes

The main drive for this research was to research within a relevant industry to assist in solving a current problem. Through consultation with Energy Queensland, an initial background investigation was performed with some aims in mind:

- Better familiarisation with the VRFB technology to better inform research decisions.
- Identify potential lacking areas of research.
- And most importantly to convey potential lacking areas to the research partner within Energy Queensland, verifying possible areas of interest and solidify context for VRFB at this stage of pilot implementation and commissioning.

1.1.1 Problem Statement

Consultation with the research partner within EQL determined research viability and interest towards:

"An Analytical Review of Environmental Controls and the Development of a Controls Framework for Future Vanadium Redox Flow Batteries"

This research is driven by the need to analyse the benefits of certain environmental controls associated with VRFB usage. An initial issue that has arisen is that this is a new venture for Energy Queensland, where historically project pilots can suffer from over or under compensation of measures and features, as defined below:

- Over-compensation of design to ensure minimal environmental impact, and impact to personnel. This results in a major economic impact and leads to identification of non-necessities or redundant controls. Over-engineering would help thwart a higher level of issues however it may also introduce potential impacts where initial controls may not have been required.
- Under-compensation of design to minimise cost, whilst considering some environmental and safety controls. This results in reduced economic impact, but lesser care is also made towards impact prevention leading to potential alterations or improvements at a later stage. Impacts from unforeseen emergency scenarios could also prove to be

significant, affecting business operation, incurring legal consequences, environmental impact and more.

Thus, the bridge in finding more responsive controls is important for continued VRFB integration into the power grid. Whilst environmental protection is paramount to operate sustainably, the incorporation of these controls would inherently draw an economic cost that could be solved with a simpler solution. While the overall goal is to effectively prevent environmental and equipment damage or other health issues, viable integration could be a major shortcoming towards achieving those goals.

These identified issues will be addressed through an environmental controls analysis and leading towards development of a framework aimed to provide a guide for control measures. The extent of the research that goes into the framework will be further addressed in the literature review however the final output has been realised on an overarching level. The framework must be viable on an engineering level but also on an administrative level to maintain simple business implementation. The overall aim of this work is to simplify control measures selection in a sound engineering manner focusing on sustainability and viability. It will be achieved whilst answering the main problem questions below:

- Are all operating behaviours of the Vanadium Redox Flow Batteries known?
- What can be done from a broad business perspective to achieve a greater understanding?
- What is the general understanding for impacts from a VRFB?
- What is the magnitude of these impacts towards operation?
- How can these impacts be utilised to best inform business decisions?

Achieving these will provide clarity on conditions and controls for risk management purposes.

1.1.2 What are Controls?

Controls can be implemented in multiple ways to address and minimise risks and for implementation, they are ranked using a tool called the ‘Hierarchy of Controls’. The hierarchy addresses different level of controls that have varying effectiveness levels as seen below.

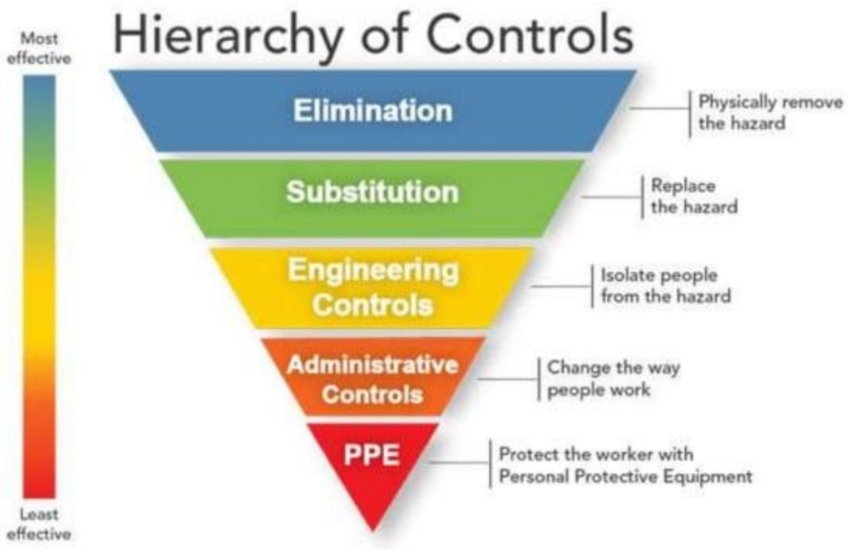

Figure 1-4: Hierarchy of Controls (Ajslev et al., 2022)

Whilst generally applicable to human risk, there is crossover towards the development of controls on a project basis. To understand the relevance of these controls, it is important to understand the significance and variety of risks involved in a project. The major risk found from a VRFB perspective is the electrolyte chemical, which is important to the operation of the battery, and used below as an example.

- Elimination is straightforward, being the removal of certain risks to achieve reduced overall risk. As mentioned, it is important for the electrolyte to be present to perform the intended operation of the battery and thus cannot be eliminated without full removal of the battery system.
- In a similar fashion, substitution of chemical is not necessarily viable as other electrolyte concentrations for the VRFB would always have a degree of chemical toxicity. There is some variance in sulphuric acid and Vanadium salt concentrations between products and manufacturers (Prieto-Díaz et al., 2024), but all have similar risk meaning substitution of initial product is not effective.
- Engineering controls from above is what can be done to isolate people from hazards which means barriers or exclusion zones. For the context of a VRFB, this is controls that reduce risk from climatic conditions such as a roof for temperature reduction. For the VRFB this is a major contributor towards reducing climatic impact on equipment as will be covered in this thesis. Legal considerations such as following legislated standards are also addressed here for the design of certain engineering controls.
- Administrative controls consist of changing the way people work to achieve the goal or in the case of the VRFB, what can be changed to promote safety, and longevity for the

goal of minimal environmental impact. These controls are implemented to complement or extend the controls devised in the engineering section, to most effectively operate.

- Lastly is PPE which from the perspective of a VRFB constitutes example equipment such as (Zhao et al., 2015):
  - Hard hats for unforeseen impacts.
  - High Visibility Clothing in the event of other human work in the general vicinity.
  - Steel Capped boots in the case of falling objects or risks from work performed.
  - Safety Glasses in the case of falling objects or risks from work performed.
  - Chemical Handling equipment if handling electrolyte.
  - High Voltage equipment if doing electrical work.

  These elements in PPE act as the last line of defence for when the risk is reduced to a level that is considered reasonable.

The main goal of these multiple steps is to promote viable operation whilst ensuring that environmental impact and safety during operation are kept to a high standard. If operation is not ideal, then more cost in repairs and more frequent exposure to non-ideal circumstances would occur. This meant there is potential for anguish and harm to the environment or living beings.

1.1.3 Battery Acquisition and Usage

To develop context for the task at hand, the EQL VRFB battery is a 250kW/ 750kWh system located at Energex's Berrinba depot in the city of Logan, Queensland. The battery supplied by the manufacturer resembles the container type solution presented in figure 1-5. The prepackaged solution consists of shipping containers with three main areas of interest:

- The electrolyte redox couple storage in the bottom containers. Evidently consists of one part of the fluid circulation system.
- The top containers which contain the generation cell stack, auxiliary systems including the heat exchanger and the rest of the fluid circulation system inclusive of pipes and pumps.
- Externally, the BMS to facilitate safe charge and discharge.

It should be noted that through faceplate information of the battery at 250kW/750kWh it can be interpreted to take three hours to charge, however the power requirements for auxiliary components operate such as pumps and heat exchangers should be considered. For example, the net 250kW system may have auxiliary components drawing a total of 30kW meaning that the battery may be producing a gross 280kW.

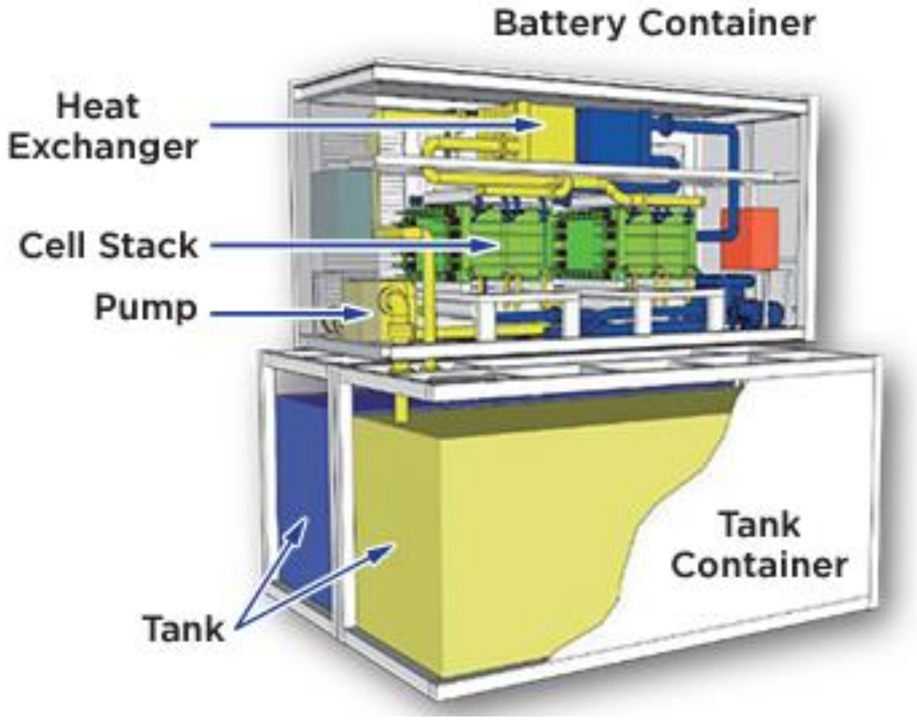

Figure 1-5: Typical Container Type Redox Flow Battery Diagram (Sumitomo Electric, 2024)

The main drive is the pilot and assessment of the performance of medium duration storage for the distribution network. It has been noted through a demonstration, it will aim to provide renewable firming by smoothing solar power generation at peak solar times (charge the battery) and distribute when necessary.

EQL has previously utilised and continuous with numerous utility sized (4MW) lithium-ion batteries as well as the ‘neighbourhood’ batteries, both utilised for their capability to dynamically absorb peak solar generation throughout the distribution network. The aim is to provide diversity in both technology and objectives. The VRFB separates power and energy, providing the diversification necessary for power system stability (Ang'u et al., 2020).

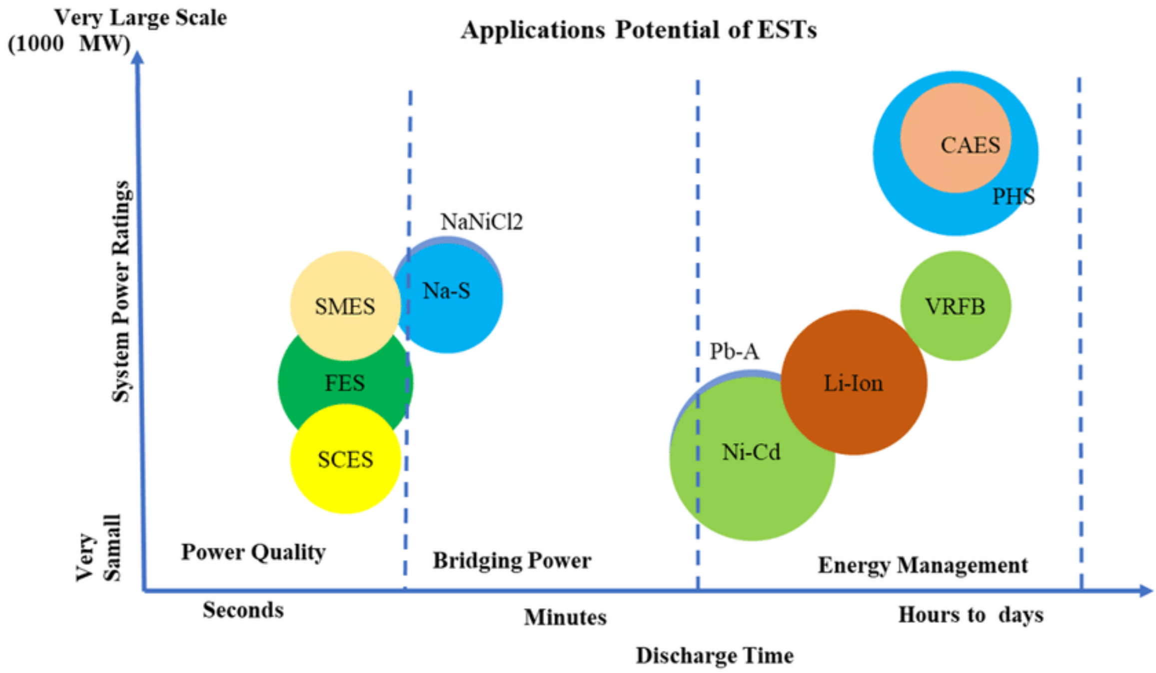

Figure 1-6: Power Ratings vs Discharge indicating BESS Applications (Behabtu et al., 2020)

1.1.4 Known Operational Conditions

1.1.1.1 Standards for Operation

The known conditions for the installation of the BESS are seen in two capacities from a Queensland perspective and an international perspective.

Products that adhere to standards are those that are voluntarily met by manufacturers to ensure that standard is applicable to their product. They are not standards deemed a legal requirement to adhere but are held in high regard to ensure a high-quality product. The battery manufacturer aims to achieve production standards from the generation standpoint, whilst Energy Queensland (EQL) should aim to meet legal conditions as well as optimising operating conditions through standard and manufacturer recommendations. The main standards are IEC Standards which are provided to members of the CENELEC council, which is a European collection of countries that comply with electrotechnical standards. Australia is not represented in this however the standards are of a quality that worldwide adoption is slowly being achieved.

IEC 61025 outlines fault tree analysis procedures, described in the flow battery standard IEC 62932-2-2:2020 as one of two risk analysis guidance documents to properly assess risk for an installation. The other standard being IEC 60812, which outlines procedures to undertake a Failure modes and Effects analysis. Whilst these procedures are recommended to be followed, hazard and risk reduction should be achieved through some form of written risk analysis and implementing inherent design measures, protective measures and the notification of residual risk to achieve safe commissioning and operation of the Flow Battery System. Risk management procedures are thus a necessity for undertaking product ownership and achieving successful operation.

As for Australian Standards and Legislation, the main Australian Standard that is important in terms of environmental impact is AS 3780:2023 which oversees the storage and handling of corrosive substances. The vanadium electrolyte is made up of numerous substances including sulphuric acid, vanadyl sulphate and more, where section 2.2.3.1 outlines further hazards and precautions involved in their usage.

AS 3780:2023 outlines requirements for storing and handling class 8 corrosive substances (Australia, 2023). For the case of the manufacturers VRFB, there are two trains of thought to consider. The first below is for without considering the exterior electrolyte tank container as a bund.

- The manufacturers' solution for the electrolyte storage is defined as a tank under 6.2(a)(ii) if the exterior ISO container meets requirements of the International Maritime Dangerous Goods (IMDG) code and has approval from either Container Safe Convention (CSC) from the International Maritime Office (IMO).
- Section 6.4.2 also outlines minimum bunding capacity for the emergency control of lost fluids. For materials of packing group II, the total volume of a compound must be not less than 110% of the largest tank within the compound, or 25% of the total capacity of all tanks; whichever is greatest. It can be identified that with the two electrolyte tanks of equal capacity then the 110% of the largest tank within the compound will be the chosen option. A vessel, an absorption pit, or a tank may be used for this purpose so long as it meets the requirements previously mentioned. For the successful harnessing of the electrolyte, it is ideal to ensure that is adequately contained and retrieved for further usage if a cleaning process is complete.
- Section 6.4.4 outlines drainage out of the bund, highlighting the assurance that dangerous reactants are not in contact and that drainage valves are located outside or operated from outside the bund. This is to be ensured during development and planning.
- Section 6.5.2 outlines that the foundation is to comply with environmental conditions and the effect of emergency spillage on foundations. Also, during development, ensure there are no increased chances of environmental harm and further condition deterioration during an emergency.

- Section 6.5.8.1 to 6.5.8.5 outline ancillary equipment such as pipes, fittings and transfer system. This is to ensure that all equipment is rated to handle the corrosive substance at the maximum pressures. The selection of materials is important and has been undertaken by the manufacturer for these purposes and for continued safe operation of the battery.
- Section 6.7 outlines that materials are almost immune from the stored substance, and tank walls have a minimum wall thickness. This is inclusive of an inner impervious lining in the case of the external tank wall not being corrosion proof.

By following guidelines set out by IEC 62932:2020 as well as compliance with AS 3780:2023, the electrolyte tanks provided by the manufacturer have the sealed shipping container exterior for weatherproof but also have an inner layer that is resistant to the Vanadyl Sulphate or Sulfuric Acid. According to previous experience from the battery provider Sumitomo (Shigematsu, 2011), it can be assumed to be polyethylene which achieves the required corrosion resistance. Another similar battery system called Gildemeister has a double walled tank for continued safe usage and a temporary redundancy measure (Gildemeister Energy Storage GMBH, 2015). The double walled tank concept is important as it leads to the second potential outcome for a bunding by using an integrated secondary tank.

This tank may meet requirements as secondary containment if it meets requirements of 6.7.8.1 and 6.7.8.2, where a tank can have an integrated compound. The major condition for their usage is to not be used with corrosive substances that also have a hazard of flammability or combustibility. Fortunately, the vanadium electrolyte is non-flammable and non-combustible so therefore a single double walled tank can be used in this instance if it meets further requirements in 6.7.8.2, with some major elements (non-exhaustive) as below:

- a) Not suitable for Packing Group one materials, which the electrolyte is a packing group two material.
- d) Designed to contain only its internal contents and not for overflow as per other bunding requirements.
- c) The inner tank is designed to be sealed adequately for the contents it holds, which is typical for other requirements in the standard section 6.7.3.
- d) The tank shall be designed and constructed to contain the entire contents of the inner primary tank, meaning that the outer tank is sealed adequately for containing the corrosive contents of the single interior tank.

- j) The outer tank should not be open so that liquid can be siphoned or removed. This refers to inhibiting vandals or other interested parties obtaining unauthorised or unlawful access to the electrolyte.
- h) The distance between adjacent tanks should be 600mm. This is one consideration that would be a potential issue as the storage tanks of the manufacturers package are directly adjacent to each other and cannot be considered a single tank as they contain separate fluids. An exception process would be followed to achieve this.
- q) Venting for the outer tank, allowing heat and gas escape which is standard for technologies with gas buildup capabilities.

The major benefit to this solution is the secondary tank does not allow rain in, which is a benefit to implementing controls. Legally, the Queensland Work Health and Safety (WHS) Act 2011 does not explicitly mention ‘AS 3780:2023’ by name however, a duty of care must be reached to avoid penalties. This duty of care includes maintaining a clear understanding of the product and the management processes for a VRFB to ensure that operation meets or exceeds the requirements of the WHS Act 2011. Meeting this requirement may mean that AS 3780:2023 is also met, however further obligations may be required before practical implementation.

1.1.1.2 Battery Management System and other operational nuances

The BMS performs most operational calculations and resolutions during battery operation and as such can be easy to rely upon. As such, it is important to understand how it operates through requirements and common industry equivalencies.

IEC 62932:2020 previously outlined standard operational procedures that would be expected to be supplied from the manufacturer, including but not limited to the inclusion of safety labelling and testing which enable safe operation of the system components. As an extension to this, compliance with safety standards also means the implementation of a Battery Management System (BMS) allows certain system protections to initiate under fault conditions. This is achieved through sensors with alarmed communication procedures. However, without non-confidential access to correct information from the manufacturer, it is difficult to assume what sensors have been included and thus the full capability of the BMS for this project. However, the standards compliance previously identified provides insight into controls implemented into the prepackaged battery solution.

Battery management systems not only have the ability for electrical operations (i.e. charging and discharging), but they also have the ability for system monitoring, interaction and protection purposes. The main system monitoring factors are terminal voltage, cell voltage (to identify dropped or damaged cells), and current for the electrical capacity. All of these provide the ability to monitor and provide typical protections such as over-voltage and over-charge. There is also the ability to sense cell stack differential pressure, electrolyte temperature and leak detection through methods of float levelling equipment (Trovò & Guarnieri, 2020a).

IEC 62932-2-2:2020 indicated for compliance, that detection of electrolyte leakage is a necessity. The inclusion of float level leak detection would likely be included in the electrolyte storage tanks as well as even in the top container for containment of leaks from piping or the cell stack. There is also benefit of pressure differential sensors for safe operation, particularly avoiding the membrane from suffering a rupture. Pressure differential can also benefit the system through detection in fluid leaks. The similar solution from Gildemeister outlines the use of flow levelling leak detection sensors for their interior tank (Gildemeister Energy Storage GMBH, 2015). Further research for leak detection indicates that BESS systems can also utilise insulation monitoring devices which could detect leakage in the outer electrolyte tank through ground fault detection. In this instance, it would reflect the exposure of the electrolyte to the container tank wall, thus bypassing the containment of the inner electrolyte storage tank.

2.0 LITERATURE REVIEW

2.1 Statistical Literature Analysis

2.1.1 Relevant Literature Types

2.1.1.1 Life Cycle Assessment (LCA)

The importance of providing a valid risk analysis was found to be an accurate outcome, which educates the decisions made on project. A life cycle assessment directly investigates impacts of each component of the multi-component system and educates personnel on the direct environmental consequences of the project. This assessment proved beneficial to consider as not only are environmental impacts listed but also why the investigation for each impact would be important. LCA's for this topic addressed a range of Sustainable Development Goals (SDG's) including (International Organisation for Standardisation; Sanyé-Mengual & Sala, 2022):

- Goal 12 which outlines 'responsible consumption and production' as well as the other goals below.
- Goal seven in this context outlines the achievement and maintaining of 'Affordable and clean energy'.
- Goal 13 which outlines taking 'climate action'.

They also exist to promote effective business operation through environmental insights towards alternative approaches. This is achieved through assessment of overall environmental impacts of the products lifecycle (Ayres, 1995). (McManus & Taylor, 2015) concluded that undertaking an LCA is also pertinent for modern development as sustainability and environmental awareness has transformed as a major component of business decision justifications. This highlighted the importance of the tool particularly benefitting viability and resilience for effective business operation.

It was found that there are multiple methodologies for undertaking LCA's, most considering the outline for LCA's made in the standard ISO 14044 (International Organisation for Standardisation, 2006). For the case of a VRFB, it has been assessed on a cradle-to-grave and cradle-to-gate basis. For the matter of context for this project, it was found that the gate-to-grave section is most relevant. It represents in-field operation and had not been assessed individually. This was assumed as businesses not wanting to reveal how their products and projects have been developed.

Cradle-to-gate in the context of the project, was the finalisation of battery construction for EQL's VRFB and waiting for the system to be shipped. Cradle-to-gate examinations as mentioned have plenty of exposure for the VRFB capacity as seen in (Gouveia et al., 2020), and (Dassisti et al., 2016). These have results that see increased environmental impacts in damage to ecosystem, acidification, and human toxicity (Dassisti et al., 2016).

For the cradle-to-grave assessments, this included the actual operation of the system and its eventual expenditure including processes of waste removal and recycling. The materials utilised in VRFB are recyclable or reusable in one way or another as found in (Santos et al., 2021), and may find better classification as a cradle-to-cradle assessment to consider recyclability aspects of the product. Special considerations must be made to this end as electrolyte is only reusable if it is in a condition that it can be reused. The conclusion reached here is that assessing operating conditions over its' lifetime would be a careful necessity.

A major environmental impact found was in transport, where currently the materials transportation from Japan to Australia is a major impact. Future sourcing of electrolyte in Australia would lessen this environmental burden, thanks to the development of Vecco Industrial's Vanadium manufacturing facility in far north Queensland (Grace Grace MP, 2024).

LCA's for VRFB's require some form of methodology standardisation or sensitivity analysis on existing methodologies for confirmation of best usage. Otherwise, it appeared that VRFB's are an established technology for LCA investigations. These established methodologies reflected towards the availability of online tools, and databases for adequate completion for an LCA. Individual circumstances for each installation proved to have differing results towards the highest environmental impacts mostly due to location-based nuances and sourcing procedures. Software programs as Umberto LCA+ (Blume et al., 2022), SimaPro (Tsai et al., 2023), OpenLCA and eTool were found best capable of performing the Life Cycle Assessment. It was found that the obtainment of accurate data is more important than the tool in some cases, which are sourced from databases that include relevant information to the Vanadium Redox capacity such as Ecoinvent (Blume et al., 2022). These databases have a high financial cost to obtain but are thorough with information sourced directly from numerous manufacturers and similar about product and procedure impacts. For context, (Tsai et al., 2023) performed a comparative LCA of the VRFB and Lithium-Ion technologies and introduced the aspect of quantifying differences in this manner utilising data from the Ecoinvent database.

2.1.1.2 Case Studies and Technology Improvement

Case studies are important as they include more than just environmental impacts. It was found that they consist of a variety of considerations for the development and improvement of the VRFB technology. Improvements have been observed in multiple components, including in the electrodes, bipolar plates, electrolyte concentration, equipment material mixtures and internal operating conditions (Monteiro et al., 2018). If these improvements are used, they would find advantages in varying degrees and as such is an important consideration to make for context at hand. On the other hand, their usage in certain cases proved to offset other performances such as electrical power converted versus pump power loss (Huang et al., 2023). Case studies also form the closest literature to industrial implementation, therefore providing insight into real life usage understanding and system characteristics. (Cunha et al., 2014) explored this through typical uses in a power system in a current capacity as well as into the future. There is much value to be gained through analysis of the current outlook on the battery technology and how it can be adapted and utilised for the future. Overall, it was found that there is not a vast amount of publicly available information regarding the usage of the VRFB in field. It is speculated that this is due to companies not wanting to release privileged information and lose a competitive edge.

2.1.1.3 Heavy Metals Toxicity

Heavy metal toxicity is present in this system due to the Vanadium used in the VRFB system. It was found that heavy metals are metal elements with relatively high atomic densities, and pollute the environment as well as contributions towards bioaccumulation (Mitra et al., 2022). Ensuring that the toxic potentials are effectively investigated was found to be important to verify the implications of heavy metal exposure to the environment. Studies have been performed investigating the contamination of various heavy metals as well as the ecological risks associated with their exposure to the environment (Deng et al., 2024). As could be expected, there was some gain found in heavy metals such as iron and zinc in small exposure but become toxic with higher exposure. This exposure then led to acute mental function alteration and inflammation (Fisher & Gupta). Overall, the analysis into heavy metal toxicity appears to be focused on environmental and health impacts. Through diversification of literature, may provide insight into the extent of damages based on what has been found in multitudes of research.

Exposure for heavy metals such as Vanadium can be found through rainfall tracing contaminants into waterways, as well as other avenues such as metalwork, medication and other forms of consumption (Tchounwou et al., 2012). Whilst obvious, there was found to be a maximum amount of Vanadium that should be consumed daily (believed to be approximately 20μg), there was also found to be a minimum amount that should be consumed (Hu, 2023). The form used in the VRFB is not suitable for any forms of consumption and leakage could prove lethal to humans if absorbed or consumed. It would also prove to be harmful to the environment as well.

2.1.1.4 Reliability and Failure

Understanding reliability and failures is useful to understand the effects of failure on operating conditions. The main goals of ensuring system reliability were found to be to minimise downtime, economic impacts, environmental and safety through increased exposure (Goel, 1998). Investigating different forms of reliability approaches as well as modes of failure is thus an important concept to achieve a more complete understanding. Reliability associated with VRFB's were addressed in a few different capacities, including:

- Modelling failure over time, thus concluding a Mean Time To Failure (MTTF) (Reichelt & Müller, 2020).
- Modelling potential improvements in material that performs a main task of failure risk reduction (Sankaralingam et al., 2021).
- Failures in other flow battery installations (Rana et al., 2023)

Assessment of reliability was thus determined as an important factor for the assessment of controls implemented. The differing failure likelihood of components and the differing effects of external conditions mean that controls in installations may vary not only on a site-by-site basis, but also find value by accounting for extreme weather conditions for the site the VRFB rests on. Unfortunately, as has been found in (Reichelt & Müller, 2020), there is little found on reliability assessment of components beyond individual component information such as pumps and valves from existing databases. And furthermore, system probabilistic failure and reliability has not been assessed on a system level, rather only through assessment of cell stack reliability dependent on material inclusion. Overall, it was determined that work is required to develop a methodology for the systems time to failure for a set package such as the OEM variant. Further work is also in qualitative and/or quantitative probabilistic analysis for the integration of a maintenance plan and controls schedule. The downside to a complete package offered for the VRFB is the addition of failure types that have not been contiguously investigated on a VRFB basis. This means that further research into individual components is necessary to help understand relationships of operating conditions and limitations.

2.1.2 Literature Analysis Methods and Quantification

2.1.2.1 Literature Analysis Main Concepts

A Literature analysis and review is an important component of any thesis, where analysis techniques prove particularly important for projects with vast amounts of separate concepts. Various techniques and tools can be used to develop understanding. A quantified literature Content Analysis for example could effectively present as a secondary literature review, forming the basis of a methodology. (Mengist et al., 2020) used a method to create a systematic literature review which sought to use statistics in both quantitative and qualitative ways. The purpose of this was to identify potential unknown relationships and patterns between the literature, whilst assessing outcomes to understand implications and benefits observed. Use of the literature review section has history of research in the main methodology section as observed in (Snyder, 2019), meaning that a literature analysis as a main research component is viable to undertake. Guidelines are established to ensure a replicable, and consistent outcome, showing the applicability of extending this methodology to other areas of research sections. This is done to ensure depth and rigor is achieved to avoid forms of bias whilst undertaking the literature analysis.

The literature types explored above exist mostly as qualitative research with various concepts identified. To relate these together, it was identified that a quantitative comparative literature analysis would be an ideal approach as it may best understand the significance in relationships of the different literature types as performed in (Coe & Scacco, 2017) for analysis purposes. It was identified in this piece that sampling, reliability and validity of methodology was important for a successful analysis. The authors intent and achieving a clear understanding of each paper's investigatory focus and key outcomes was therefore necessary before undertaking an analysis. This helped distinguish slight changes in each paper and thus assess the reliability of the differing goals onto the quantification of literature.

2.1.2.2 Quantifying Literature concepts and methods

The benefits of quantifying literature for an analysis have been established an important component of identifying relationships between literature. Further exploration showed important aspects of quantifying literature which include:

- Finding information that is relevant to quantify and understand that the literature itself must be assessed on an individual basis to ensure relevance (Aarseth et al., 2017).

- Finding all matching data sources, ensuring they are categorised correctly for accuracy purposes.

(Aarseth et al., 2017) investigated sustainability literature exposure on a time to frequency basis, and indicated that there needs to be an independent variable for a literature study. For the purposes of the content for a VRFB, the independent variable is the frequency count on terms, which best explains the relationships for the different types of literature content. This was best explored in (Dicle & Dicle, 2018) using a developed set of basic functions for frequency count and word cloud visual presentation. An example of filtering used in the literature piece consisted of words with a minimum letter count of three letters per word.

Investigation into content analysis indicates that despite best efforts for removing bias, there remains elements of content reduction due to a loss of dimension. Processing methods also reflect subjective interpretation however if implemented with a systematic approach, it can prove to be reliable and replicable (Erlingsson & Brysiewicz, 2017). Essentially this can be summarised as ensuring that each paper utilised in the investigation is treated in the same manner, which ensures the content can be replicated accurately.

Quantification is found to also mean that with a consistent methodology and approach towards words, that data analysis can be used as a means of providing the pattern and relationships. One methodology of comparative data analysis for finding relationships was found to be a matrix correlation analysis and is a valid method of converting frequency counts of categories into an output to explore relationship significance (Graffelman & de Leeuw, 2023). It was stated in (Boehmke) that the correlation matrix is reproducible by means of manual input, python or ‘R’ programming indicating applicability in a modern fashion. Large reproductions of the correlation matrix are thus possible and made easier through programming but can be found to be difficult to interpret in the case of large instances. To this end, existing solutions such as Hierarchical Clustering Analysis (HCA) can be used for simplification and effective visualisation of relationships which is the case in (Nazari et al., 2018). The development of understanding of the correlation matrix and HCA is further explored in section 2.1.2.3.

Other examples of data analysis are Principal Component Analysis (PCA), however this was found to thrive by summarising datasets rather than the investigation of relationships between set terms (Jolliffe & Cadima, 2016). The goal of undertaking a relationship assessment was to ensure all dimensions were kept individual for representation which rendered PCA unsuitable for processing. Additional techniques such as exploratory factor analysis (EFA) that can be used to statistically validates theories and hypothesis and are utilised for psychological assessments

(Watkins, 2018). Again, it was found that this approach was not directly applicable as the relationship required must be a measurable matter to signify the depth of relationships for further discussion. Extending on EFA capabilities and requirements is the Adequacy Test that would normally be utilised in scenarios to explore with factor analysis. This was found to only be undertaken if the categories in a matrix can be reduced and explained (Bartlett, 1951), which as is the case with EFA. The adequacy test can be used to explain the degree of variance or significance in results, and therefore finds a degree of relevance towards the distinguishing of relationship significance.

2.1.2.3 Correlation Calculations

It can be found that typical correlation calculations utilised the Pearson correlation coefficient, which represents the significance of a relationship between two variables (Schober et al., 2018). Accurate data is thus important to implement to reduce the potential for inaccurate bias or skew. The Pearsons correlation coefficient was found as below for each entry within the matrix (Ataei et al., 2022), derived from frequency content.

$$r_{pearsons} = \frac{n * \sum(X * Y) - \sum X \sum Y}{\sqrt{(n * \sum X^2 - (\sum X)^2) * ((n * \sum Y^2 - (\sum Y)^2)}} \tag{2.1}$$

Where:

$$n = Observations\ count$$

$$\sum XY = All\ observations: Sum\ of\ each\ pairs\ product$$

$$\sum X = First\ Variable: Sum\ of\ Observations$$

$$\sum X^2 = First\ Variable: Sum\ of\ Squares$$

$$\sum Y = Second\ Variable: Sum\ of\ Observations$$

$$\sum Y^2 = Second\ Variable: Sum\ of\ Squares$$

The formula supports investigation of the Pearsons coefficient for all variable entries within a matrix, which established its' ideal purpose for finding relationships or trends. This ability to calculate and display relationship significance in a numerical form is its' strength. However, it can be found that in some scenarios that the relationship between values must also be investigated to a greater extent. Such instances of strong correlation may at times be exhibited due to variation of another unseen variable such as preprocessing issues (Schober et al., 2018), which further clarifies the importance of validity and a clear analysis methodology.

2.1.2.4 Hierarchical Clustering Analysis

Hierarchical Clustering Analysis (HCA) is an algorithm that performs correlation calculations and can display the results in a simple manner. This is done with measures of distance that are utilised to calculate clustering by minimising the variance inside those clusters. It is capable of this for the benefit of the user, able to form further categories based on the distance. The benefit of this process is that any measure of distance can be utilised to approach clusters if the user understands variations between methods.

For example, the common 'Wards Method' also allows the identification of a term known as 'ward's length' which is a measure of the number of linkages before terms relate to each other. This ward's length is found using minimization of Euclidean distance techniques (Murtagh & Legendre, 2014) (Ultsch & Lötsch, 2022).

$$D_{Euclidean} = \sqrt{\sum (x_i - y_i)^2} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{2.2}$$

The python library SciPy further explores the Wards variance technique utilised in its python library function (SciPy, n.d.):

$$d(u,v) = \sqrt{\frac{|v| + |s|}{T} d(v,s)^2 + \frac{|v| + |t|}{T} d(v,t)^2 - \frac{|v|}{T} d(s,t)^2} \tag{2.3}$$

$$Where:$$

$$u = newly\ joined\ cluster\ consisting\ of\ clusters\ 's'\ and\ 't'$$

$$v = unused\ cluster\ in\ the\ 'forest'$$

$$T = |v| + |s| + |t|$$

$$|v| = |s| = |t| = Respective\ Cardinalities$$

$$d(u,v) = distance\ between\ 'u'\ and\ 'v'$$

$$d(v,s)^2 = Squared\ distance\ between\ 'v'\ and\ 's'\ clusters$$

$$d(s,t)^2 = Squared\ distance\ between\ 's'\ and\ 't'\ clusters$$

$$d(v,t)^2 = Squared\ distance\ between\ 'v'\ and\ 't'\ clusters$$

The function operates in an incremental fashion until a minimum variance is achieved within a cluster. It merges clusters in an incremental fashion that minimizes the total value of the sum of squares for each dataset. This dynamic grouping procedure finds benefit in identifying different degrees of clustering as can be observed through the comparative figure 2-1 below.

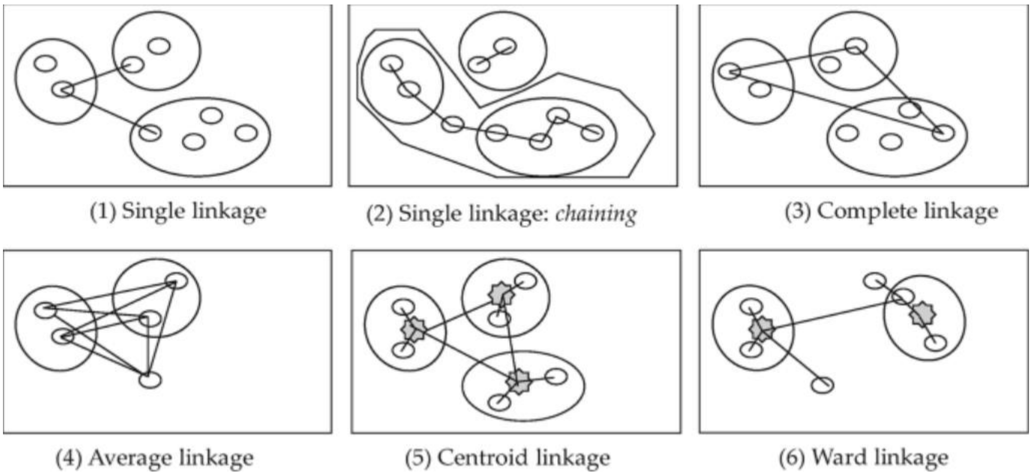

Figure 2-1: Clustering Methods (Cleff & Cleff, 2019)

Investigating the extent of the python library function SciPy will prove beneficial and satisfactory for assessing final formulae used in calculations.

It is often seen that HCA outputs are in the form of Dendrograms which present systematic and ranked grouping of the terms which can be interpreted in two different ways (Murtagh & Legendre, 2014).

- Firstly, in a top-down or divisive clustering manner which aims to look at how the clusters divide based on individual content relationships.
- Second is a bottom-up or agglomerative clustering manner which seeks to explain why individual terms cluster and what they cluster with. It can be observed that agglomerative clustering is more widely used for finding insights (Burghardt et al., 2022).

Wards methods also provide benefits in this presentation due to intuitive data presentation using the 'wards length' values in a comparative manner.

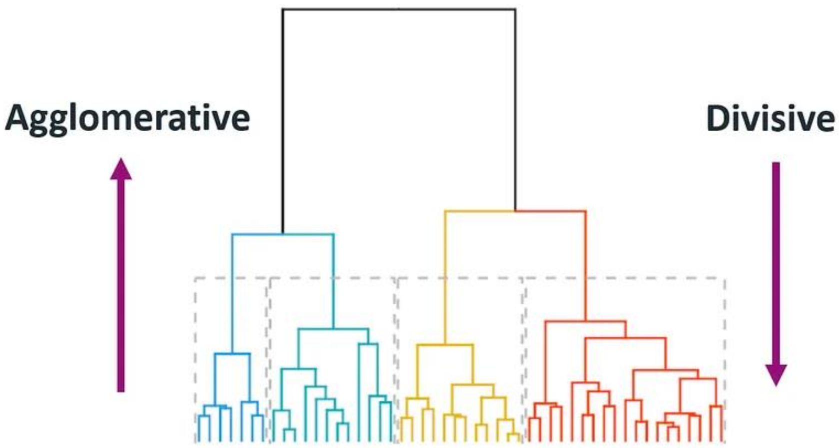

Figure 2-2: Dendrogram interpretation (Re, 2023)

2.1.2.5 Significance Tests

The last element of data quantification was identified to be the measure of significance which is a simple measure of correlation matrix overall data variance. Significance of relationships has been established as the comparison between a correlation matrix and an identity matrix which depending on the result, can determine relationships between matrix entries (Aletras et al., 2010). The applicability of a matrix that is not undergoing EFA is to determine the probable overall strength of variance between literature pieces.

A common adequacy test is performed using python inbuilt functions for the Bartletts Test of Sphericity that calculates the Chi Square Statistic and the 'p' significance level. The function utilises a comparison for the chi square statistic by comparing a correlation matrix compared with an identity matrix. A significant outcome is one that determines a correlation matrix does not resemble an identity matrix. The overall variation score is then presented as the Chi Square statistic as calculated from the below equation, with the degrees of freedom utilised (Bartlett, 1951).

$$\chi^2 = -\log(\det(R)) * \left(n - 1 - \frac{2a + 5}{6}\right) \tag{2.4}$$

$$degrees\ of\ freedom\ (v) = \ a\ * \frac{(a\ -\ 1)}{2} \tag{2.5}$$

$$Where:$$

$$a = no.of\ variables$$

$$n = no.of\ observations$$

$$R = Correlation\ matrix$$

Some potential problems can arise with computing the chi square statistic in this manner where the determinant (signified by $\det(R)$) can be equivalent to zero. When using the equation 2.4 with a chi square statistic of zero, that logarithm of zero is equal to infinity. This means that the matrix variables are either highly correlated, and the computer is incapable of performing the precision required or the matrix variables are perfectly correlated.

The python module 'Factor_Analyzer' utilises the calculated chi square value from above, and the degrees of freedom of the data. This information can then input to another function that uses a survival function which is defined as 'x being above a certain value' (Jeremy Biggs & Nitin Madnani, 2022). In this context, it can be interpreted as the probability of the 'p' value exceeding the 'chi square' value.

2.2 Environmental Risk Management Processes

2.2.1 Risk Management Frameworks

From the consultation period, the project was found to resemble a broad risk analysis to provide insights into risks and potential controls to implement. A coherent risk management process involves methods of identification, quantifying impact, providing controls and analysis of their effects. The risk management process followed to ensure a thorough outcome was by utilising the standard ISO 31000 which outlined an established framework for risk management guidelines. The main processes followed in this standard are explored below.

2.2.1.1 Risk Identification

The underlying concept of identification was found simple in concept however issues can be encountered towards adequate identification, and as such various techniques can be utilised to achieve a successful outcome. Identification of established risk research is important for first stages of identification as this forms the foundations of risk development (Blišťanová et al., 2022). The literature review forms a major part of initial concept building however extending this identification using certain techniques was deemed common. Some techniques included are expert advice, peer interviews and contributions (Kheir et al., 2022). Other options included here was the reuse of existing information and perform trend analysis to develop relationships (Aven, 2016). This option proved more reliable as the VRFB operating characteristics are established and understood through the industry meaning that conditions for operation are known. Trend techniques can also identify current and historical data to identify unknown trends as is commonly done in a market capacity and for emerging risks in food chain systems (Palmas et al., 2022), meaning the technique is diverse. The combination of all these techniques forms the basis for the determination of trends between established research, particularly keywords and major themes.

2.2.1.2 Risk Analysis

Analysis of risks was identified to finding an underlining reasoning of why risks exist and their characteristics including conditions that exacerbate risk. A risk analysis can provide quantitative (objective) or qualitative (subjective) data depending on the requirements of outputs (Moon et al., 2021). For terms of analysing risks involved with operating conditions, examples are found to be probability distributions through reliability (Edimu et al., 2011) or risk matrices developed from those distributions to rank and provide operational weighted substance as used in (Lemmens et al., 2022). The use of analysis tools such as the reliability assessment perform the main tasks of comprehension however initial understanding through risk identification is an important factor. It ensures that the information used in the risk analysis section is of quality and can be used for further analysis.

2.2.1.3 Risk Evaluation

During the research process, risk evaluation was important for understanding risks and their controls, which can then be used to compare advantages and disadvantages. This was found to be done using some form of quantification to effectively understand how risks can be mitigated. It can be defined as the process of comparing the results of the analysis with risk evaluation criteria (Refsdal et al., 2015). For the established context, this is the assessment of risk of equipment conditions and reliability to an established baseline risk. For an environmental capacity this can be seen as identifying positive and negative impacts a project will have on the environment, and establishing the potential forms of remediation to be made before implementation for risk reduction purposes (Ezinne et al., 2023).

Thus, the steps to achieve this were found firstly to understand the identified risks and potential outcomes through a process like an event tree analysis, which could be undertaken in extension from the risk analysis section. Evaluation can also be undertaken either quantitatively or qualitatively to differing outcomes. Quantitatively, it is performed with probabilistic values, but qualitative analysis can also be undertaken through adequate comprehension of processes to identify event significance as explored in (Ferdous et al., 2009). The major benefit of qualitative analysis is that expert advice can be utilised to form conclusions, however this may introduce an element of bias into risk and control development.

To find where risk improvements reside, it was found that a comparative analysis is the most beneficial in achieving this. Established conditions can provide a baseline to understand risk factors through systemic evaluation as was undertaken in (Ezzati & Heggenhougen, 2008). This is found to be as simple as a risk matrix or model developed from events that is evaluated against a baseline or target like the approach in (Friedewald et al., 2016). It can also be performed in more complicated manners, such as the relevant analysis and evaluation technique called Life Cycle Assessments (LCA's) (Basu & Basu, 2017). Undertaking an LCA can be a complicated task with a thorough understanding of contextual components such as material acquisition required. It also requires knowledge of processes broken down into basic components to perform analyses through supplementary product and material database usage.

2.2.1.4 Risk Treatment

Treatment in this context was deemed as how a risk is controlled or averted, particularly what can be employed to reduce, avoid or prevent a negative outcome (Epstein et al., 2020). For systems with operational conditions, avoidance measures could be utilised by altering time of day of operation as well as systems that can vary operations based on sensed current conditions. Treatment is sometimes found a cyclical process to find the most efficient solutions, be that financially, viably or legally to achieve the best solution of risk mitigation for the scenario (de Oliveira et al., 2017). On a broad scale, the introduction of frameworks that consider risk impact and mitigation strategies are among those most effective. If designed well, they can provide broad capabilities as well as simultaneous targeted solutions and process for business operation as explored in (Locklear, 2011).

2.2.2 Major Health and Environmental Risk

2.2.2.1 Combustibility

The Vanadium electrolyte used in the battery is non-flammable meaning that combustion sometimes encountered with batteries such as lithium ion will not be exacerbated by the chemical within the VRFB (*Vanadium Electrolyte Solution MSDS*, 2022). Other componentry such as pumps and electrical cables may encounter wear or operational limitations, leading to overheating or combustion. Otherwise, due to the general design of the VRFB systems, this would likely be contained within the package which is a sealed ISO shipping container for a time before emergency services arrive.

There were other effects found including operation of the battery concerning gas production such as Oxygen during oxidation processes and Hydrogen. Hydrogen Evolutionary Reaction (HER) is the production of hydrogen gas as a side effect of the battery reaction process in the negative half-cell (Fetyan et al., 2019). It generally occurs during hydrogen transfer between cells through the Ion exchange membrane, where this hydrogen gas can cause pressure imbalance throughout the system. This can lead to higher chances of undesirable hydrogen combustion. To combat this, it was found prudent to involve these controls below:

- Differential pressure sensors in the cell stack for pressure imbalance, otherwise leading to membrane puncture etc. (Kim & Park, 2022). It also has the capability of sensing leakage events. This has been previously identified as a likely condition due to IEC 62932:2020 contributions.

- Adequate ventilation and dispersion capability of combustible gasses for either the prepackage VRFB product and or the room that contains it (if applies). Adequate ventilation is a requirement through the previously mentioned IEC62932:2020 and AS 3780:2023. The established technology of nitrogen purging or venting may also prove benefit in the dispersion of both the oxygen and hydrogen gas out of the VRFB system and out to atmosphere. Ventilation is thus established for both the VRFB package perspective and the requirements of a sealed structure.

2.2.2.2 Toxicity

The major contributor to environmental incompatibility with a VRFB is the Vanadium electrolytes toxicity and corrosiveness. Vanadium electrolyte solution is a packing group II material meaning that it is a medium toxicity material in regards to the below scale (*Vanadium Electrolyte Solution MSDS*, 2022). Additionally, it was identified that there are also respiratory issues identified through the inhalation of Vanadium pentoxide gas (Agency for Toxic Substances and Disease Registry (US), 2012). The exposure to humans through toxic controls measures is thus required, including typical chemical handling PPE during the initial fluid transfer process.

Packing group	Oral toxicity LD_{50} (mg/kg)	Dermal toxicity LD_{50} (mg/kg)	Inhalation toxicity by dusts and mists LC_{50} (mg/L)
I	≤ 5.0	≤ 50	≤ 0.2
II	> 5 and ≤ 50	> 50 and ≤ 200	> 0.2 and ≤ 2.0
III [a.]	> 50 and ≤ 300	> 200 and ≤ 1000	> 2.0 and ≤ 4.0
Tables note:	**a** Tear gas substances are included in packing group II even if their toxicity data correspond to packing group III values.		

Figure 2-3: Toxicity Exposure Levels

As mentioned, there are four different states of electrolyte, meaning there are four different compounds used within the battery that sustain a level of harmfulness to land and water environments. From utilising the MSDS as well as international hazard and control statements, an understanding of the depth of solutions required can be achieved. To this end, the makeup and mixture of the electrolyte solution compounds with relevant hazard classifications are below derived from (United Nations, 2023).

Table 2-1: Vanadium Electrolyte Hazard Statements

Substance Name	% of Mixture	Hazard Statements
Water	40-80	Not Classified
Sulfuric Acid	15-25	H290
		H314
		H318
		H335
		H402
Sulfuric Acid, Vanadium (3+) salt (3:2)	10-20	H314
		H318
		H361
		H372
		H400
		H410
Vanadyl Sulphate	10-20	H290
		H302
		H314
		H318
		H361
		H370
		H372
Diammonium Phosphate	≤5	H402
		H412
Magnesium Chloride (MgCl2), hexahydrate	≤5	Not Classified

There are multiple hazard statements that are repeated through the list based on the material utilised. It was found important was that a different percentage of substance throughout the mixture out of the scope seen here may alter the hazard statement outcomes. A potential outcome for varying percentages is through water evaporation leading to higher concentrations of corrosive and harmful fluid.

Table 2-2: Vanadium Electrolyte Hazard Definitions

Hazard Classification Code	Signal Word	Definition
H290	Warning	May be Corrosive to Metals
H302	Warning	Harmful if swallowed
H314	DANGER	Causes severe skin burns and eye damage
H318	DANGER	Causes serious eye damage
H335	Warning	May cause respiratory irritation
H361	Warning	Suspected of damaging fertility or the unborn child
H370	DANGER	Causes damage to organs
H372	DANGER	Causes damage to organs through prolonged or repeated exposure
H400	Warning	Very toxic to aquatic life
H402	-	Harmful to Aquatic life
H410	Warning	Very toxic to Aquatic Life with long last effects
H412	-	Harmful to aquatic life with long lasting effects

There are numerous concerns present in all substances that make up the electrolyte. The vanadium (+V) occurs naturally in water basins however any sort of leachate or spillage of the vanadium solution into waterways was identified to have the ability to harm water and plant life due to concentration and acidic content (*Vanadium in freshwater and marine water*, 2000). There is also concern for effects on sperm production after exposure to the vanadium (+IV) ion where sperm count reduction was recorded in mice proving adverse effects of exposure and bioaccumulation (Aragón & Altamirano-Lozano, 2001). First and foremost, controls must be utilised to ensure there are no adverse effects on human health or the environment. Controls must also be utilised to remain in alignment with precautionary advice from the Globally Harmonized System (GHS).

IEC 62932-2-2:2020 outlines the reduction of risk regarding toxic and corrosive gas accumulation, which highlights the need to be able to scrub the air of the gas produced. Again, the OEM product aligns with IEC 62932-2-2:2020 and is required to include ventilation and a battery support system capable of ensuring safe operation of the Flow Battery System. This includes the elimination, dilution, scrubbing and limitation of human access to toxic gas exposure ensuring that effecting risk with an inbuilt hierarchy of controls (IEC, 2020). Ventilation and gas reduction techniques can be achieved in this manner through the inbuilt nitrogen generator system that performs purging services for the system.

Furthermore, is the added effect of natural air flow required for an open Flow Battery system compared to the requirement of forced ventilation if situated indoors. Forced ventilation with the battery located indoors provides toxic risk reduction but will also help with indoor heat reduction.

2.2.3 Operational Failure Factors

2.2.3.1 High Temperature

Queensland covers a broad range of temperatures but the state experiences warmer temperatures up to the recorded maximum of 49.5°C. The higher ambient temperatures need to be considered for effective operation of the device. VRFB's were found to operate best between 10°C and 40°C and thus with harsh ambient temperatures there is benefit found in attempting to reduce undue overheating issues. Overheating issues may result in electrolyte precipitation leading to damaged operation in the ion exchange membrane, reduced efficiencies and effective aqueous capacity (Alphonse & Elden, 2021), (Wang et al., 2023). The main thermal sources within the battery are from vanadium crossover through the membrane leading to reduced system capacity, and other exothermic reactions during the charge period. Other identified considerations are hydraulic friction, and overpotential from non-optimised electrolyte molarity concentrations (Ren et al., 2023). When combined with a high operating ambient temperature, these may provide unsatisfactory operating conditions for safe and reliable VRFB operation which highlight the importance of controls for thermal management.

High temperature values can also be caused by other factors such as unsafe operation component failure due to dust ingress. The heat exchanger can suffer from dust ingress through the OEM package container walls leading to fouling (Wang et al., 2017). If the fan for the heat exchanger no longer functions correctly and operation continues then the VRFB will face potential damage from overheating or system response in output reduction.

2.2.3.2 Pumps and plumbing Failure

Compliance with standards has been found to mean that some testing is necessary before implementation and commissioning of a VRFB. The OEM package will comply with UL 1973 for ensuring safe and reliable use of the battery in real life conditions. Additionally, IEC 62932-2-2:2020 outlines various testing procedures for the commissioning of the battery. Both standards refer to components in the battery such as pipes, valves and pumps and their respective testing procedures for commissioning purposes. It was found a common occurrence that incorrect plumbing practices and installations are common and therefore adherence with standard commissioning procedures is important for operation (Hekmati et al., 2020). Issues during operation were also identified with pressure issues due to pipe resistance that apply to piping systems and adhered to extend longevity (Ispas-Gil et al., 2024). The most likely failure rate was found to be static material failure in tube leakage which is identified as the greatest failure rate, which is an important characteristic of installation material quality (Reichelt & Müller, 2020). The Polyethylene (PE) piping utilised, as well as the glue used to connect the pipes together can structurally deteriorate over time, especially if the initial connection was not performed adequately. This failure type can also be affected by temperature, where excessive heat can reduce the life expectancy of this before maintenance is required.

Other system failures are from moving parts within the system, including the magnetic drive pumps for electrolyte circulation and valves for restricting fluid flow when necessary. Through the inclusion of redundancy components and fluid paths, the failure of these components could lead to a downtime of less than 1% (Reichelt & Müller, 2020). Without some degree of component redundancy in place there will be further exacerbation to the downtime experienced regardless of repair time incurred.

2.2.3.3 Cell Stack Components Failures

The VRFB's cell stack is the most important and valuable part of the battery for power conversion purposes, and experiences variety in components and materials. It also was found to have a range of potential failure types prevalent, mostly based off variation in climatic conditions and improper BMS running. Within the BMS, the electrodes are made of a porous material that allows the flow of electrolyte through each battery half-cell dependent on polarity. It translates the chemical energy into electrical energy by means of hydrogen exchange through the membrane, which allows electrons to shift through the electrical contacts. As such, it must have good conductivity properties as well as remain porous enough to allow electrolyte flow. Over time, performance decrease can be found due to degradation of the electrode surface and eventual cell failure (He et al., 2022).

The membrane was found to suffer from numerous issues ranging from excess vanadium crossover during operation (Lutz et al., 2021) to structural damage due to failing mechanical strength over time (Ye et al., 2024). Increased temperatures exacerbate vanadium diffusion effects through the membrane, physical punctures can allow increased electrolyte seepage leading to a chemical short between the sides of the membrane and subsequent system outage (Lulay et al., 2023). Before failure, this can lead to less capacity in the electrolyte forcing reversal procedures to be undertaken (Poli et al., 2021). Further failures exist in the membrane as a mechanical failure in the membrane such as pinholes. There are also other degradation modes that have the capacity to cause reduced operation or damage. The internal membrane damage and rupture was caused by long term exposure to the vanadium exposure on system components. Non-optimal operating conditions such as vanadium concentrations or climatic conditions felt within the cell stack have been found to exacerbate these failures (Zhang et al., 2015). Effectively, the main concern from the perspective of the ion exchange membrane can be summarised as controlling system conditions to reduce crossover and diffusion that lead to failure.

Bipolar plates are multi-functional by being capable of providing structural support, electrical linkage between individual cells and the prevention of electrolyte mixing between each individual cell. Like the electrodes, an overcharging scenario is found to cause oxidation and corrosion on bipolar plates (Satola, 2021). Other failure for the bipolar plates exist are surface and structure defects from overcharging leading to hydrogen gas formation, as well as blockages through the fluid circulation system caused by degradation and contamination (Satola, 2021). As a consequence, this can also lead to swelling and electrolyte leakage (Gautam & Kumar, 2022). Ultimately, most types of failure will result in reduced battery efficiency however can lead to subsequent reasons for replacement but indicates that State of Charge and Temperature control are paramount.

2.2.3.4 BMS, Sensor and Switch Failures

Certain operating conditions can lead to faltering of equipment such as sensors and float switches and electrical connections. Sensor failure was expected in have varying outcomes due to the range of different measurements and conditions required for successful system operation. These failures can lead to lack of thermal control, State of charge disparity, pump control and more. These elements all tied together perform avoidance, detection and handling of faulted outcomes within the BMS (See et al., 2022).

Faults in electrical connections as well as switch mobility can be affected through corrosion. Corrosion is due to excessive humidity exposure, as well as through exposure to Sea Salt Aerosol (SSA) otherwise known as ‘salty air’. Tropical regions have been known to experience advanced corrosion of daily use electronic components, and small moving parts (Yadav et al., 2021). Material selection was thus found important for these moving parts and sensor equipment should be selected for risk reduction.

BMS failure can also be experienced leading to potential risk of system overheat and poor control of cyclic performance. BMS failure can be caused due to electronics damage through climatic conditions such as the corrosion already mentioned or instability from poor communications between components the main unit. Software faults can also occur leading to improper responses to information received from sensors (Su & Lin, 2024). Evidently there are a multitude of factors for BMS failure that need to be managed during operation.

2.2.4 GIS Mapping Evaluation

Considering the various climatic conditions, the inclusion of mapping or Geographic information Systems (GIS) as a method to inform the application of controls was found to be useful. Using mapping procedures follows traditional engineering thinking processes of accounting for the environment and other potential conditions (Ahasan & Hossain, 2020). As mentioned, thermal considerations can be accounted for such as mapping for maximum and minimum temperature variations (Lagrini et al., 2020). Temperature parameters can also be identified using local expertise meteorological data such as information from the Bureau of Meteorology (BOM).

The main benefit of including a battery is being able to operate alongside renewable energy and provide system strength for the intermittent resources. Attributing to this is the benefit for GIS modelling, is including solar irradiance and realised solar potential for optimal battery placement (An et al., 2023). The National map through the Queensland Government has layers attributed to energy production in the manner of realised solar potential and probabilistic wind flow (OMNILINK, 2024). Furthermore, the methods of integration of energy sources into the grid was found to vary depending on solar installations and tariff pricing such as the solar soaker tariff (12C) which is found to support higher energy demand from consumers through the day (Ergon Energy Retail, 2024). This counters traditional solar generation of lowest demand during the middle of the day and may otherwise skew optimal operating times for the battery from the middle of the day to other periods.

The section for toxic controls also briefly covered resource availability and distances from supply hubs to required sources for resource supply and planning purposes (Robin et al., 2019). Additionally, pollutant susceptibility for waterways (Al-Adamat, 2017) also proved to be a beneficial investigatory tool, including but not limited to the man-made potential contaminants and the distance to them. Proximity, however, will prove more beneficial to drawing conclusions in the capacity of risk assessments as generally, toxic waste can be carried into the environment more easily through waterways compared to dirt. In some cases, there is some potential for waste reclamation of these leachates as has been undertaken by landfill operators (El-Saadony et al., 2023). Understanding physical proximity and water flow behaviour within an area is an important consideration for the selection of risk control measures.

The deduction of controls combined with ideal scenarios for where the controls would be implemented is to achieve an ideal output. It allowed categorisation of controls and their potential best suited locations (Rikalovic et al., 2014). However, one limitation of GIS or mapping data is it not expansive when minimal amount of information is provided (Saastamoinen et al., 2022). For example, it would be beneficial to understand workforce availability and travel expenses rather than physical proximity as initial response times can vary (France-Mensah et al., 2017). The current best utilised tool for most of these aspects is through Life Cycle Assessments which can provide a general comparative outlook on the different extent of environmental impact through locational categorisation which can alter final decision outputs (Sabet et al., 2023). The importance of situational understanding should not be underestimated for each installation, especially with limitations on worker availability and knowhow according to the maintenance required for these machines.

2.2.5 Operational Maintenance

Typical maintenance undertaken can be found using a separate similar solution. The system outlines basic maintenance including but not limited to cleaning ventilation openings, inspecting for corrosion and inspecting the condition of external components. Internally; any seals and the fluid circulation system is inspected to ensure there are no leaks, inspection of sensors, ensured electrical and emergency system operation and general cleaning are all undertaken (Gildemeister Energy Storage GMBH, 2015). There was found to be no outline of recommended part replacement periods, rather a recommendation to contact a service partner for issues. (Minke & Dorantes Ledesma, 2019) address this with the adoption of various maintenance scenarios, where a pump, membrane and cell stack are to be replaced after 10 years operation.

Due to extreme membrane degradation, it may be more cost effective for a complete cell stack replacement, dependent on cell layout and age. If degraded, the ion exchange membrane can also allow excessive Vanadium ion exchange which contributes to reduced capacity. The initial membrane composition as well as the operating conditions of the battery can also contribute greatly towards the rate at which the membrane degrades (Pichugov et al., 2023). There are techniques available for restoring the capacity of the Vanadium electrolyte through simplified means of balancing electrolyte charge levels by adding the respective electrolyte mix (e.g. reducing V(V) to V(IV) in the positive tank to equate the V(II) concentration of the negative tank)(Poli et al., 2023).

For the fluid circulation system, there is minimal literature exploring the maintenance and periodic replacement of parts beyond the 10-year replacement previously mentioned. This may be due to a low-pressure fluid circulation system, comparable to typical plumbing installations. Modes of maintenance could then be compared to that of those systems, ensuring regular interval maintenance or inspections are undertaken (Rodby et al., 2020). This concludes with pump repair and replacement, where typical magnetic drive pumps have an approximate service life of 10 years where they can suffer from surface degradation (Etminanfar et al., 2020). Another aspect of maintenance is the occurrence of failures through maintenance incorrectly performed, as a person working a component may unknowingly damage another component or its ability to operate. A potential case for this is the servicing of fluid circulation components and a tool is dropped through piping for the circulation and travels through to the electrolyte tank due to not following correct isolation procedures. From this aspect, over maintenance may give rise to more potential impacts from human error which can be unpredictable when it occurs.

2.2.6 Controls Review

2.2.6.1 Assessing Toxic Controls

Implementing toxic controls is important from both an environmental and business perspective. It has been highlighted that a majority of the toxic component in the VRFB is the electrolyte which contains Class eight corrosive materials. The GHS was found to be quite extensive in the addressing of potential controls ranging from prevention to response, storage and disposal (United Nations, 2023). All codes mentioned above are important to consider but codes discussing immediate health concerns such as seeking medical assistance will not be considered further in the table below. Please see Appendix C for a table with more extensive precautionary codes.

Table 2-3: Relevant Toxic Precautions

Prevention Code	Definition
P234	Keep only in original container.
P271	Use only outdoors or in a well-ventilated area.
P273	Avoid release to the environment.
P280	Wear protective gloves/protective clothing/eye protection/face protection/hearing protection/...
Response Code	
P390	Absorb spillage to prevent material damage.
P391	Collect spillage.
Storage Code	
P403+P233	Store in a well-ventilated place. Keep container tightly closed.
P405	Store locked up.
P406	Store in corrosive resistant/... container with a resistant inner liner.
Disposal Code	
P501	Dispose of contents/container to ... (in accordance with local/ regional/national/international regulations)

By following the controls of hazards outlined in the GHS system, it can be summarised that the electrolyte is to be:

- Stored in a secure container with an inner resistant lining as previously identified as the most likely option in section 1.3.3.1.
- Stored in a room with adequate ventilation (if a room is used), of which the current EQL installation at Berrinba is stored therefore additional rooftop ventilation is to be assumed and recommended.
- Correct operational and handling procedures for when spillage occurs. Section 1.3.3.1 outlines bunding requirements for the category II packing group material.
- Equipped with developed disposal procedures that are accurate for the location of concern. This is to be developed through project planning; however, electrolyte is desired to be reused if possible.

Overall, spill prevention through adequate containment provides an ideal solution for reduction in the negatives consequences on the environment (Weidhaas et al., 2016). A bund is open for spillage capture but has a rooftop or similar overhead structure preventing rain ingress. (Environment Protection Authority South Australia, 2016) identified that if rainfall does infiltrate a bund, then the water will either evaporate through natural means or requires means of correct disposal. Analysis on all vulnerabilities is thus determined as necessary to achieve a reduction of legal mechanisms inclusive of storage and handling for emergency engineering controls.

A further dimension for toxic control is through emergency response in a temporal manner as response time is an important consideration for choosing controls for leakage significance. Typical travel time methodologies for GIS or mapping related systems include live traffic data, distance, and road type including its' speed limit. Travel time reliability is understood as an issue to overcome in (Taylor & Somenahalli, 2010), and thus it was highlighted that a successful emergency strategy should be implemented to overcome unreliable travel times. (Caulfield & Charly, 2022) for instance highlights the necessity of environmental modelling to estimate travel times as well as undertaking human and ecological risk assessments. In the context of the VRFB, material availability at certain locations may not be ideal and as such, resources for repairs are an extra consideration. In addition to that is under an emergency scenario of spilled electrolyte, there may be an indeterminate period of time to perform emergency maintenance or repairs (Shrestha, 2010). For the aspect of general business controls, this much detail may not necessarily be required as other strategies can be implemented such as resource and employee allocation. It may then be more important to facilitate common worker populace centres and resource allocation for location assessments (Hamasha et al.). Consultation with relevant stakeholders should keep these points in mind when selecting set locations. To summarise, further understanding from a geological perspective indicates that using site-based solutions may alter the requirements of minimal travel times and adjust thought processes towards emergency controls.

Another control aspect was found is that of determining measurable impact after a spill and the subsequent recovery efforts. For projects involving earthworks or chemical usage, soil sampling was identified as an important part of the process for reasons of erosion control, acidification and more (Hou et al., 2020). For earthworks, it was also deemed important to understand if the soil is adequate for developing a foundation for a building, bridge or other construction types. As for the aspect of chemical handling with a risk of leakage, prior soil testing will help understand the quality and makeup of the soil prior to a spill and allow monitoring (Asadi et al., 2017). This acts a baseline for a spill and ensures that the parties involved in cleanup are able to reverse the damage back to the original quality, causing minimal environmental impact and soil toxicity. During project planning is when this will be undertaken and is important for rectification in the case of leakage. A lack of duty care in this scenario will lead to legal implications in the event of leakage.

2.2.6.2 Assessing Thermal Controls

Considering VRFB's preferred operating temperature between 10°C and 40°C, the ability to control these is important considering the high heat summers prevalent in Queensland. Additionally, there are cool winter mornings particularly observed in inland regional Queensland. The main reason for controlling temperature between a certain range is to reduce the ability for electrolyte precipitation and air oxidation of the negative electrolyte (oxidation reaction). Precipitation can occur in the catholyte or the anolyte, forming the precipitates of V_2O_5 and VSO_4 respectively (Nguyen et al., 2024). Designing the cell stack to reduce this impact can be undertaken however the use of a pressurised inert gas has been found as solution which minimises the amount of available oxygen within a system (Ngamsai & Arpornwichanop, 2014).

The volume of vanadium electrolyte in the VRFB acts as thermal storage, thus is a coolant in and of itself in the electrolyte tanks (Rho et al., 2022). However, as has been realised by industry leaders and researchers, this is not adequate to rely on in hot environments due to cell stack temperatures of main concern. To combat the higher heats in the cell stacks during discharge, heat exchangers are commonly used in conjunction with VRFB's to provide enough heat dissipation (Wei et al., 2014). Further identification of other system controls has been performed, including flow rate adjustment, where a larger flow rate of coolant in the heat exchanger reduces electrolyte temperature (Wei et al., 2014). In another capacity, the adjustment of electrolyte flow rate was not found to have a dramatic effect on temperature but rather other system efficiencies instead.

As for internal battery controls from the OEM package perspective, there were various controls identified that could change system development. It was identified that a higher flow rate (lower pressure) provided more cooling and also increased Coulombic, voltage and energy efficiency (Wei et al., 2014). Molar concentration of the vanadium in the electrolyte also faced benefit in optimisation, where higher molarity solutions experience fewer exothermal reactions when compared to low molarity solutions. This is due to requiring more energy to produce the chemical reaction (Alphonse & Elden, 2021). It was also identified that multiple inlets or outlets used within the battery can reduce velocity allowing more consistent pressure flow. This assessment was performed in a comparative manner with equivalent performance output allowing better scalability for larger power systems (velocity and pressure are inversely proportional) (Cecchetti et al., 2024). Internal controls are not necessarily applicable from the point of view of Energy Queensland but may find benefit in the case of future electrolyte acquisition.

It was found for cold studies that a dramatic effect is experienced on battery capacity and system voltage for varying thermal conditions, with some reduction seen in comparison from an optimal 25°C compared to 10°C. Furthermore, there was a major reduction in capacity observed at -10°C (Rao & Jayanti, 2023). Similarly to hot temperatures, a main control that could be implemented is again using a heat exchanger, which transfers heat between hot and cold fluids. Typical solutions like one from Gildemeister include adequate insulation and optional air conditioning for temperature control (Gildemeister Energy Storage GMBH, 2015).

Vanadium systems with the container style exterior are utilised outdoors however there are benefits towards integration in buildings. Buildings can be designed with a high enough thermal resistance to ensure that cold external temperatures can not affect the battery thermal management, but also for hot external temperatures with the purpose of minimal exacerbation of the operating temperature (Petcu et al., 2023). Some potential thermal issues encountered are a lack of air flow which leads to higher temperatures inside the shed at high temperature times. Building designs with excellent passive ventilation may overcome this through better directed wind flows and taking advantage of hot air's tendency to rise (Jiang et al., 2023).

Other typical shed designs for heat reduction include the use of forced thermal extraction using exhaust fans (M. Singh et al., 2020), which also double up as a potential method for removing gas build up from the VRFB's ventilation system. Roof design also forms a consideration, where structures with a pitch (Skillion Roof) or a peak in the centre (Gable Roof) both allow greater benefits in ventilation due to allowing the hot air to rise from the concerned area. The design of sheds for focused air collection or extraction is also a possibility, where the design of the roof as an orthogonal Sawtooth shape or an Aerodynamic Wave Shape. If a structure is required, the selection of a particular roof shape is important to complement natural air flow at the installation location (Lukiantchuki et al., 2023). It was however identified that an aerodynamic roof installation provided more consistent preferable air flow qualities for ventilation purposes. The battery installation, particularly in the cell stack and pumps will be sources of heat. Promoting good ventilation will reduce the overall impact from these self-inflicted and external climatic sources. Finding a combination of thermal resistance as well as adequate ventilation is important for either operational or safety aspects of the battery when considering a structure for the installation.

Another aspect to thermal control is through alteration of charge and discharge times, as it has been documented that cell stack temperature found an increase during battery discharge and a decrease during the battery charging period when compared to the external ambient temperature (Rho et al., 2022). Evidently this means there is more opportunity for precipitate formation during the discharge process. Under typical cyclic conditions for the battery would mean that temperature concerns may be greater during the afternoon and evening grid demand peaks. Further skewing toward evening operation will normally result in lower ambient temperatures, offering benefits in reduced precipitation risk.

Traditional cooling methods for the energy industry have evolved from natural cooling materials, and now evolved towards forced cooling methods. As a comparison, an Oil-Natural-Air-Natural (ONAN) cooling method involves no forced liquid or air flow meaning that less cooling is achieved however it also means better efficiency and less capital expenditure. On the other hand, Oil-Forced-Air-Forced (OFAF) means that there is forced oil flow and forced air flow translating to better cooling however a higher capital expenditure and less efficiency during operation (Xinyue Gao et al., 2024). A major consideration for these components was found that more moving parts leads to less reliability, meaning that opting for a simpler choice for cooling will prove more effective for cost reduction in some cases. Relating back to the manufacturers solution, the package has the heat exchanger with intermittent forced air ventilation meaning it can be considered an OFAF system during fan operation. The moving part translates to less reliability albeit more efficient cooling. Evidently when the fan is non-operational then the system is considered an Oil-Forced-Air-Natural (OFAN) system relying on natural convection purposes Use of an ONAN system could mean the cell stack is cooled rather by a larger oil filled heat sink like basic transformer counterparts. To achieve this goal of cooling without temporary forced convection will mean a change within the OEM solution would need to occur. This outcome would need to be discussed, and viability assessed by the OEM VRFB's engineering group.

2.2.6.3 Assessing Storm Controls

Storm Volatility was determined to be less of a concern for the operation of the actual battery but faces concerns for the damage of structural components and external electronic componentry such as the DC to AC conversion equipment. Protection of components from storm conditions is largely understood within the energy industry to achieve electrical safety and increased component longevity (Gonçalves et al., 2024). The perspective of component longevity traditionally consists of ensuring that the impacted component is effectively isolated using a tough medium such as a solid structure. This guiding premise of strengthening and design preparation removes higher necessity on system resilience, particularly for the volatile range of conditions that a storm can have (Office of the Co-ordinator of OSCE Economic and Environmental Activities 2016). Storm protections in this context, are those that help prevent component damage.

Queensland encounters a variety of storm conditions, where Southern Queensland can encounter volatile super cells, but far north Queensland can also encounter cyclonic weather mainly during the summer months (monsoonal period). Construction of a protective structure as a control therefore has locational context where the engineered structure must adhere to C1 rather than N2 building standards defined by conditions such as wind regions, shielding and slope of the site at hand (Australia, 2021). Sheds and carports as well can be designed to meet this standard, allowing opportunity for multitude of controls to be considered for a high wind scenario. Whilst the shed or carport required would be larger than these residential examples, it is still possible to ensure structures are built adequately.

2.2.6.4 Assessing Dust Controls

Dust can be a major concern for components such as the Heat Exchanger, even in areas with relatively low dust buildup due to the potential of dust fouling. The appearance of dust is exacerbated by higher wind speeds and wind-time exposure. It is also exacerbated by lower amounts of rainfall and increased wind in the area.

Biome is also an issue, where an installation near grasslands or deserts may encounter increased dust compared to an installation in a city. Dust controls are in the form of a control that prevents immediate contact, with popular solutions found as below:

- A protective dust reduction curtain for dust prevention can be implemented for minor cases. PVC strip curtaining can be used, finding benefit when facing a direction where dust particulates are numerous however it requires a structure and can notably reduce wind flow (Xiu et al., 2022).
- For a major case, a completely enclosed structure with an effective ventilation and filtration system could be used (Noll et al.). The most effective method however comes with an increased cost, as well as continued ongoing maintenance and cleaning of the filters. Achieving this is essentially like achieving a certain ingress protection rating, like the IP 54 rating from the Gildemeister solution which outlines limited dust ingress (Gildemeister Energy Storage GMBH, 2015).

- Water misting to attempt better containment of surrounding dusty areas (Prostański, 2013). This is not viable for remote areas due to available resources as well as the system becoming another system that can face reliability issues with moving parts such as a pump.
- Windbreaks or dust fences can also be used externally of any equipment to be protected for dust control (Prostański, 2013). Dust fences have a particular geometry that allows minimal pressure differential between sides of the fence but block most dust from penetrating. Coal stockpiles utilise this to ensure the material does not blow away due to wind (Park & Lee, 2002). More basic examples are dust control meshes used on construction sites such as FenceWrap™.

Dust controls can also be implemented on a basic level during site selection. Prioritising dust minimisation firstly may lead to less dust exposure. This could be achieved through comparison of similar sites in a region during the planning process.

2.2.6.5 Assessing Ultraviolet (UV) Controls

Damage caused by the sun varies dependent on the material it is affecting, and as such the controls required are also dependent on the material. In context of the OEM batteries there are several UV exposed components including:

- The shipping containers.
- The platform or concrete slab that supports the batteries' weight.
- The electrical enclosure and BMS for grid interaction.
- The electrical cables to the interface.

The above components will all be designed to ensure material longevity such as the cables with a protective sheath, painted exteriors, or metallic surfaces. Some metallic surfaces are resistant to UV, but copper, zinc, aluminium and iron can face increased corrosion due to UV exposure (Forsyth, 2000).

Electrical cables normally have internal insulation for the wires such as Cross-Linked Polyethylene (XLPE) but also have an external protection layer. Commonly, PVC is utilised for this purpose and as such has been to undergo a transition to brittle behaviour under UV exposure, particularly in low temperatures (Naskar M. et al., 2018). Maintenance can be performed on electrical components to replace conductors when necessary but UV controls such as a shed or secondary covering for the cables will provide some benefit towards damage from UV exposure.

The ISO shipping container on the other hand whilst facing limited corrosion does rust due to properties of the CORTEN Steel Alloy, providing long term protection through the utilisation of this rust layer. Some exacerbation of this rust layer is identified through moisture cycling and UV exposure (Mahmoud et al., 2005), although a solidified idea on failure rate is not necessarily identified. Furthermore, inhibition to rust and UV exposure can be improved through a painted surface along with ongoing maintenance in this regard.

UV controls will face a reduction of direct exposure to indirect exposure, essentially comparing a non-shaded area to a shaded area. Whilst a shaded area will not only be cooler, but it will also have far less UV exposure and as such, any controls that perform this function will be effective towards UV exposure reduction. It should also be noted that the exposure to UV in shade is not necessarily zero so there will normally be some degree of indirect exposure remaining (Saric-Bosanac Ss Fau - Clark et al.). To summarise, the components that face UV exposure for the battery are UV resistant and controls are not necessary for most cases. The main concern is in the electrical capacity where degradation in the UV protective sheaths can occur, albeit unlikely.

2.2.6.6 Assessing Humidity and Moisture Controls

Humidity controls find importance particularly for remote areas or those with high exposure rates to moisture and within a small proximity to saltwater. These elements can lead to corrosion of the internal components of a battery if controls are not implemented.

Dehumidification systems are utilised for batteries however are for Lithium-Ion production to ensure a reliable product is produced (Ma et al., 2024). VRFB however faces less issues with no identified effects of humidity on electrolyte or operating efficiency. There is some concern with humidity, and salt exposure for auxiliary equipment operation and thus increased corrosion rates. The use of a dehumidifier will allow less concern for the corrosion of these components however will lead to less efficient output of the whole system. This is a similar factor to shed forced ventilation mentioned below. Further aspects in dehumidification are in desiccant bags, capable of absorbing moisture up until a maximum absorption for the material and simply retains until the moisture evaporates or is baked away in a maintenance process. Proof of its effectiveness has been achieved for green coffee which is highly susceptible to moisture retention issues (Anokye-Bempah et al., 2023).

If a shed is used for storage, then ventilation systems can assist at regulating a range of conditions within a structure including humidity. Shed design is important in this regard where a higher air flow rate through the installation reduces moisture levels for an indoor environment, meaning lower humidity and is preferable as it allows healthy air for human interaction (Seppänen O, 2009). The other aspects covered in the 'assessing thermal controls' section also apply towards structure design. The utilisation of dehumidifiers can also assist in this regard allowing less chance for humidity buildup.

Cathodic or Anodic protection like those found in marine installations could find some benefit in corrosion resistance for aggressive environments (Bradford & Meyers, 2003). Unfortunately, it does not prove viable for this scenario as an electric current must be running for it to operate. Utilising electrical currents on electrical equipment will lead to electrical shorts, destroyed equipment or more. Thus, the use of anodic protection is not viable in this case.

2.2.6.7 Assessing Shock or Earthquake Controls

Physical impacts on this system can be prevalent due to vehicular impacts, damage from projectile objects through storms or violent shaking from earthquakes. The shock impact from these can cause acceleration of system components through inertia, causing damage from the high force impact. To reduce the force of the impact, it could be assumed that there would be impact shock displacement protections for the important components such as the cell stack (Long et al., 2018). This will help ensure that electrolyte leakage and expensive componentry is not adversely affected.

Australia does not suffer significant seismic events with the largest recorded earthquake being a magnitude 6.0 (± 0.3) measured in moment magnitude (M_W) (Martin et al., 2024). This is compared to Japan's 9.1 measured in the same scale (M_W) (Hashimoto et al., 2012). The damage caused to buildings and other objects in the impact zone is the acceleration felt through the shaking, which is defined as Ground Acceleration, with the maximum acceleration during an event defined as the Peak Ground Acceleration (PGA). Typical PGA values and impacts are as follows (United Nations Office of Disaster Risk Reduction):

Table 2-4: PGA Common Ratings

PGA (g) (g = 9.81 m/s^2)	Potential Damage
<0.1	Low Damage
0.2 < 0.8	Moderate Damage
> 0.8	Major Damage

To counter this, Japan in particular designs buildings are designed to various PGA's for damage reduction. Some controls utilised to achieve this purpose include regular building geometries for force dispersion, dampening systems for oscillation reduction, as well as promoting flexibility through material selection (Shareef, 2023).

Applicable earthquake or impact controls for the manufacturers system are through container mounting or internal component protection. The internal component with the greatest concern is the cell stack, as similar structured PEM's can suffer from excess vibrations (Nan et al., 2022). As such, a mount with a dampening system could be implemented as a suitable control to ensure the cell stack stays operational and undamaged. The fuel cell is the heart of the redox chemical process and as such needs to be protected. Other damaged internal parts from an earthquake could for example be leaking joins and flanges for piping (Bata et al., 2022) or exposed electrical wiring and joins.

The focus for protections has been on the internal equipment, however complete protection of the whole OEM package could serve for impact shock reduction techniques. Protection can be offered in this capacity using external protection such as walls of a structure, fencing, trees or a similar barrier (Gan et al., 2021). In extension, a concrete bund may also provide some sacrificial support in the event of a targeted fast-moving object. As mentioned, Australia faces little risk from earthquakes and as such, external dampening mounts for the shipping containers is not necessary and may not provide other protections.

2.2.6.8 Assessing Vandalism and theft Controls

Vandalism have been found to be less random encounters and more often found that events are targeted (Killen et al., 2017). This means that vandalism and theft can be exacerbated through public distrust, outrage or dislike of installation visuals (Mushtaha & Hamid, 2016). Public perception goes far further than addressing vandalism and theft reduction and is an optimal manner for addressing issues and ethical dilemmas. Trust between a company and the community is an important perspective as good public perception can mean less conflicts during operation as well as community assistance towards achieving goals (Rijal, 2023).

However, poor public perception can lead to theft, vandalism and other operational issues such as disallowed construction of a project. Therefore, first and foremost, ensuring public trust is a major goal in the development of new projects as misinformation and mistrust may run rampant (Walsh et al., 2017). It is also important for any ongoing installations or onsite deterrents to remain visually acceptable to reduce the backlash from the community.

Ensuring that public perception has been previously highlighted, further vandalism and theft preventative measures are available. Examples of this are access inhibition through locks, extra access layers, fencing and more. It could be assumed that locking equipment will be used on the container doors of the OEM package, and further inhibitions could be a sealed and locked shed removing the installation from the public eye. Another method applicable to this case is an external fencing boundary that is of adequate height, which can act as a natural deterrent for the access of thieves and other culprits (Odunlade et al., 2023).

2.3 Reliability Modelling

2.3.1 Existing Reliability and Failure Methodologies

It has been identified that for dedicated VRFB failures, there is limited literature available discussing the existence, magnitude and probability of the different forms of failures. The main reasonings for this is companies will not publicly report failures to protect their image. These failures, however, can lead to the development of maintenance schedules with typical dedicated machine downtimes. These types of documents can form failure prevention strategies with reliability centred investigations, acting as a control and information source. A way to overcome this lacking data was proposed in (Reichelt & Müller, 2020), where reliability analysis was utilised through VRFB literature where possible. However, the usage of generic and similar system reliability estimates on components such as pipes and valves formed a basis for making assumptions on the rest of the system. Utilising generic or similar system data in this manner is useful for developing models but does have downsides. The main issue being that accurate failure modelling is not necessarily achievable as different materials, plumbing adhesives and operating conditions are being assessed.

The VRFB is a multi-component system and as such may have under some failure circumstances, a series of failures that all stem from a single failure. Therefore, the determination of system reliability stems from an understanding of two major components:

- System dependencies and relationships.
- Determination of reliability on a time-use basis.

A system dependency method is followed in (Wang et al.) for reliability modelling using a statistical function; however, this focuses on relationships between components based on configurations. Whilst understanding the aspects of varying system dependencies is important, further benefit was found through focusing on functional reliability aspects for a whole system. This is because the OEM package does not necessarily allow great variance during operation.

It has been identified in (Xiong et al., 2019) and (Prabhakar Murthy et al., 2004) that a Weibull probability distribution method is beneficial to achieve this. Probability analysis is identified for addressing mechanical failures of individual components inside the cell stacks during system operation (Reichelt & Müller, 2020). It also has merit towards integrating time-based independencies rather than pressure as the independent value. It is however identified through this work that without enough statistical input, there is some limitations towards the effectiveness of Weibull Analysis (Prabhakar Murthy et al., 2004). The general concept behind Weibull analysis will be easily achievable with enough statistical observations through determination of Weibull model characteristics by using MATLAB and/or Excel optimisation logic for verification purposes (Mathworks, 2024). Understanding system components and modes of reliability variance will be key to ensure the Weibull system provides the greatest ability to assess conditional reliability.

Presentation of Weibull reliability results can be done with simple curves; however, these don't necessarily inform the user of how a multiple component system experiences failure. This is achieved through concurrent use of other curves that display the effects of reliability from separate components. This is useful for devising system controls through assessment of the impact on reliability from individual components. The univariate Kaplan-Meier or multivariate Cox curves are tools used significantly for displaying outcomes in a single component fashion (Dudley et al., 2016). These step curves breakdown information into separate components allowing the magnitude of step changes to be observed. The benefit to this is the ability to understand how reliability curves change dependent on the behaviour of components. To this end, the combination of these tools will also be important to understand the overall effectiveness of the data at hand if there is lacking statistical observations. Any assumptions made to fill missing information need to be accurate (Andrade, 2020), and the use of step function information can help inform them. A reliability assessment is vital to measure if conditional understanding is beneficial to controls development.

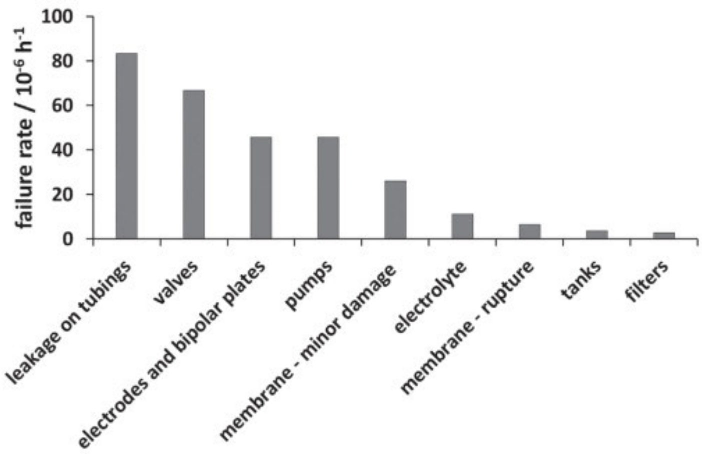

Figure 2-4: Typical VRFB Failure Rates (Reichelt & Müller, 2020)

2.4 Knowledge Gap

There is information needing to be confirmed both as a general measure and in terms of knowledge for a business perspective.

The first is for confirmation for EQL and other concerning stockholders including governing bodies that locational considerations have been completely considered for the prepackaged system supplied by the manufacturer. This confirmation of ensuring all impacts and relationships have been assessed correctly and all controls have been implemented in a sensible manner to reflect those impacts.

The next lies in assessing system reliability, where there will always remain some lack of continuity between prepackaged and in-house developed products. This is due to variations in quality of supplied products such as pipes, pumps and more, which can affect individual reliability in an unpredictable manner. The main remaining question remains is if distinguishing between these is necessary for ensuring that maintenance is up to date. This allows the ability to understand the system before and after maintenance or controls are implemented.

The last remaining gap is for VRFB's in general where there is a lack of information regarding control measure implementation beyond general information for safe usage provided in IEC 62932-2-2:2020. Assessing control measures based off various scenarios will help to assess if certain control measures are required from an environmental standpoint.

Lastly, remains a larger interest from a business point of view through the development of an environmental controls framework for standard business project development. Whilst this will mostly be addressed through the three other knowledge gaps identified, there is also a lack of literature that investigates best forms of business integration for this type of document beyond performing risk assessment investigations. This is due to ensuring information remains privileged and out of competitors hands, however environmental analysis and sustainability is important for future proofing the planet and must be undertaken.

3.0 METHODOLOGY

The literature review covered aspects in environmental impact and assessment of VRFB's, individual components and conditional interaction. This thesis utilised some of those concepts to build up the methodology and is approached as a risk assessment found in ISO 31000. The main approach taken of each step in the risk assessment is as below:

1. Identify the impacts, and hazards associated with the implementation of the VRFB
2. Assess the risk from the impacts and hazards.
3. Implement Controls to address the associated risks and evaluate environmental outcomes.
4. Consider best forms of business implementation for simple integration.

It has been established that controls are developed to reduce or negate risks and as such it was important for the below methodology to have a strong foundational understanding of the multitude of considerations.

3.1 Methodology Outline

The methodology can be broken down into four stages below, with more in-depth explanations provided in each stage during the Analysis and Results section:

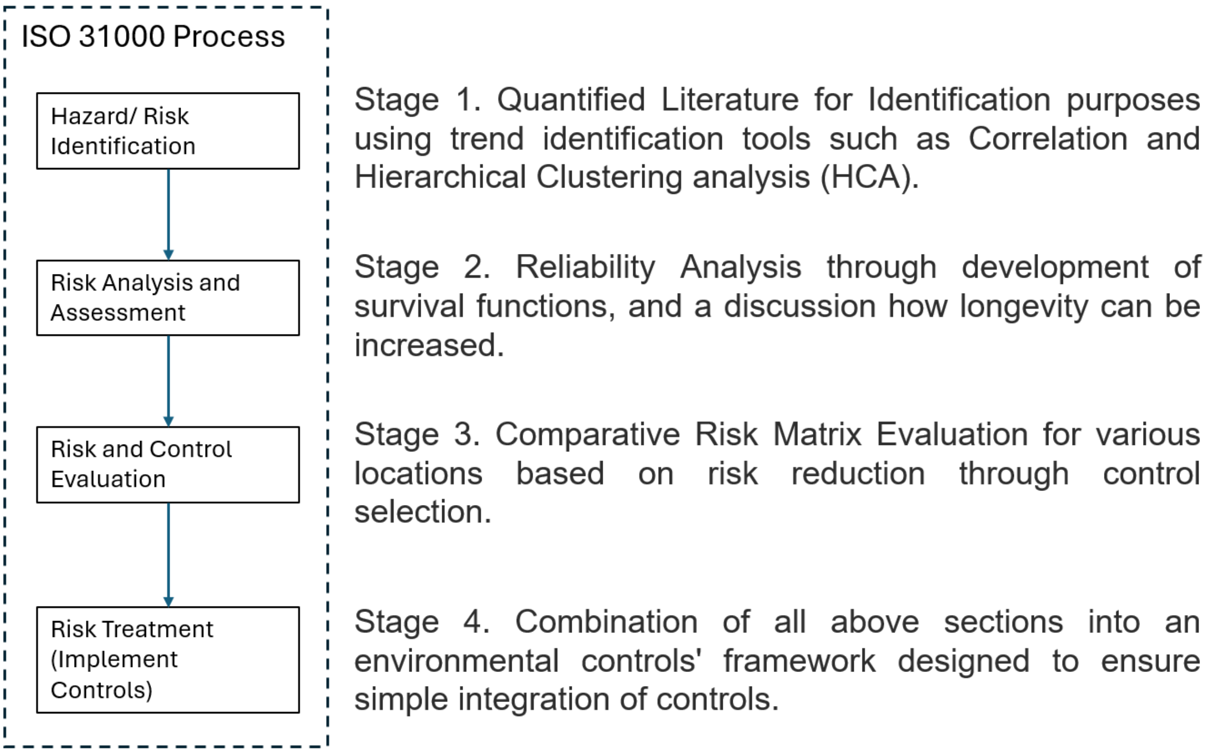

Figure 3-1: Risk Management Breakdown

3.1.1 Stage 1: Quantified Literature Assessment for Risk Identification

This stage was for the Determination of Environmental Impacts and unidentified relationships. It formed part one of the risk assessment outlined above which follows the general outline below:

- Find literature and group them together into relevant categories as necessary. Literature found consists of:
    - Life Cycle Assessments
    - Reliability and Failures
    - Heavy Metal Toxicity investigations
    - Case Studies.
- Write up Python Code capable of reading each word in the literature to perform frequency. It then finds relationships between the categories of literature and the terms mentioned. The main investigatory functions used include:
    - Frequency Count.
    - Correlation Analysis.
    - Hierarchical Clustering.
- Discussion about results, including the identification of key terms and observed relationships.

3.1.2 Stage 2: Reliability Analysis for Risk Analysis

The overall goal of this stage was to determine the magnitude and frequency of operational failures of a VRFB. This section followed the general outline below:

- Find and investigate the typical time to failure experienced by VRFB components and investigate modes of failures. This was done to understand inherent effects of scenarios and equipment on reliability.
- Utilise the extracted relevant data to develop a system within Excel that can calculate optimised Weibull probability distribution coefficients to model the probability of failure effectively. In turn, this also means modelling reliability over time as well.
- Discussion of the impacts from modelling, including how the probability of failure may warrant certain controls over others. This helped provide context towards how impactful controls will be for the system at hand, to devise more accurate risk matrices for operating conditions.

Outcomes in this stage originally aimed to provide quantitative context for a subsequent LCA comparative analysis (see section 6.6 for information on why this was not undertaken) however this proved difficult to achieve for reasons including accuracy and resource availability.

3.1.3 Stage 3: Comparative Risk and Controls Evaluation

This section allowed understanding the effects of certain controls on overall risk for set locations. The ability to compare the locational benefits of certain controls will help determination of applicable outcomes. The major steps involved in achieving this were as follows:

- Derive an event tree using the risks found from previous section, this allowed viewing of the outcomes of their occurrence based on contextual clarification. This visual tool helped in control development, including determination when controls may be most effective.
- On a locational basis, form risk matrices based on previous stage research and locational conditions for three installations:
    1. Berrinba: Since this was the chosen pilot site, this acted as a control to inform the other risk matrices. This helped in consistent ideology ensuring that the risk approaches were consistent.
    2. Blackall: Provided an insight into controls used in a location with higher consistent maximum temperatures, high wind, low rainfall as well as remoteness.
    3. Cairns: Provides an insight into controls used in a location with consistent higher temperatures, high humidity, higher rainfall, and a proximity to saltwater.

  Performing a no control versus control matrix evaluation for each location helped with control selection and for comprehension of site selection considerations.

- Verification of the risk matrices and potential controls reviewed and adjusted before implementation into the Environmental Controls Framework. This includes the determination of sensible controls to reduce risk through lack of redundancy or containment.

Initially, a Life Cycle Assessment was to be undertaken in place of the risk matrix in a comparative basis however this was proven to be unsuitable whilst undertaking. The comparative approach was kept however see section 6.6 for notes on this.

3.1.4 Stage 4: Implementation of Controls Framework

Considering all the outputs of previous sections, an operational controls framework was developed as a mechanism to support the integration of VRFB's or other projects into the company.

The framework considers items such as impacts, controls, obligations towards the operation of the VRFB. The framework is designed in a manner to ensure:

- Simple and scalable business integration.
- Individual checklist for technologies that include Risks, Controls and what reduction of risk could be achieved through the utilisation of those controls.
    - The sample developed in this instance is the VRFB system for risk and control determination.

The framework is based upon other business control frameworks to form a general concept of typical information flow. It was performed through the following steps:

1. Research business implementation measures and frameworks.
2. Develop overarching framework for the business integration.
3. Develop individual checklist for risk and control management.

3.2 Limitations

3.2.1 Stage 1 Limitations

An observed limitation with this approach is that terminology is not necessarily equivalent so there may be some bias unknowingly implemented. A portion of this bias is reduced through careful investigation of terms and filtering out, as can be seen with the python code in the analysis. This bias cannot be completely removed however so due care must be made during discussion and interpretation stages.

3.2.2 Stage 2 Limitations

The main limitation from this is that not all VRFB systems are equivalent to each other nor to the system used by Energy Queensland and thus may not represent a true probability of failure. Different countries for example may operate using different methodologies such as temperatures, material condition and installation procedures. Therefore, researched failure rates may not be exactly comparable.

Furthermore, the depth of failures is not extensive of a complete VRFB system and would be inappropriate to assume this is the final extent of system reliability factors in either an optimal or non-optimal scenario.

3.2.3 Stage 3 Limitations

Limitations to this section stem from limitations in ensuring accurate weather conditions, particularly from the modelled inputs which have been found as unvalidated. Local familiarity with weather conditions would finalise what the general correct outcomes could be.

3.2.4 Stage 4 Limitations

The usability of the Framework is not complete at this stage and requires some further discussion within EQL as to the complete scope. At this time, the framework would be considered only useable in a VRFB capacity. Further development of checklists would rectify this.

3.3 Outputs

Ultimately, the main expected output from this was a simplified draft version of the environmental controls framework to be used during the planning stages of future VRFB and similar technology sites.

Other outputs to be acknowledged include:

1. Understanding of environmental impacts from a VRFB and potential hidden relationships from the stage one assessment.
2. Understanding of reliability impacts from stage two, particularly from a maintenance control standpoint.
3. Finalised event tree analysis, risk impacts, likelihoods and risk matrices from stage three. These are used to populate the checklist for stage four.

3.4 Timeline and Workload

The final approximate timeline followed is as below. The workload was distributed with an initial literature review and consultation performed towards the beginning of the year and the equivalent to full time work was put into the dissertation from August onwards.

Due to the later full-time workload put into the project, the risk of non-submission and a poor submission is outlined in the risk matrix section.

Table 3-1: Original Timeline Approximate

Month / Item	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Initial literature Review											
Consultation											
Literature Review											
Research design and Analysis											
Framework Development											
Presentation											
Dissertation Writing											

3.5 Thesis Risk Matrix

Despite a mostly online/ digital project, some inherent risks are still involved including that of a site visit for the BESS currently in development. See **Appendix A** for a risk assessment provided through the SafeTrak risk assessment register, which includes only the personal risks as below.

Table 3-2: Risk Assessment

Personal Risk Assessment (See Appendix A for SafeTrak Register)					
Risk	**Areas Affected**	**Severity**	**Likelihood**	**Risk Impact**	**Recommended Actions**
Site Visit to VRFB	Potential for injury or harm	Generally unacceptable	Not Likely	Medium	Employ all PPE required for site visit. Follow instructions of those in charge
Performance Mismanagement	Quality of Work	Generally Unacceptable	Not Likely	Medium	Change of work chair increased early ergonomic problems. Monitor height has addressed eye strain concerns.
Project Risk Assessment					
Computer Operation	Loss of data or computer access (operation)	Generally unacceptable	Possible	High	Ensure all aspects of the report are backed up or saved to cloud storage.
Incomplete dissertation at deadline	Final Project Output	Generally unacceptable	Not Likely	Medium	Ensure that timeliness is monitored, and all issues addressed as soon as possible to prevent any chose of an incomplete or failed submission.
Alteration of Dissertation Scope	Final Project Output	Tolerable	Possible	Medium	Ensure that supervisor, research partner are on board with thesis topic and agree that content is deliverable.
Failure to access required spatial or literature data	Quality of Work	Tolerable	Not Likely	Medium	Consider reasonable assumptions that could be made to complete the task. Displays engineering knowhow if achieved to a high degree.
Incomplete Literature Review	Quality of Work	Generally unacceptable	Possible	High	Take time to produce literature review and considering all potential information for concepts not identified.
Data Confidentiality	Final Submission Redactions	Generally unacceptable	Possible	High	Ensure that the published report has redacted all areas that need to be redacted (if needed).

3.6 Equipment and Resources

3.6.1 Software Access

The software used consisted of data manipulation and coding software, data management of mathematical model development tools and other Microsoft suite tools such as:

- Python: For finding the frequency of relevant terms to ascertain important environmental aspects. Achieved using a range of inbuilt libraries and functions, as well as the development of code outlined in Chapter four and in Appendix B.
- Excel: Used for the development of the probability and reliability models using established mathematical formulae.
- Word and PowerPoint: Development of the final dissertation report, potential data reporting and PowerPoint for the development of the thesis Showcase Presentation as well as flow diagrams etc.

3.6.2 Data Access

An initial limitation found important to be noted here is that Energy Queensland data may have some inclusions that need to be redacted to protect information, i.e. that should not be public such as customer data or network ringfenced information. Great care has been taken during the development of this thesis to ensure that this is not infringed upon.

Other data is derived from existing literature found and from publicly available sources such as 'The national map' which contains various GIS layers including a series of energy layers that were used here.

3.6.3 Site Access

Few site visits were made under supervision of an EQL professional. The first site visit was during construction, where a risk assessment was completed for the site visit by an EQL site supervisor. This visit has been registered in the above risk matrix and through UniSQ Risk Register 'SafeTrak'. A subsequent visit made under operational conditions meant less risk however standard PPE was used during the inspection.

The site access was beneficial in understanding current controls undertaken, including the reasonings or thought processes involved. Further understanding was achieved in what conditions are situational controls required such as:

- The heat exchanger fans are not always operational whilst the rest of the VRFB is, this increases reliability aspects.
- Dust filters are optional on the VRFB installation. There is also the option of choosing different filtering capabilities to balance dust control and temperature control purposes.

4.0 QUANTIFIED LITERATURE FOR RISK IDENTIFICATION

4.1 Process Breakdown including software and Limitations

4.1.1 Process

The process undertaken to achieve this section was as below:

1. Researched and tabulated all the literature to be used in the correlation analysis.
2. Developed python code in Jupyter Notebook for frequency counting on both an 'individual literature' basis and 'grouped by literature type' basis.
   - Imported Documents and converted to a readable form using various functions and steps to achieve this.
     - Cleaned PDF files by using Python code with function 'PyPDF2' based code. Additional filtering was done manually to remove the references, author and publishing information to not skew data. This was kept consistent across literature pieces.
     - Removed common stop words as addressed above by utilising the python package 'Get_stop_words'. Further words that this package did not identify have been removed as can be seen in Appendix B.
     - Removed all words with numbers, the reasoning for doing this was numbers are either due to file misconstruction or descriptors for concepts, rather than the concepts themselves.
     - Filter out words of length equal to '1'. The reasoning or this was that single character terms did not provide measurable impact towards understanding. A two-character term on the other hand may be an abbreviation and thus provide some significance in utilisation.
   - Split documents into individual words and ensured that words are identified properly by accounting for variances in punctuation.
   - Iterated through document, whilst counting frequency of words and maintaining lists whilst iterating.
   - Sorted the document list by largest frequency items.

- Repeated this process for all relevant literature pieces, finding the 100 most popular terms overall. By using the 100 most popular terms, significant relationships between terms can be found.

3. Calculated statistical significance to ensure that there was significance to the data being interpreted. This is done within the Jupyter Notebook code. This was done to find a general significance of matrix variability for all matrix elements.
4. Upon confirmation of significance apparent, correlation matrices were developed to compare all the major terms in literature pieces. Another correlation matrix was also performed between literature pieces to ensure visualise how each file related to each other.
5. Discuss the results of the analysis, including the limitations and potential improvements. This was mostly performed by analysing the results, however there is some inherent effects that could be apparent in the work further along in this project.

4.1.2 Software

- Jupyter Notebook was used with supporting packages:
    - Get_stop_words: A series of 'stop words' such as 'it', 'they', 'and' that can be filtered out of selection
    - String: To find a series of punctuation to filter out, ensuring that various forms of the same word are not interpreted as separate. An example of this is 'battery' versus 'battery?', where without explicit direction the term would be treated as separate in the python coding environment.
    - Matplotlib: Provides the ability for plotting and images to be used for presentation of results including the correlation matrix. The benefit of this inclusion is evident in the results section for more simplified viewing of the terms at hand.
    - Seaborn: For presentation and development of hierarchical clustering in conjunction with the correlation matrix for easier identified groupings.
    - PyPDF2: Various Portable Document Format (PDF) functions used in this context for the reading, extracting and the development of the text documents.
    - OS: Used for systematic file extraction, resulting in a more automated Python development and results system.

4.2 Tabulation of literature used for comparison

The literature explored was chosen to address the problem at hand for the implementation of environmental controls. A diverse range of literature was chosen to provide more potential for relationships to be identified, whilst also ensuring an adequate range was provided.

It should be noted that the work, outcomes and conclusions reached by the authors in their original work is not reflected in this work. This is due to the processing and loss of dimension found in a literature analysis. As such, for complete context and outcomes, refer to each literature piece for accurate outcomes rather than the outcomes derived in this project. Appendix B is provided to form a basis for work reproduction upon file access.

The literature utilised to perform this work is sourced as below:

Table 4-1: Case Study Literature

Count	Case Study	Case/ Improvement
1	(Ceraolo et al., 2021)	Experimental Implementation
2	(Reynard et al., 2019)	Electrolyte Purification
3	(Hossain et al., 2024)	Electrode Improvement
4	(Cunha et al., 2014)	Technology Review
5	(Trovò et al., 2023)	Regulation and Safety Issues
6	(Monteiro et al., 2018)	Component Case Study

Case Studies: The consideration of case studies was found to be important as a broad number of concepts are covered and in turn provide some potential insights between environmental, operational and reliability control sections. Mechanisms in improving system operational characteristics provided a potential link to controls less evident in an environmental capacity. The benefit of its' inclusion was the introduction of another element of exploring unknown relationships that could be altered using a suitable control.

Table 4-2: Heavy Metal Literature

Count	Heavy Metals	Notes
1	(Zhang et al., 2024)	Contamination Removal through Fungi
2	(Tereshchenko et al., 2024)	Vietnam particulates including Vanadium
3	(Abebe et al., 2024)	Ethiopia physiochemical characteristics of heavy metals
4	(El-Sorogy et al., 2024)	Egypt Sediment Quality for heavy metal contamination
5	(Bashir et al., 2024)	Nigeria Heavy metal assessment
6	(Vidal et al., 2024)	Heavy contamination of neotropical bats

Heavy Metals: This heavy metal section of literature is the section of literature that was concluded as the least relevant literature to VRFB installations but aimed to provide further insight into the environmental concerns surrounding Vanadium leakage and toxicity. An example of this is in concepts such as bioaccumulation on local wildlife and its' effect on water quality, which have both been explored briefly in the literature review as potential negative effects explored by the range of LCA's. The above literature was chosen to explore broad toxic terms as a measure of environmental impact.

Table 4-3: LCA Literature

Count	LCA	Boundary
1	(Tsai et al., 2023)	Cradle-to-gate
2	(Blume et al., 2022)	Cradle-to-Gate
3	(Gouveia et al., 2020)	Cradle-to-gate
4	(Díaz-Ramírez et al., 2020)	Cradle-to-gate
5	(Y. Li et al., 2024)	Cradle-to-Grave
6	(Han et al., 2023)	Cradle-to-Grave Cradle-to-Cradle

LCA Pieces: These literature pieces were chosen as a method of exploring a mix of environmental impacts and inherent effects from the usage of a VRFB. A blend of the different LCA methodologies allowed variety in concepts, as operational or usage stages may include effects not inherently obvious or experienced in the cradle-to-gate methodology. Some influence is also identified through recycling and reuse aspects of VRFB operation in a cradle -to-cradle fashion.

Table 4-4:Reliability and Failure Literature

Count	Reliability	Type
1	(Wang et al., 2023)	Thermal Management
2	(Briot et al., 2022)	Aging Modelling
3	(Xiong et al., 2018)	Material failure through mechanical stress
4	(Beyer et al.)	Determination of Electrolyte Imbalance
5	(Huang et al., 2022)	Analysis of all critical issues
6	(Huang et al., 2020)	Reliability Investigation

Reliability: The literature chosen for this section was done so through attempting to include as many concepts as possible regarding the reliability of a VRFB. The focus on the system in this regard is to make a link between VRFB systems and potential controls to be implemented and explored further in the discussion section of this chapter. Furthermore, by utilising this literature it was understood that the reliability for the most concerned VRFB components would be highlighted as one of the most frequented words, leading to concern drawn to that component for controls implementation.

4.3 Python Code Outline

Appendix B contains the code used in the project to retrieve the results. This section includes an outline and pseudocode involved in the retrieval, manipulation and presentation of data into a usable form.

4.3.1 Literature Conversion

Converting the PDF's to the text files was a simple process that follows the diagrammatic pseudocode below:

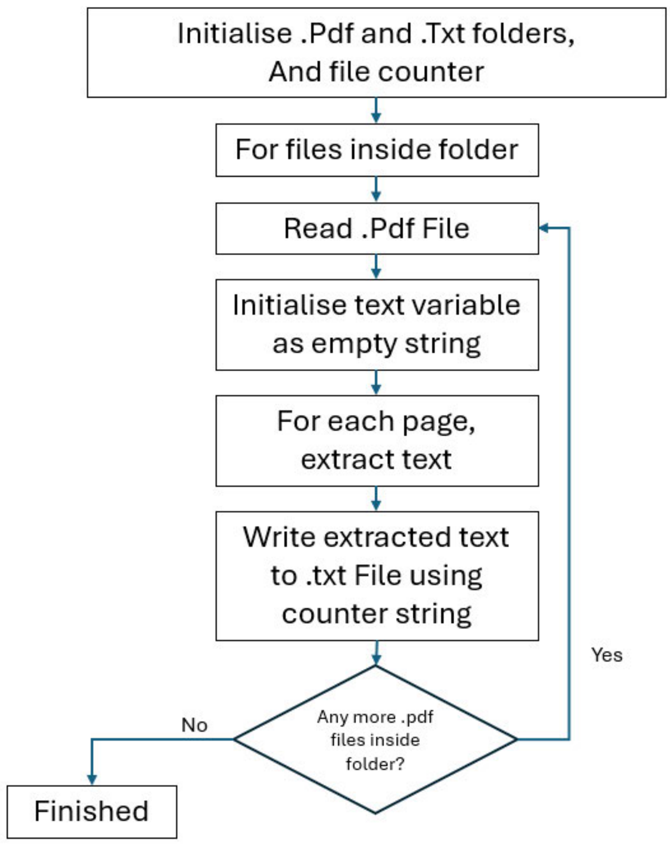

Figure 4-1: Literature Conversion Pseudocode

4.3.2 Literature Cleaning and filtering

4.3.2.1 Punctuation Function

The punctuation function performed a simple replacement of all punctuation within the string text. The function is provided by the string package. It contains the punctuation observed in the following diagram:

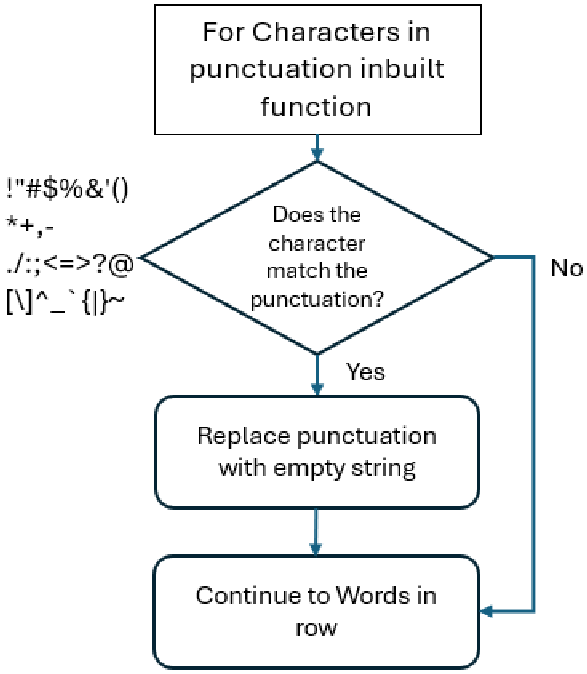

Figure 4-2:Literature Punctuation Pseudocode

4.3.2.2 Filtering Code

The main section below performed the filtering code functionality by breaking down each files text into rows. It then broke down the row into individual words that then check for the presence of digits, stop words and a length of '1' for each word iteration. After searching through all words, it then continued to the list building and sorting section of the code.

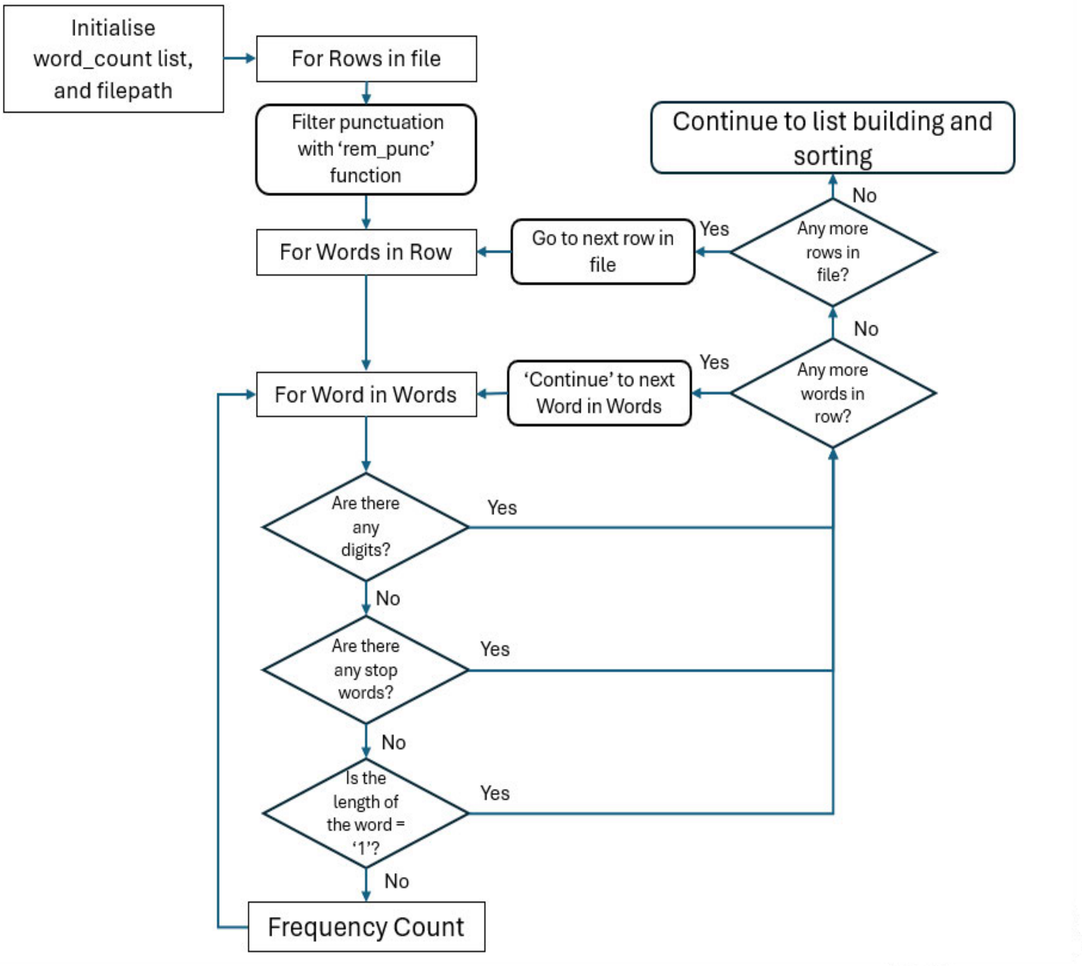

Figure 4-3: Literature Filtering Pseudocode

Testing of the main code resulted in the outcomes in the below table, and thus testing of justification for the design choices is demonstrated.

Table 4-5: Testing of Filtering Section

Test Article (Rao & Jayanti, 2023)		
Filters	**Word Count**	**Justification and notes**
No Filter	15392	This value represents the raw information derived excluding references and author information.
Stop Words (‘can’ added as stop word)	10752 (accumulative)	Common stop words are excluded as they do not provide any value in this case.
Len(word) == 1	10516 (accumulative)	It was found in the counting process that there were several words that contained only singular letters including but not limited to ‘a’, ‘h’, ‘x’ and more. It was concluded that their value was not important to the outcome and excluded from consideration
Digits Present: Provides a logic split to analyse thought process **‘Any’: Filtered words out with any digits present** **‘All’: Filtered out words with only digits**	Any: 9784 (Accumulative from 10516-word count stage)	It was concluded that the value of digits in this case of finding patterns between concepts and terms was negligible and as such, if there is any digit present in a word then the whole word is to be excluded. This was the final choice of filter for this article as it best represented the need to find concepts but did not remove a great deal of impact term frequency.
	All: 10059 (Accumulative from 10516-word count stage)	This final count included words of impact but also words that contained numbers including but not limited to ‘2h’, ’12-34’. It was concluded that their inclusion was not necessary or relevant to achieve the final goal. To conclude, this filter was NOT included in the final filters but shows the justification process and limitations involved.

4.3.3 Frequency Count

The frequency count is included the main code section but treated as a separate function. It is either initialised as a zero if the word has not been called yet or is incremented by 'one' for each loop of its' occurrence. Visualisation of this is below:

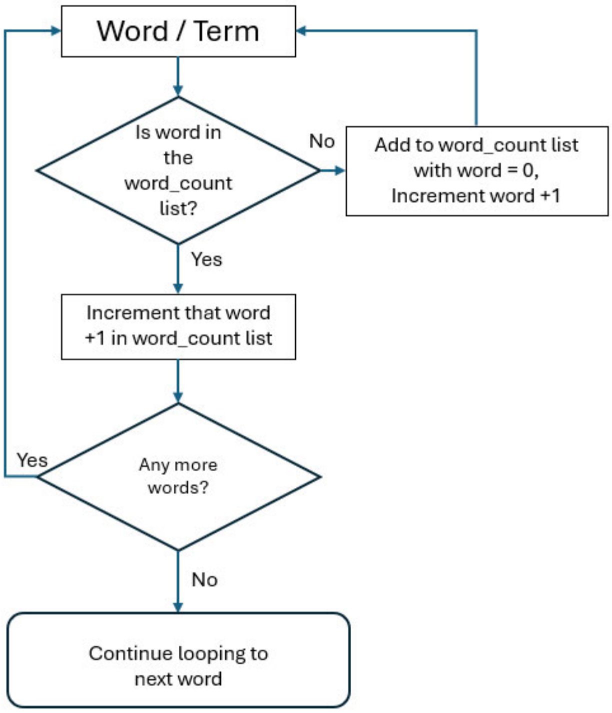

Figure 4-4: Frequency Count Pseudocode

4.3.4 List and Array Building

This section consists of the development of each file's most frequented words, based on an overall 100 most frequent terms derived from all literature pieces. The purpose of this was to find what literature have some significance to the topic at hand, whilst building up to the final task of understanding adequacy and correlation of the terms and concepts.

To being with, the sorting list takes all words found in each file and sorts them from most frequent to least frequent. This is undertaken for each individual file and as such meant that future frequency counts could be taken from here if necessary.

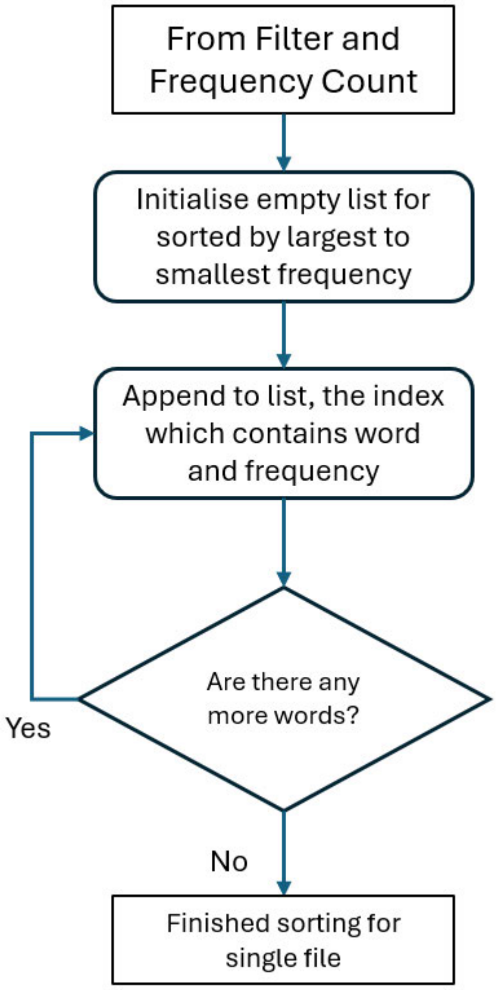

Figure 4-5: Sorting Pseudocode

The next major section finds the frequency of the top 100 terms in all the files utilised and builds up from the output of the previous sorting section. For 100 iterations the code appends to a new list, each individual term and its' frequency of appearance. This is to be used for a frequency of each file for the 100 most popular terms in the next step.

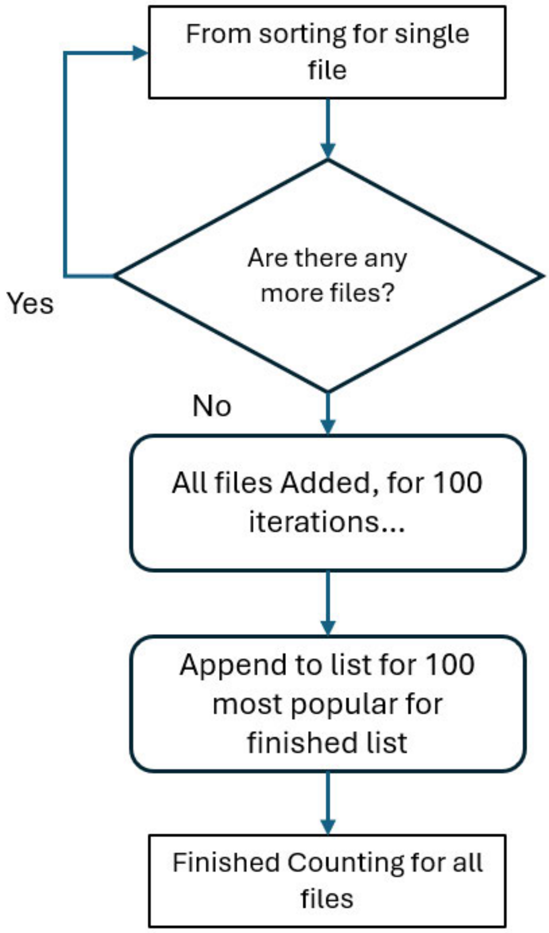

Figure 4-6: Most Frequent Terms Pseudocode

From this point, counts have been made and frequency lists developed for both single files and all files (i.e. single counts and total counts). The last step before introducing the testing was the array development for the frequency matrix, which includes counts from all files but only for the 100 most frequented terms on a total count basis.

4.3.5 Adequacy Test

The Adequacy Test was covered in detail during the literature review and requires simple coding to present. Note that in Appendix B, the test was grouped within the correlation and hierarchical cluster analysis section that presents the final outputs and steps.

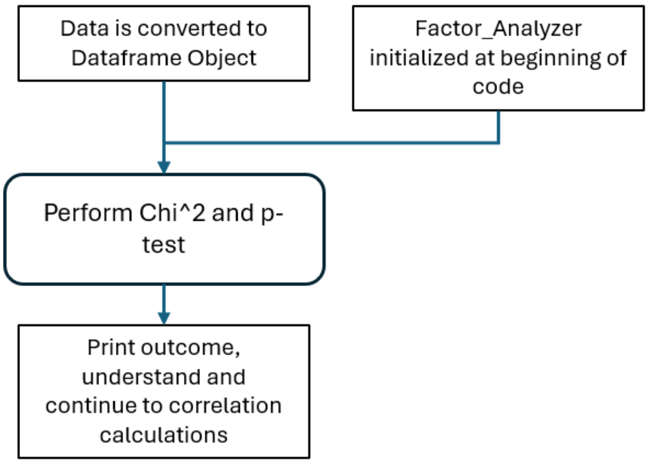

Figure 4-7: Adequacy Testing Code

4.3.6 Correlation and Hierarchical Cluster Analysis

This section of code involved the transition of the required data from an array to a Dataframe for the ability for further code to understand the data at hand. The main reasonings for using correlation and HCA was covered through the literature review. The body of the code for this section of information was straightforward through development but requires knowledge of the python libraries themselves. The code utilised for the Correlation and Hierarchical Clustering Analysis can be found in appendix B and is performed through the additional python libraries:

- SciPy: For the dendrogram and Hierarchical Clustering Tool
- Pandas: For the Dataframe building and correlation matrix calculations

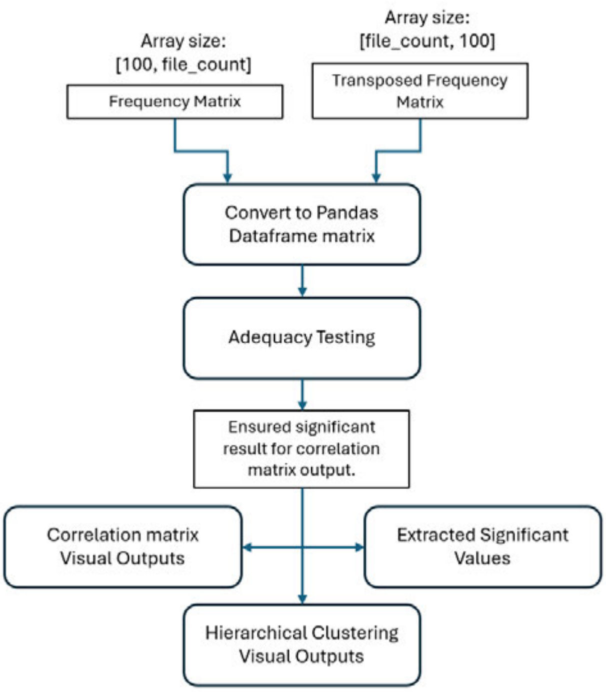

Figure 4-8: Final Processing and Outputs

4.4 Frequency, Adequacy and Correlation Results

4.4.1 Frequency Tabulation and Adequacy Check

The 100 most frequent terms were calculated with their frequencies and their file distribution as per the below table.

Table 4-6: Top 100 Words - Frequency and File Distribution

Word	Frequency	Distribution	Word	Frequency	Distribution	Word	Frequency	Distribution	Word	Frequency	Distribution
battery	910	19	energy	818	20	electrolyte	795	18	vrfb	607	15
vanadium	502	21	flow	485	20	system	479	24	cell	463	20
batteries	447	18	water	423	21	storage	396	19	electrode	384	15
redox	366	18	high	365	22	capacity	352	20	stack	346	15
environmental	320	18	power	319	21	concentration	313	18	current	309	21
vrfbs	308	13	process	304	20	membrane	298	18	potential	296	24
study	282	24	cycle	266	17	performance	264	16	electrodes	261	13
materials	259	20	different	259	22	impact	252	17	discharge	232	20
density	229	14	rate	226	18	thermal	225	13	higher	224	21
emissions	224	10	concentrations	223	16	impacts	222	13	electrolytes	219	17
electrochemical	218	17	carbon	213	15	surface	211	14	analysis	206	22
life	205	20	efficiency	205	15	temperature	203	14	material	197	18
negative	194	22	species	190	16	positive	188	22	model	187	11
components	187	21	manufacturing	185	8	charge	185	14	voltage	180	12
low	179	21	area	172	19	reaction	171	13	technology	170	13
increase	168	23	systems	167	22	cycles	167	16	electricity	161	14
total	158	23	active	158	17	metals	156	11	studies	155	21
air	155	17	lower	152	22	reactions	151	15	significant	150	18
operation	149	18	associated	147	17	cost	145	16	reported	141	19
heavy	141	9	ions	140	12	shown	139	23	value	133	21
production	133	19	method	132	17	design	131	15	time	129	21
compared	129	23	acid	128	19	electrical	127	15	elements	126	13
copper	126	15	chemical	124	18	contamination	123	13	present	122	20
observed	120	20	main	120	18	conditions	118	19	sources	117	19
solution	116	18	effect	115	19	treatment	114	13	lca	114	6

Immediate observations showed a high degree of variation between file distribution with only three of the top 100 words having recorded a file distribution of less than 10. This indicated that the data has high potential for measurability on a surface level. Another indicator showing plentiful data is the minimum frequency observed is '114'. This large minimum frequency count is represented using Word Clouds as evident in the below figure. The word cloud is single dimension and did not explain the interaction between terms, which underlined the importance of undertaking a correlation analysis.

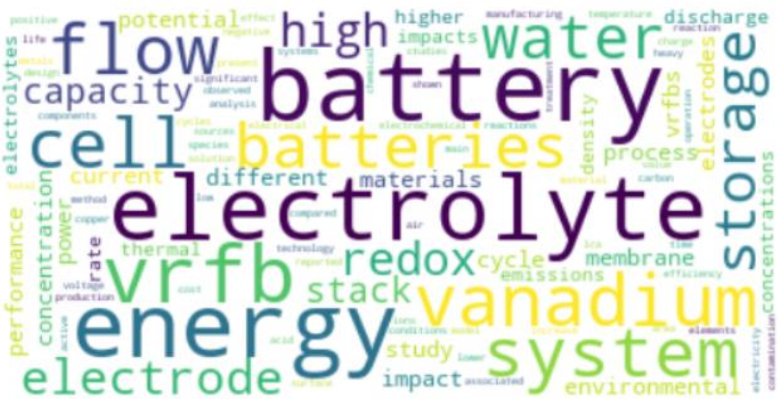

Figure 4-9: Word Cloud - Top 100 most frequented Words

The last measure considered before implementing the main analysis of word relationships was to calculate the Bartletts test of sphericity to indicate matrix significance.

Table 4-7: Adequacy Test

Bartletts Sphericity	Chi^2 Test	'p' Significance Test
Per File Basis	1140.2	2.5e-105
Per Word Basis	-inf	1.0

On a per file basis, the 'p' significance is an extremely small non-zero value. The null hypothesis that the variables in the population are uncorrelated is therefore rejected as it appears well under agreed significance levels of 0.05.

As for the per the word basis, the Chi^2 test recorded '-inf' due to the determinant of the matrix equal to zero. The literature review explained this concept which means that the values are extremely highly correlated or perfectly correlated, however this is mentioned to be a case of the vast number of variables included in the matrix that have a degree of correlation, which can lead to a determinant under the minimum precision levels of the code.

4.4.2 Correlation and HCA – Per File Basis

A comparison of files and topics covered was identified as important for linking concepts between the types of literature and the content of the literature. This identification led to better understanding of terminology and concepts going forward. See Table 4-8 for file identification before reviewing the correlation and HCA outcomes.

The following Correlation matrices show significant correlative values tending towards '1', no correlation tends towards zero and negative correlation tending towards '-1'.

4.4.2.1 Correlation

Table 4-8: File Number Categories

File Count	Categories
1-6	Case Studies
7-12	Heavy Metal Contamination
13-18	Life Cycle Assessment
19-24	Reliability and Failures

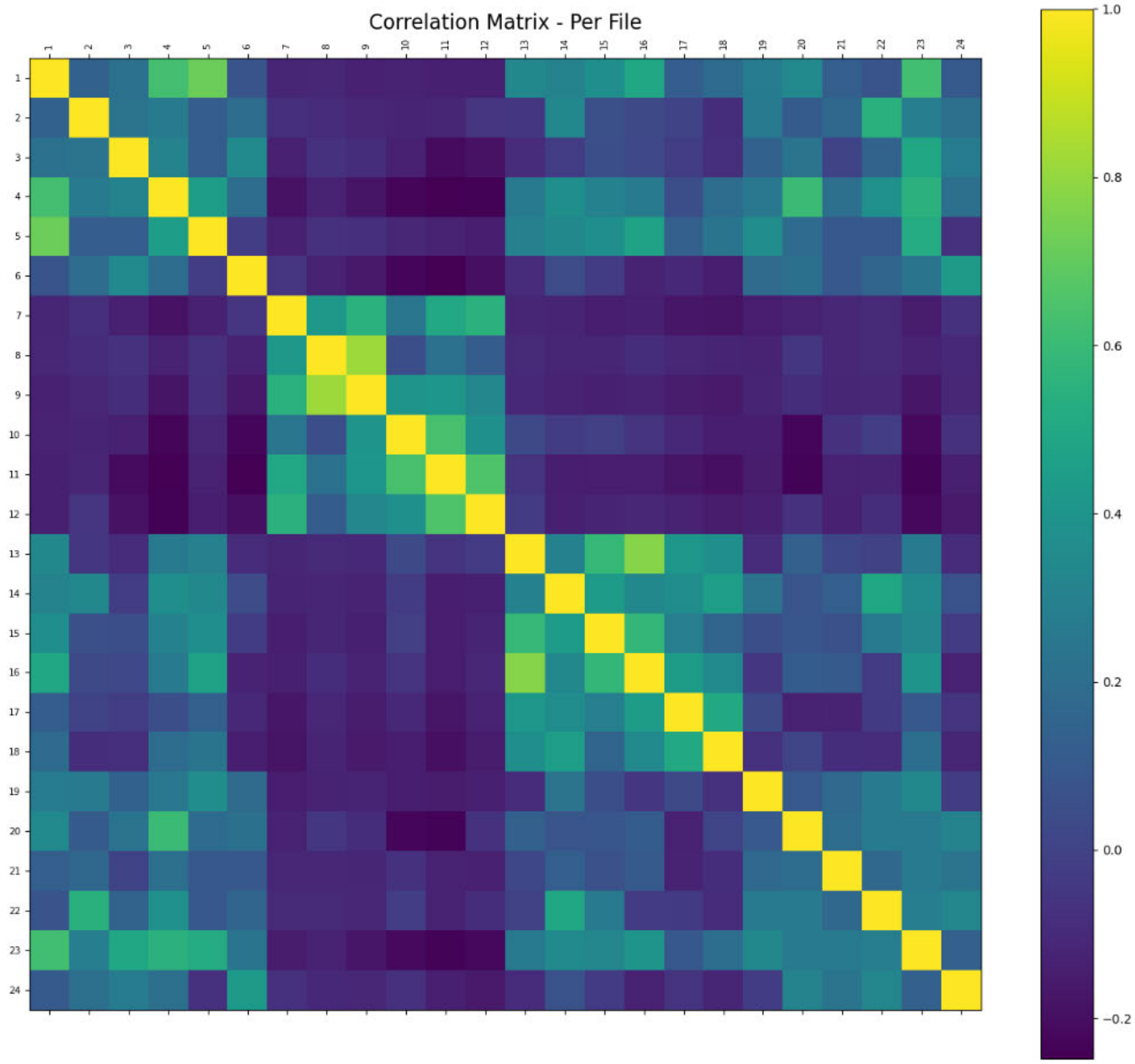

Figure 4-10: Per File - Correlation Matrix

4.4.2.2 Hierarchical Clustering

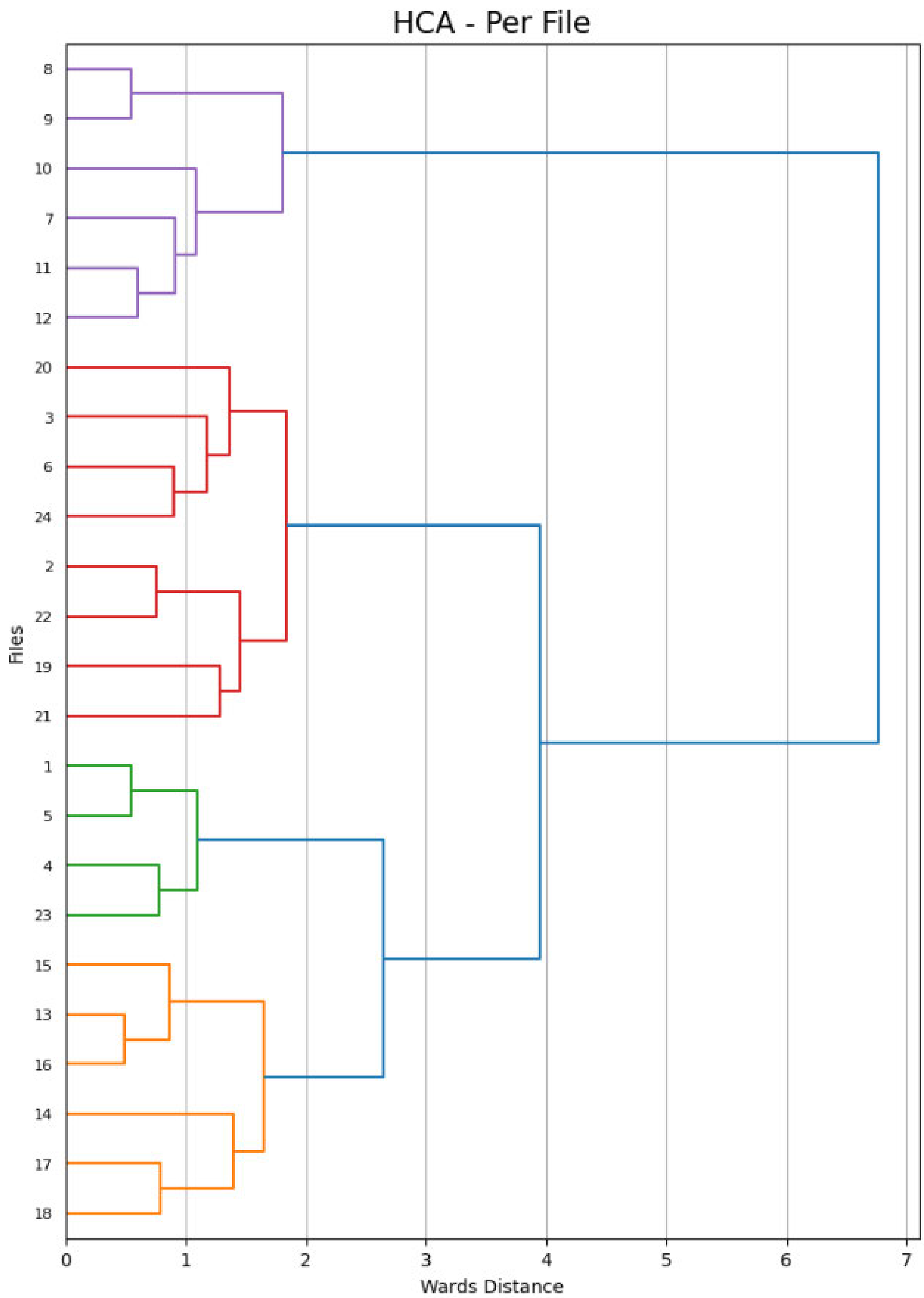

Figure 4-11: Per File - HCA

4.4.2.3 Discussion

It would be expected that the file groupings would closely resemble a pattern where every 6 files form a group to best fit in respective categories. This can be observed for the Heavy metal contamination (files seven through 12) and the Life Cycle Assessment (files 13 through 18) groupings. It was particularly obvious for the heavy metal contamination through analysis of the correlation matrix which showed low degrees of correlation with other file types. This was to be somewhat expected as the pieces do not fully encapsulate the extent of VRFB operation and are rather just a single potential concept in environmental impact.

- Cluster two of the HCA has multiple small groupings such as files '2' and '22' both discussing electrolyte imbalance in different capacities, one focused on methodology on improvement and the other focused on analysing and implementing failure methodology.
- Files '6' and '24' found similarity in their testing methods, one focused on performance parameters for an experimental implementation and the other that focuses on understanding the long-term reliability characteristics of the battery. Evidently there is a close link between the concepts discussed in case studies versus those that are discussed for reliability and failure. This is due to main concepts; one where certain case studies and particularly the improvements are made to address reliability issues and two that the background content discussed is very similar in most of these styles of articles.
- This was also observed in cluster three, which contains three entries from the Case Study and improvement pieces and one from the reliability pieces, their relationship can be explained through the pieces both discussing the operational characteristics of the VRFB including but not limited to system operation and individual componentry.
- Large degrees of negative correlation are be observed for the heavy metals category with numerous instances approaching a significance value of -0.2 or less. This provides clarity that although toxicity is a relevant issue for the development of VRFB installations, contamination has not been prevalently discussed for development purposes. This was perceived to be due to the style of other literature pieces not necessarily representing in field installations.

Overall, the impact of the literature types had varying degrees of effect, the main outlier is the 'heavy metal' files which face heavy relevance only when compared with the other files of their type. The intended outcome was the identification of significant linking between concepts of the various literature categories. Despite a higher degree of correlation for the Reliability and Case Study types, it can be said that there was not much unexpected correlation between the pieces. A focus purely on the environmental impacts may prove beneficial in this regard, but this would also narrow down the benefits of relationship tracking. The benefit to keeping a broad file type selection was to also implement the operational elements of the battery.

4.4.3 Correlation, HCA and Discussion – Per Word Basis

A comparison of terms was identified as important for linking relationships of major concepts. This identification led to better understanding of terminology and concepts going forward. See

The following Correlation matrix show significant correlative values tending towards ‘1’, no correlation tends towards zero and negative correlation tending towards ‘-1’.

4.4.3.1 Correlation

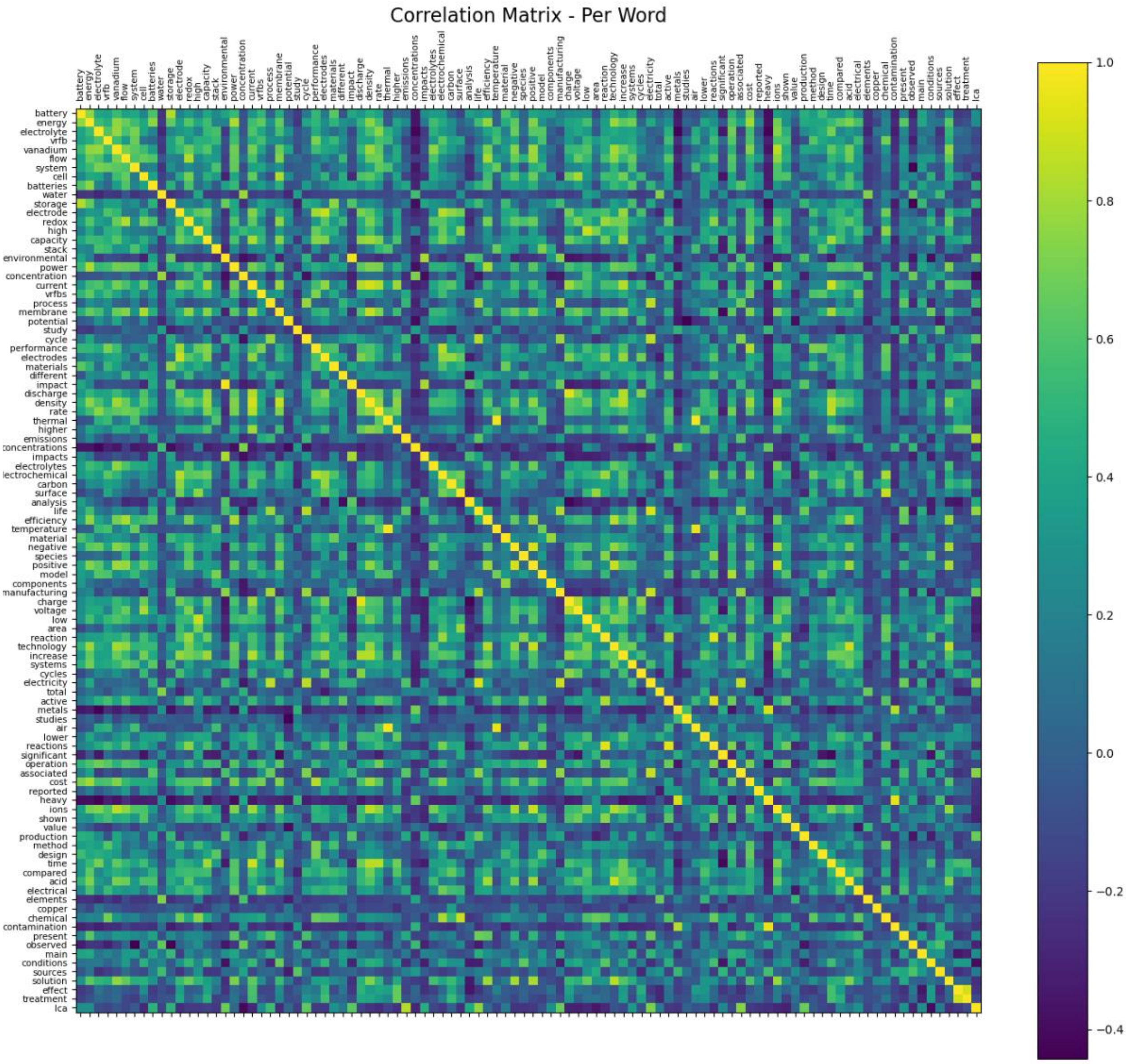

Figure 4-12: Per File - Correlation Matrix

4.4.3.2 Hierarchical Clustering

The hierarchical clustering analysis was performed to provide a visual clustering of the extent of words in relation to the correlation matrix. This can be seen through the interpretation that words have closer relationships the closer they are to the source words (left side of figure). It should be noted that the clusters highlighted in their respective colours are done so until an equivalent of five ward lengths are reached.

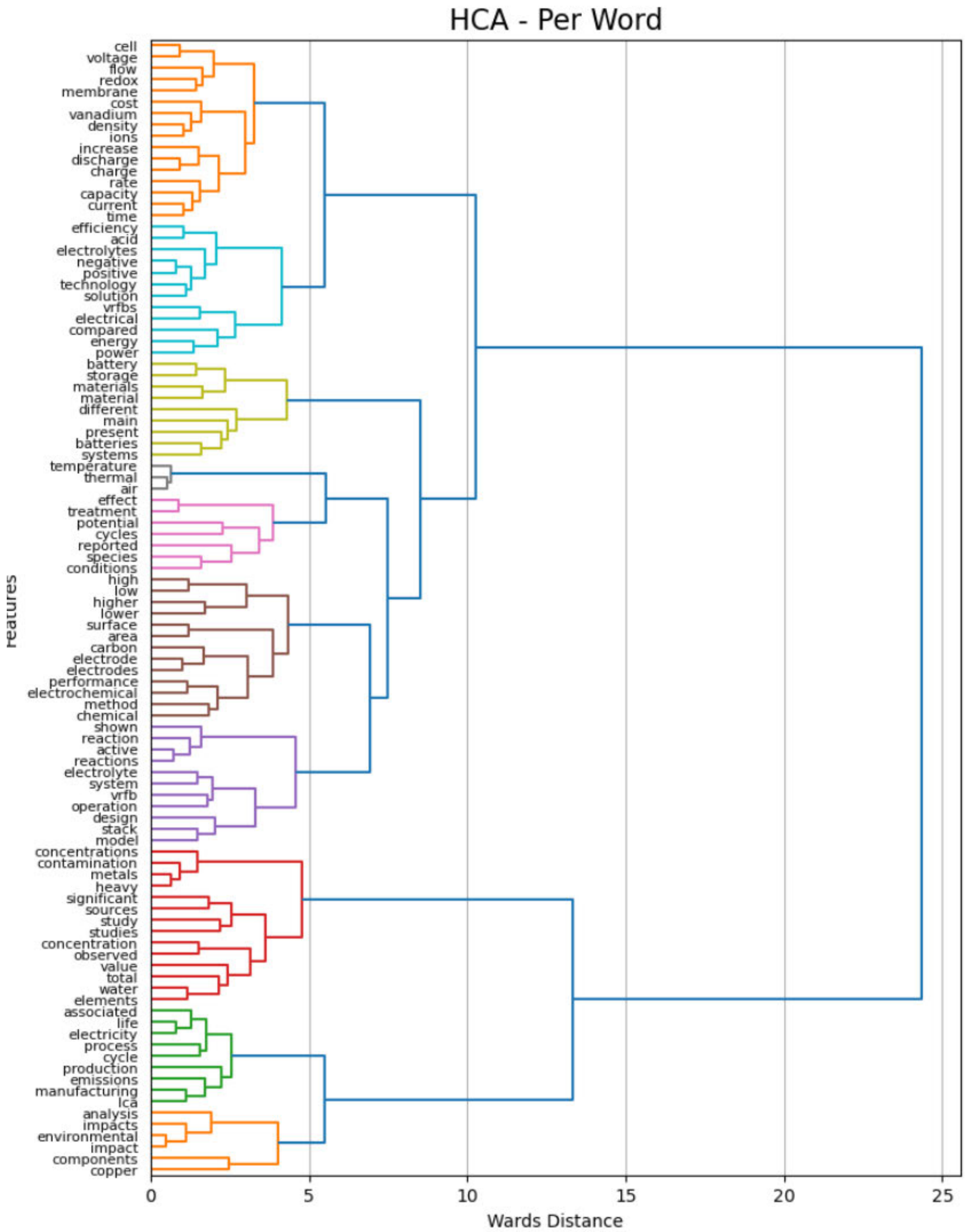

Figure 4-13: Per File - Hierarchical Clustering

4.4.3.3 Discussion

Through observing the correlation matrix, it was apparent there are groups of words that have some relation to each other, however more evident are those that do not relate to each other as well from the rows comprised of the dark blue colour. Otherwise, a great deal of significant data was observed, particularly with a correlation significance greater than approximately '0.6'.

Another note of interest was that as the word frequency reduces, the relationship significance between words also reduces. The word distribution over files was consistent for most of the words, therefore the reasoning for this significance behaviour can be attributed to the non-normalised count favouring relationships with higher frequency counts. This does not necessarily mean that the data is not applicable, as this context favours relationships for the most frequent words rather than the consistency of their distribution. To change this outcome, it may be beneficial for the implementation of a frequency count average over the files that the information appears in for future work.

Further quantification through the HCA shows that the first cluster addressed concerns of whole system operational characteristics and the thermal effects during operation:

- 'Charge' and 'Discharge': Simply the natural capacity variation of the battery dependent (tending towards full or empty).
- 'Current' and 'Time' with 'Capacity' and 'Rate': The most basic concept here is simply that rate of capacity usage is affected by the current draw by the system at certain rates. Inherently, the idea of varying power consumption is varying current levels. Some potential further links are with increased current density within the cell stack, the capacity decreases and vice versa. Note that there is some separation between these terms and 'Density', but does indicate some relationship between current density variation during operation and the overall capacity of the battery (Liu et al., 2020). A higher current density at initial stages and lower current density of the discharge or discharge stages appears to be a more optimal solution in this regard, assisting beneficial operating characteristics and avoiding major Vanadium Ion crossover in the membrane (Zarei-Jelyani et al., 2023).
- 'Density', 'Ions' and 'Membrane': Explained ion exchange membranes which can be altered dependent on the characteristics of the material used. The power density of the system can be inversely related to the ohmic resistance of the membrane. This is where

ohmic resistance directly affects ion exchange and electron exchange within the cell stack. However, this section more than likely refers to the current density mentioned in the previous point (Kumar et al., 2018).

Cluster two was made up of terminology commonly found regarding the VRFB battery stack with evident strong relationships between terms such as:

- ‘negative’ and ‘positive’ with ‘electrolytes’: Summarised the concepts of electrolyte polarity in each tank.
- ‘Technology’ and ‘Solution’: This pairing suggested that solutions are found with changing technology outputs and behaviour. Due to the variety of case study and improvement pieces, this was an important behaviour to have monitored. It may suggest that with engineering thought implemented there may be solutions towards the environmental controls that can be implemented on an operational basis as well.
- ‘Energy’ and ‘Power’ with ‘compared’: The separation of a VRFB’s energy and power characteristics is an explanation of the operating ideology of the technology where comparisons between other technologies as well as separate instances of energy capacity vs power can be drawn.
- One major interesting relationship observed is between ‘acid’ with ‘efficiency’. This could allude to the existing relationship where the concentration of acid vs vanadium in the electrolyte can lead to varying levels of efficiency in the cell stack, (Yu et al., 2024). Evidently, the control of modulating electrolyte usage was found during the planning stages of the project and is difficult to control beyond the sourcing stages. This would most likely be an issue considered by the SME’s at the electrolyte production facilities. The only limitation of this theory is that the ‘concentration’ term and those being discussed have five degrees of separation suggesting further relationships to be observed.

The third cluster approached batteries in a broad manner:

- The term ‘Battery’ is paired with ‘storage’ and ‘material/s’: This shows that battery storage is a common term and the materials that go into the production of it are an important consideration. The conclusion was also made that this can refer to the importance of material selection through the storage of the battery including the electrolyte, however this concept can be extended to the whole installation.

- Interestingly the similar term ‘batteries’ is paired with ‘systems’ and closely related to ‘main’. The plural term of ‘battery’ offering different results is unexpected but makes sense when considering the types of systems that go into a battery. This is inclusive of components such as a battery management system, a battery auxiliary system, a battery support system etc. The implementation of the separate systems aims to provide support and redundancy measures and as such, there may be further indication that best methods of control implementation is through new redundancy systems.

Cluster four was very well islanded by itself but had some relevance to cluster five regarding the effects of temperature on operation.

- ‘Thermal’ and ‘Temperature’ with ‘air’: It has been covered so far that thermal effects are apparent during the operation of the VRFB, particularly involved with ambient temperatures where without the use of a heat exchanger, precipitation may occur. The great significance observed here for these three terms indicates that temperature control is a major consideration for the successful operation of the battery.

Whilst cluster five had some keywords such as ‘effect’, ‘treatment’, ‘cycles’ and ‘conditions’ outlining that operating characteristic associated with heat effect on the reliability of the battery, and treatment processes such as the heat exchanger or even electrolyte reversal techniques can be utilised to achieve control in continued operation. Cyclic operation can have wear on components without maintenance, but its’ effect is greatly exacerbated by conditions.

Cluster six was another cluster that focuses on the equipment that undertake the electrochemical processes with typical relationships such as:

- ‘Electrode/s’ and ‘Carbon’: This was identified a simple relationship as carbon is the material used in electrodes.
- ‘Chemical’ and ‘Method’ with ‘Electrochemical’ and ‘performance’: This was found to refer to methods of operation that result in differing levels of performance. It could also have been the chemical rebalancing of the electrolyte that results in continued higher levels of electrochemical performance. Less impact was evident towards the ‘chemical’ term in an environmental impact sense.
- ‘High/er’ and ‘Low/er’ with ‘Surface’ and ‘Area’: This section relates back to the effect of surface area of the electrode back to the performance of the system, as thoroughly covered in (He et al., 2023). It can also be observed as three degrees of separation from being related back to thermal terms. As such, whilst surface area is more signifying of

chemical performance, there was an identified minimal aspect of thermal cooling through surface area control.

Cluster seven extended on the concepts of electrochemical operation with the relationships below:

- ‘Stack’ and ‘model’ with ‘design’: This refers to a commonality for the cell stack to be modelled for operation, in a capacity for either thermal monitoring or management purposes. It showed three degrees of separation from thermal terms and observed to have one degree of separation away from ‘electrolyte’ and ‘system’ signifying the relationship where larger bodies of fluid take longer to heat up as well as cool down. The temperature rises in the Vanadium system comes from ambient conditions as well as exothermic reactions within the cell stack, and thus a heat exchanger is utilised to reduce this chance of precipitation in the stack itself (Kirk et al., 2021).
- ‘Active’ and ‘Reaction/s’: Presented the relationship of the chemical system for the generation of electricity.
- ‘Electrolyte’ and ‘System’ with ‘VRFB’ and ‘operation’: At its core, the main operational characteristic of the battery is the use of electrolytes for chemical reactions to produce electricity. This was found to be the clearest grouping of terminology that explains how the battery operates.

The eighth cluster focuses on the elements effects on water contamination, appearing to derive heavily from the ‘heavy metal contamination’ literature:

- ‘Heavy’ and ‘metal’ with ‘contamination’ linked closely with ‘concentrations’: This indicates that the concentration of the heavy metals is often prevalent through groundwater studies. The link to ‘water’ and ‘elements’ was also closely related, indicating that heavy metal contamination in water is one of the greatest concerns for the leakage of electrolyte from the VRFB. Waterways have been identified as methods for easier contamination in comparison to gravel or dirt.
- Further break down of this cluster pertains to the significance of concentration when considering heavy metal contamination. The importance of this may come from the introduction of certain processes to investigate concentration control.

The ninth cluster summarises the whole of life process for the VRFB:

- ‘LCA’ and ‘emissions’ with ‘manufacturing’: This indicated that the manufacturing stage of the Battery is the most covered component or that emissions for the battery are associated with the manufacturing stage. Due to the high emissions given off by electrolyte production (Blume et al., 2022), further linkage towards the second idea can be identified.

- 'life' and 'electricity' with 'cycle' and 'work': These components are all closely related and is the link of generation of electricity or the work undertaken by the VRFB over its' life cycle. This work undertaken is considered beneficial as it performs emissions reduction compared to if fossil fuels were used instead.

Evidently, the LCA literature contributed greatly to the development of this last cluster:

- 'Impact/s' and 'Environmental' with 'Analysis': This grouping indicated that the investigation towards environmental impacts has been undertaken to a significant degree. The missing link was identified in this case as environmental controls to assess these impacts, which supports the research undertaken in this thesis.
- 'Components' and 'Copper' with 'Production': This section considered what elements are made up of and how they are produced. For example, the current collectors at the end of the cell stack are made up of copper due to preferable conductivity behaviour.

Whilst relevant to the implementation of the actual VRFB itself, controls for preservation of the components are an important consideration to cover especially considering weather conditions but also UV exposure and preventative maintenance.

4.4.4 General Discussion

The preprocessing was beneficial in assessing cluster points between files and thus overall appearance of the data, particularly in the per file correlation and hierarchical clustering results. This added step of grouping prior to adding into the main file allowed easier identification of cluster groups for types of files not overly relevant to others. This was observed mostly for the 'heavy metal' categorical files where their terminology was least like the other types, due to minimal inclusion of terms relating directly to the VRFB system. This is somewhat as designed, as their inclusion was done to verify environmental relationships between certain terms which did contain some prevalence within the files.

Overall, the relationships between terms produced some interesting concepts for consideration of controls during the future stages of this project such as:

- Technological adaptation for toxic and corrosive waste control, including assessment of concentrations.

- Thermal cycling as well as general temperature conditions for impact control.
- Reliability concerns due to different operating conditions, particularly in cell stack and auxiliary functions.
- How to improve controls whilst reducing the environmental footprint including contamination and production processes, including the additional material and componentry that would be utilised.

4.4.5 Limitations

Evidently, the frequency count element reduces any relationship between descriptive elements and their concepts. This reduction in dimension may therefore negatively skew any false descriptors as being more important if their frequency count is higher. The element of correlation was incorporated to reduce some of this between the literature but would only exacerbate the issue if certain descriptors are used without knowing the context. Some assistance was also made in this regard for the exclusion of certain terms and punctuation explored previously, including common stop words.

The amount of preprocessing undertaken on the literature was also a downside towards the potential of exact reproduction of the methodology, as while all general steps undertaken have been listed, PDF to text file reproduction can be troublesome dependent on PDF literature layout.

Due to the variety of terms included in the analysis, there were few that have been excluded that did not appear to offer any significance to the results. These terms, such as ‘based’ or ‘considered’ have been filtered out to focus on terms with significant content. With this, the authors opinion of ‘important words’ would vary compared to that of another individual and thus a personal bias is introduced. More indication of the final terms included in this can be found in Appendix B.

5.0 RELIABILITY ANALYSIS

The reliability analysis was performed to understand environmental impacts and their associated reduction on system reliability. The outcomes aimed to achieve what failures cause less reliability in what VRFB subsystems, which led to an understanding of maintenance processes from desirable and undesirable conditions. It considered material types and their types of failures in a situational context by following the below process:

1. Firstly, the determination of system duty cycle by considering the common operational characteristics of a VRFB over the course of the day. This is regarding Daily Demand and where the VRFB may find the prevalence in its' usage.

$$Duty\ Cycle = \frac{Time_{on} * avg_{cycles,per\ day}}{24} \tag{5.1}$$

2. Break down the VRFB system into its' individual components and assess the relevant failure types including context and significance. This was to apply mean time to failure values to each component and provide contextual understanding to failure mode types. The use of the pre-determined duty cycle also faces importance to apply Queensland context.

$$MTTF_{New} = \frac{MTTF_{Old} * \frac{Time_{on,old}}{Time_{on,new}}}{Cycle_{Scalar}} \tag{5.2}$$

$$MTTF_{Final,Normalized} = \frac{MTTF_{New}}{Count} \tag{5.3}$$

3. Use the adjusted individual components 'Mean Time to Failure' to develop Weibull probability distribution and reliability models from. Further elaboration of this more intensive process is during its' respective section. This was performed for both typical and reduced longevity circumstances for:
   - Subsystems of the VRFB including Fluid Circulation system, the Cell Stack and Auxiliary support components.
   - The whole VRFB system which is inclusive of the subsystems listed above.

   It should be noted that due to being a stationary container with an expected useful life dramatically different from other components in the fluid circulation system, the 'electrolyte tank/s' have been included as an auxiliary component like the shipping containers. This aims to not unnecessarily skew other elements in the fluid circulation system through appropriate assumptions.

4. Further discussions are made for components that could thrive from the implementation of certain controls as well as those that are not affected by certain controls.

5.1 VRFB Duty Cycle

Another element of reliability assessment is the overall availability or run time of the devices. The VRFB finds both stationery and runtime capacities in the pump, Cell stack and the heat exchanger components, where evidently increased usage of those components reduces the overall time to failure more so than if the system was in a stationary position. Fortunately, through assumptions a day usage ratio, this can be found if both stationary and operational failure rates are found. The determination of appropriate run times and work performed was firstly undertaken:

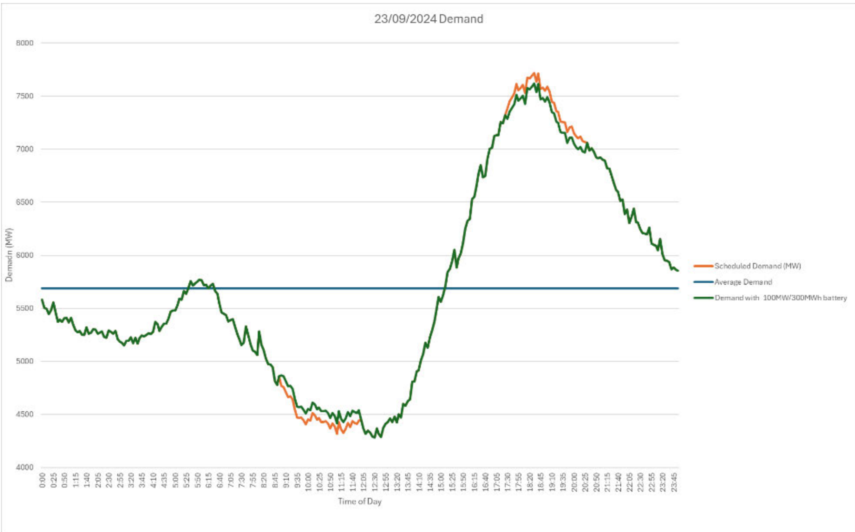

Figure 5-1: AEMO 23/09/2024 QLD Scheduled Demand (AEMO, 2024)

Referring to the plot above, an example 100MW/ 300MWh aggregate battery solution was chosen to visualise an impact. Over the three hours of operation, it has a consistent 100MW output and varies from completely charged to completely discharged and vice-versa. Real life conditions vary however the main concept is it reflects ideal selection of times when battery charge and discharge may be implemented to vary the daily demand profile for Queensland. To support typical grad characteristics it may be seen that a single charge and discharge cycle per day is observed, somewhat like those identified in literature (Weber et al.) of 1.12 cycles per day, helping conclude a daily duty cycle for the battery for an operational vs non-operational capacity. Tariff pricing such as tariff 12C through Ergon Energy Retail may alter the time of day for best battery implementation, however the same concept of a typical minimum and maximum would be observed. Supporting this information, and by utilising equation 5.1, the duty cycle for the battery can be found as below through time on and a normalising scalar.

$$Duty\ Cycle = \frac{Time_{on} * avg_{cycles,per\ day}}{24} = \frac{6 * 1.12}{24} = 0.28 * 100\% \ = 28\%\ on$$

$$Time_{on} = 28\%$$

$$Time_{off} = 1 - Time_{on} = 72\%$$

5.2 VRFB Failure Modes

The identification of potential VRFB failure modes is important to consider in a raw manner, as it may identify areas where controls from a design perspective can be used such as sensors etc. However other benefit was found during the usage stage of the system for identifying ongoing controls.

- It is assumed for calculation purposes that after a single failure is encountered regardless of component, then the whole system is offline. This removes the consideration towards repair times whether the system would be operational or not.
- To account for changes in methodology for calculating mean time to failure's, the formula 5.2 was utilised, as it considers variation in charge/ discharge cycle duration and the typical number of cycles experienced per day. It used the values as below:
    - $Cycle_{Scalar}\ is = 1.12$ (higher daily case through (Weber et al.))
    - $Time_{on,old} = 6$ hours
    - As well as respective $Time_{on_{old}}, and\ Time_{on_{new}}\ values$

  This formula below considered the MTTF for each component, considering the total count. MTTF for components when run in parallel follow the equation:

  $$MTTF_{a//b} = \frac{MTTF_a * MTTF_b}{MTTF_a + MTTF_b} \quad (5.4)$$

  However, for when the MTTF's are the same which is as could be expected for a single identical component, then the equation can be simplified to equation 5.3.
- The values were not necessarily reflective of the actual life expectancy of the VRFB solutions as there are controls implemented. Examples of this are preventative maintenance to ensure optimal operation over time, as well as protections through the battery management system. Thus, the reliability analysis assumes all components are either non-repairable or are negligible in the time it takes to repair the item, hence no inclusion of Mean Time to Repair (MTTR) or Mean Time Between Failures (MTBF). This

helped identify worst case scenarios during operation and highlighted what sections of the VRFB would require careful operation and preventative maintenance measures. The main sought outcome in this analysis was to understand what longevity could be provided to the system by changing installation controls.

Potential failure types for all relevant components were identified and tabulated below to form the basis for understanding the context on reliability from a qualitative standpoint.

Table 5-1:VRFB Failure types and significance

Components	Sub-components	Modes of Failure	Notes on Failure
External Ancillary System	Shipping Containers	Puncture	Loss of external protection for inner layer, patch may be possible (Hoffmann et al., 2020).
		Corrosion	External corrosion avoidable through painting surface (King et al., 2024).
	Heat Exchanger	Coolant Leakage	Immediate loss of cooling capability (Tian et al., 2021).
		Degradation	Eventual efficiency loss, long term means maintainable (Addepalli et al., 2015).
		Dust Fouling	Consistent cleaning reduces fouling effect (Wang et al., 2017).
Cell Stack	Carbon Electrode	Corrosion	Carbon corrosion and gas evolution lead to lacking performance.
		Degradation	Reduced stability and generation distribution over usage (A. K. Singh et al., 2020).
	Nafion Membrane	Oxidative Decomposition	Eventual Vanadium Ion crossover causes capacity loss of Electrolyte (Lulay et al., 2023)
		Pore Blocking	Lower membrane permeability (Lulay et al., 2023).
	Current Collector	Material Leach	Byproduct of Bipolar Plate breakdown (Reynard et al., 2019).
		Detachment	Improper electrical contact.
	Gaskets/ Sealants	Leakage	Effective sealing is required with fluid presence (Sujali et al., 2016).
	Bipolar Plates	Corrosion	Enables copper current collector leachate (Reynard et al., 2019).
Fluid Circulation	Vanadium Electrolyte	Heat Precipitation	Can lead to membrane damage and capacity Loss (Kirk et al., 2021).
		Contamination	Any form of contaminant (e.g. Current collector leach) (Reynard et al., 2019).
		Oxidative Decomposition (loss of capacity)	From oxidative decomposition through membrane.
	Magnetic Drive Pump	Dry Running	Can lead to overheating and other worn components such as bearings (Simon, 2018).
		Impeller Blockage	An impeller with a buildup of contaminants may experience blockage or buildup, reducing efficiency.
	PVC Pipes	Seal leakage	Sudden leakage from pipe joins (Makris et al., 2020)
		Brittle	Extreme Low Temperatures can exhibit negative behavior on PVC (Makris et al., 2020). Solar exposure can be an issue for impact strength (Andrady et al., 2023).
		Softening	Higher temperatures can soften the material, leading to warping (Makris et al., 2020).
		Cyclic Fatigue/ Stress	Long-term usage of the pipe can degrade the quality of the material.
	Hand Valve	Seal leak	Caused by old adhesive, poor installation leading to leaking component.
		Cyclic Fatigue / Stress	Pressure over time could lead to part deformation.
	Electrolyte tanks	Rupture	Rupture Contained briefly by Shipping Container if container is not compromised. Usually from major structural integrity damage of tank over time (Almomani et al., 2023).
		Puncture	Puncture can be briefly contained by shipping container, may be cause by a sudden piercing of a section (Lai et al., 2021).
BMS	BMS	Loss of Communication	Loss of system communication only means that the system may still operate however all elements rely on communication for effective running (Hajeforosh et al., 2020).

Table 5-2: MTTF Component Reliability Table

Sub-components	Count	Modes of Failure	Share of Failure	MTTF Combined	Final MTTF Hours
Shipping Containers	3	Puncture Corrosion	- -	• 12-15 Years in Harsh Conditions • Assume 25 Years for less harsh conditions • 21.9e4 Hours (Hoffmann et al., 2023)	7.3e4
Heat Exchanger	1	Coolant Leakage Degradation Dust Fouling	0.354 (Ryden, 2003) 0.273 (Ryden, 2003) 0.373 (Ryden, 2003)	• Typical Dust: 0.6e4 Hours On (Lingeswara et al., 2016) and 1.54e4 Hours off[3] • High Dust: 6.49e2 Hours on and 16.69e2 Hours off[3] • Does not need scaling as only an 'ON' MTTF.	Typical: 2.14e4 High Dust: 2.32e3
Carbon Electrode	1 (Grouped)	Corrosion Degradation	- -	Typical: • 20+ Years Cell Stack Reduced: • Accelerated Corrosion: 10.12 Years[1] (Nourani et al., 2019)	Typical: 17.52e4 Corrosion: 8.86e4
Nafion Membrane	1	Oxidative Decomposition Degradation	- -	Typical: • 6.00e4 Hours on[2] (Kamarudin et al., 2009) • 15.42e4 Hours off[3] Reduced: • 2.160e3 Hours on (Xing et al., 2021) • 5.55e4 Hours off[3]	Typical: 24.45e4 Reduced: 5.77e4
Bipolar Plates	1 (Grouped)	Degradation (leading to Current Collector Contamination)	-	Typical: • 20+ Years Cell Stack • Like Carbon Electrode Reduced: • Anodic Corrosion: 3.92e4 Hours[1] (Reynard et al., 2019)	Typical: 17.52e4 Corrosion: 3.92e4
Vanadium Electrolyte	1 (Single Contained System)	Heat Precipitation Contamination Oxidative Decomposition (loss of capacity)	-	• 1e4 – 1.5e4 Cycles (Vlasov et al., 2023) • 6e4-9e4 Hours • Choose for the worst case.	Typical: 9.0e4 Reduced: 6.0e4
Centrifugal Pump (Magnetic Drive)	2	Degradation Complete Failure	0.676 (IEEE, 1986) 0.324 (IEEE, 1986)	• 5.24 Years (IEEE, 1986) • 4.59e4 Hours	2.30e4
PVC Pipes	1 (Grouped)	Seal leakage Brittle Softening Cyclic Fatigue/ Stress	- - - -	• 1.6e4 Hours (Uhrig et al., 2020) • Similar System so assumed as equivalent.	1.6e4
Hand Valve	4 (Either Side stack cell)	Seal leak Cyclic Fatigue / Stress	- -	• Outdated: 10.76 Years (IEEE, 1986) • Choose 10 Years (BRAY) • 8.76e4 Hours	2.19e4
Electrolyte tanks	2	Rupture Puncture	- -	• Polyethylene: 15-20 Years (PolyProcessing, nd) • FRP/GRP: 25 Years (Harle, 2024) • Assume 20 years. • 17.52e4 Hours	8.76e4

[1]The source indicated a 4-hour charge or discharge at one cycle per day. Corrected using chosen 3-hour charge or discharge at 1.12 cycles per day.
[2]Indicated by the products approximate design life rather than its' MTTF.
[3]Calculated using Duty Cycle of 28% On to 72% Off.

The various notes below are assumptions that were made on system component reliability sources to provide clarity to the table for the purpose of devising MTTF values. The assumptions made aim to best reflect conditions universal to a VRFB installation.

- The shipping container lifespan was retrieved from a shipping container that undergoes maritime shipping conditions, and therefore a container on land would likely not be consistently exposed to harsh conditions such as corrosive salt air, water and rough weather conditions. The scenario assumes a lifespan double of typical maritime conditions.

  One element not understood that could face issue was from Vandalism where the damaging of the external tank wall may lead to a puncture in the Electrolyte tank. Vandalism may also degrade it to a condition that leads to puncture at a later point. An example of this was found to be vandalism from vehicle impacts, or deliberate puncturing using tools or weapons (Wang et al., 2021). Dependent on electrolyte capacity, it is understood that there will be changes in the internal container material width meaning that puncturing the internal tank is not a constant reliability consideration.
- Multiple sources of failure data may have led to inconsistencies, particularly from the outdated standard IEEE 500 which uses data from 1984 and not ideally reflective of the current reliability of components such as the centrifugal pumps. A component failure rate database such as the Component Reliability Database (CRD) from the product safety and management company Exida may prove beneficial for accuracy however this proves to be a great expense for a multitude of parts and as such is not viable on the project scale. Another method for accuracy improvement was identified as the obtainment of component reliability data directly from manufacturers however this data was not available for this scenario.
- Identification of the valve used was identified through case studies as well as intended usage for each type of valves. The most suitable for this scenario was found to be through use of either a ball valve which has better sealing capabilities or the butterfly valve which does not seal as reliably but provides a lightweight and cheaper solution. Ball valves were found to also provide better performance on aggressive services including toxic materials compared to butterfly valves (Sotoodeh, 2018). To benefit both types of valves in their selection is the no requirement for flow rate throttling, which is not a strong characteristic of either valve type. The single function for the valves is the ability to isolate the upper and lower containers under emergency scenario or similar, and normally operating in an open condition. The main failure conditions here are thus, leakage from sealing pipe to valve or

leakage through the valve sealing component which can be exacerbated from misalignment during operational conditions. Modern design of butterfly valves mean that this can be minimised through a locking mechanism for the normally open and normally closed conditions. Considering isolation conditions are reserved for maintenance and emergency conditions only, it could also be assumed that the cycling of the valve is minimal. According to (BRAY - The High Performance Company, 2017), the normal useful life of a valve is between 10 to 15 years, which can vary dependent on numerous conditions. These conditions consist of cycling frequency, flow media, temperature, pressure and the valve positioning in plumbing installation. Due to low cyclic rate from operation in only emergency conditions as well as assumed non-metallic wetted components such as PTFE lined valves (BRAY), a MTTF of 10 years was assumed. This accounts for daily temperature fluctuations, corrosive material affecting seals, and pressure fluctuation leading to creep (Wang et al., 2024).

- Assessment of the BMS was one of the questionable entries as the assessment of an acceptable number of case study installation samples including failures is not viable and there is no indication of BMS lifespan beyond examples of Lithium-Ion thermal runaway which is an example of incorrectly communicated overcharge. In turn, it is not included in the final reliability assessment however it remains as a single point of failure within the BMS and should not be underestimated. Further research into the environmental effects on electronic componentry is necessary to achieve this, but final determination of failure rates is outside the scope of this project.
- Another element of failure not understood on a deep enough level is that of the current collector. It was found to contribute to a component of failure through copper leaching throughout the electrolyte due to graphite bipolar plate structural breakdown (Reynard et al., 2019). However, it also finds issue through detachment of the plate, but this was not easily assessable due to only one instance of its' occurrence found through literature which did not include any information regarding a failure rate. This single instance might mean it is a rare occurrence, and as such was not included in the analysis to not draw unfounded conclusions. Overall, it appeared that the deformation and effects brought by the current collector are secondary to other components such as breakdown and swelling leading to copper mechanical failure.
- Whilst the graphite bipolar plates have properties of good corrosion resistance and stable long-term operation (Xin Gao et al., 2024). It was experience in (Reynard et al., 2019), that a cracked bipolar plate eventuated after three years of operation. This is likely due to

mechanical stresses inherent to fuel cell design in the fastening of all the components. A single fracture has the potential to compromise the overall operation of the bipolar plate, which overall reduces structural integrity of the system and allows leakage (Satola, 2021).

- The last component within the cell stack is the sealing gaskets, made of PTFE (Teflon®). PTFE has identified characteristics of 'remarkable' chemical resistance and faces limited problems when correct mechanical load is applied. The minimal exposure meant for the VRFB capacity that there is little mention of reliability in literature. A potential issue arises in long term static loads, with extreme adjustments in temperature over $100°C$ which far exceeds the operating temperature of the VRFB. This conclusion leads that the major concern for leaking from the PTFE gasket, is the initial installation or construction of the fuel cell stack (Zheng et al., 2017). This can be mitigated through typical testing or commissioning procedures of plumbing installations where due to the importance of the pipework for the case of corrosive electrolyte, this can be assumed as already undertaken.
- Polyethylene characteristics at a mixture of <50% sulphuric acid as is the case for electrolyte (water, sulphuric acid, vanadium mixture) were found to provide satisfactory resistance to the sulfuric acid indicating that serviceability would not be impaired with its usage (CDF Corporation, 2004). Furthermore, polyethylene tanks have usage of 15 to 20 years (PolyProcessing, nd) whilst other solutions such as Fibre or Glass Reinforced Polyethylene has observed comfortable 25 years' service life with minimal degradation (Harle, 2024). Typical outlooks for VRFB life expectancy are 20 years meaning that as the material is stored away from UV inside a shipping container, the electrolyte tanks should face minimal degradation in this manner. The mean time to failure of an electrolyte tank chosen is therefore 20 years.
- The heat exchanger has varying MTTF values in literature, which is dependent on conditions. As can be identified from the literature; preventative maintenance, dust, temperature, corrosion, and operational stresses are all major causes and forms of degradation in the MTTF of the heat exchanger (Addepalli et al., 2015). For the context of this section, there is increased interest in the effects of dust and temperature as major contributors towards failure. Other failure types are those that can be addressed through ongoing maintenance and is not applicable towards worst case scenarios. An agreed value for MTTF values is 6000 hours for a shell and tube heat exchanger and was utilised in the analysis, despite possibilities of crossflow or pipe reduction systems being used for the OEM solution. As for potential failure rates, it should be noted that 649.35 hours was

recorded in one section under extreme dust fouling conditions (Lingeswara et al., 2016). This provides an indication that dust fouling is a major contributor towards premature failure of parts.

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5.3 Analysis

5.3.1 Excel Functions

Excel was utilised to both find the function parameters but also using the function itself to visualise failures of each subsystem as well as the total system under variation of MTTF in fault conditions. The Microsoft Excel reliability function $Weibull.dist(t, \lambda, \beta, Accumulative)$ can be utilised with Accumulative set to 'FALSE'. This allowed the calculation of probability distribution, which is equivalent to using the equation below.

$$\Phi_t = \frac{\beta}{\boldsymbol{\lambda}}\left(\frac{t}{\boldsymbol{\lambda}}\right)^{\beta-1} \exp\left(-\left(\frac{t}{\boldsymbol{\lambda}}\right)^{\beta}\right) = Weibull.dist(t, \lambda, \beta, FALSE) \quad (5.5)$$

$$t = current\ time\ in\ hours * 10^4$$
$$\lambda = Weibull\ Scale\ Factor$$
$$\beta = Weibull\ Shape\ Factor$$

The same excel function was also used to determine the reliability survival function using 5.6 below:

$$Reliability = 1 - Weibull.dist(t, \lambda, \beta, TRUE) \quad (5.6)$$

The accumulative mode set to 'TRUE' allows correct interpretation of the curve through each step, incrementing the value rather than restarting from '1' each time like the typical probability distribution function would. Furthermore, to show the natural progression of the Weibull reliability function, the Kaplan-Meier curve was used to show the step increments that the Weibull reliability survival function follows, verifying that the MTTF entries in each equipment do follow the designed Weibull reliability function. This also had benefits towards the best determination of individual component impact.

5.3.2 Tabulated Curve Parameters

The above excel functions were used to find curves that fit the function for MTTF determination in the scale of 10^4 hours. The shape and Scale values for each Weibull curve function are presented below respectively.

Table 5-3: Shape Factor for Total System and Subsystems

Shape (β)	**Typical Operation**	**Reduced Operation**
Fluid Circulation	1.388	1.899
Cell Stack	6.350	3.369
Auxiliary Systems	2.331	0.897
Total	1.194	1.458

Table 5-4: Scale Factor for Total System and Subsystems

Scale (λ or η)	**Typical Operation**	**Reduced Operation**
Fluid Circulation	4.186	3.440
Cell Stack	2.128	6.912
Auxiliary Systems	6.851	5.226
Total	9.870	5.125

The type and magnitude of Failures played a significant component in the development of the likelihood distribution of failures. To explain with reference to the above β values:

- Failures from old age could be considered those who undergo rapid wear but only after a certain period, hence indicating a right skewed distribution curve from the MTTF. This behaviour is considered typical for β is greater than 4.0.
- Whilst low cycle fatigue, bearing failure, corrosion and more of those considered long-term exposures have lower Beta values approximately β greater than 1.0 and β less than 4.0.
- Other relevant failure rates such as dust storms, or vandalism would be site specific however is considered random failures where β equals 1.
- Lastly, values where β is less than 1 represent improper installation, or component faults not as regularly witnessed.

As for the Scale Factor (λ), it provides a contraction or extension along the time scale, therefore larger MTTF's will also have a larger Scale Factor Value and vice versa.

The interpretation of both λ and β values showed that they fluctuate under varying mean time to failure conditions. This was to be expected as even though the β value best determines the direction of the failure curve; the scale factor can change how much time this occurs over.

The cell stack failure parameters stood out compared to others due to very large beta and scale values, which reflects a larger MTTF and less immediate reliability distribution curve up until a sudden failure experienced. Ensuring optimal conditions will play the main part in MTTF extension to the expected life of 20 years and should be performed as the cell stack is a major and expensive component of the system.

The standout at the other end of the scale is in the auxiliary system which finds immediate failure rates expected with a $\beta < 1$ indicating that failure rates are more prevalent from installation and controls will need to be assessed immediately. The auxiliary system also has a large-scale value, indicating a slower degradation overall which is skewed by those components with longer life expectancies.

Table 5-5: MTTF Values for Total System and Subsystems

MTTF $(1 * 10^4\ Hours)$	**Typical Operation**	**Reduced Operation**
Fluid Circulation	3.82	3.053
Cell Stack	19.80	6.207
Auxiliary Systems	6.070	5.509
Total	9.296	4.643

5.3.3 Graphical Results

Table 5-6: Typical Operational Reliability and Probability Distribution Density

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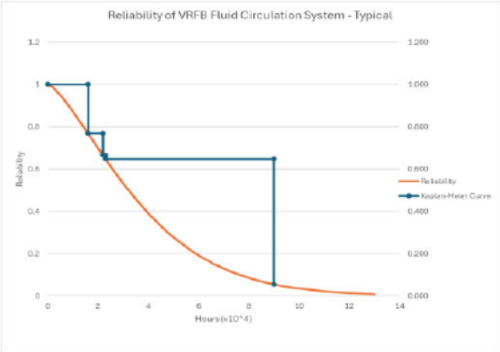
<td>
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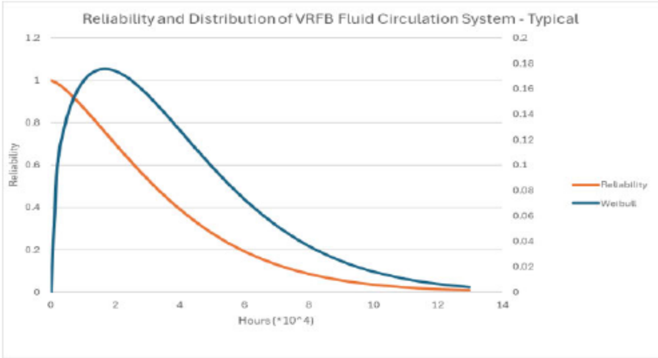
<td>
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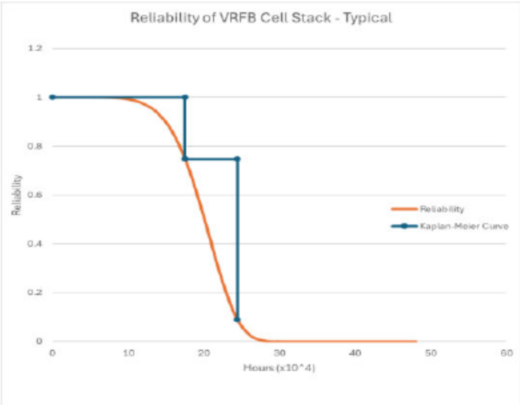
<td>
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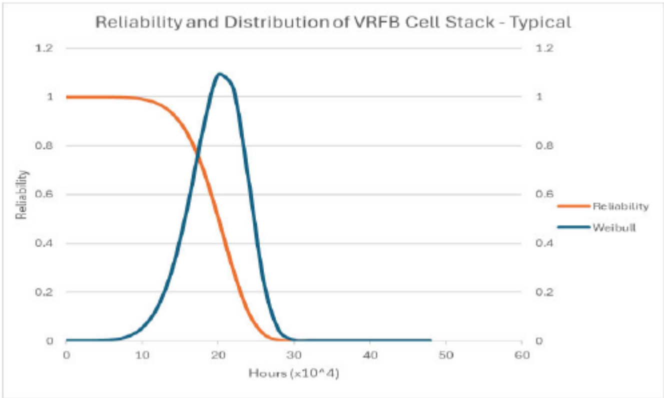
<td>
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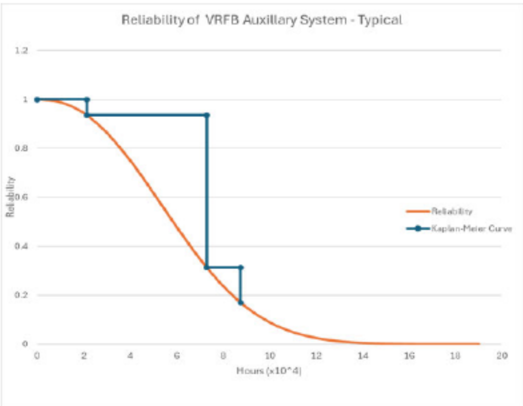
<tr>
<td>Auxillary/ Support Systems</td>
<td>
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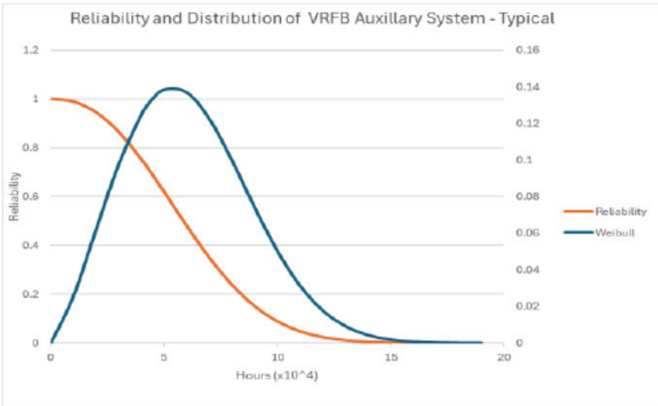
<td>
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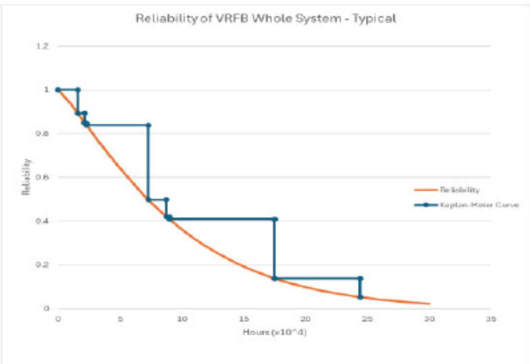
<tr>
<td>All Systems Combined (Complete VRFB)</td>
<td>
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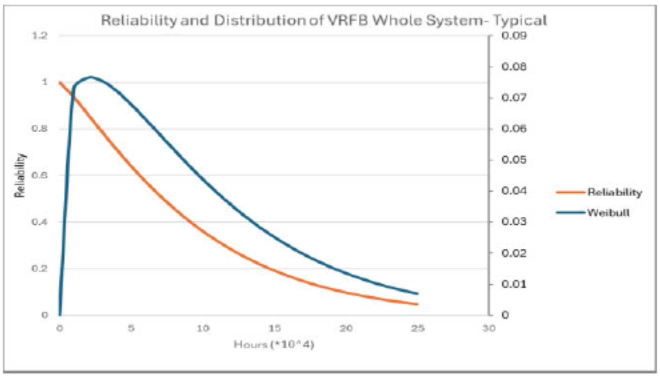
<td>
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Table 5-7: Reduced Operational Reliability and Probability Distribution Density

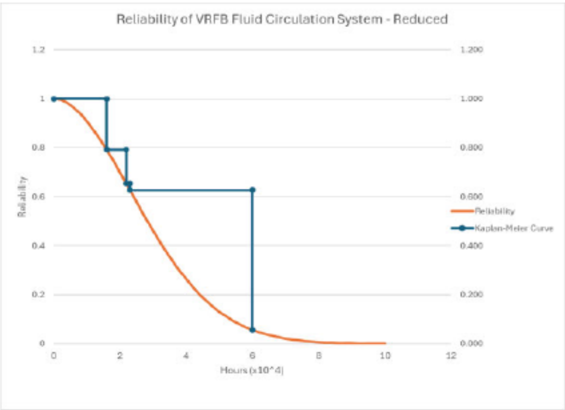
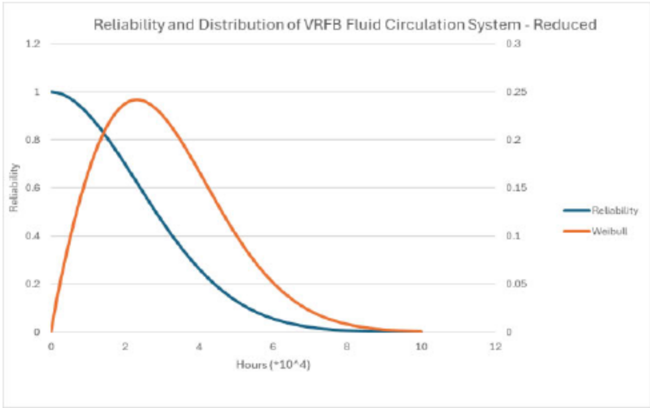
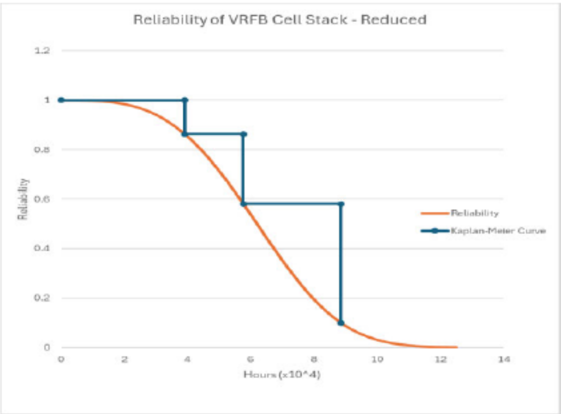
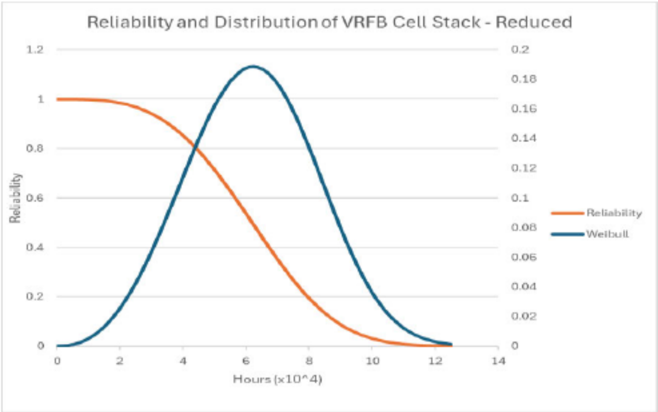
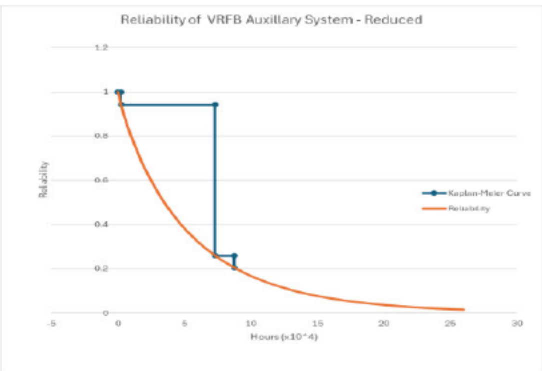
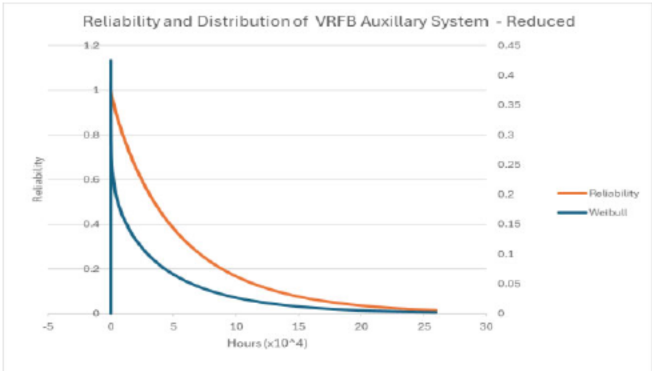
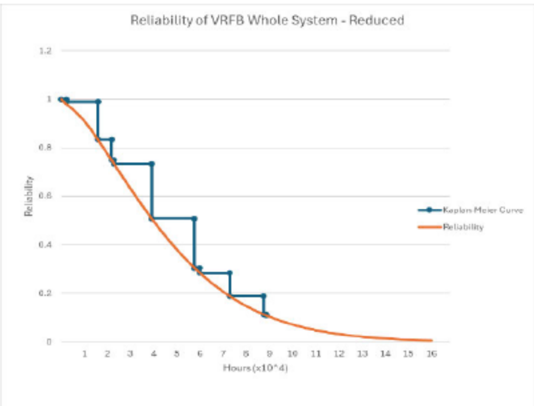
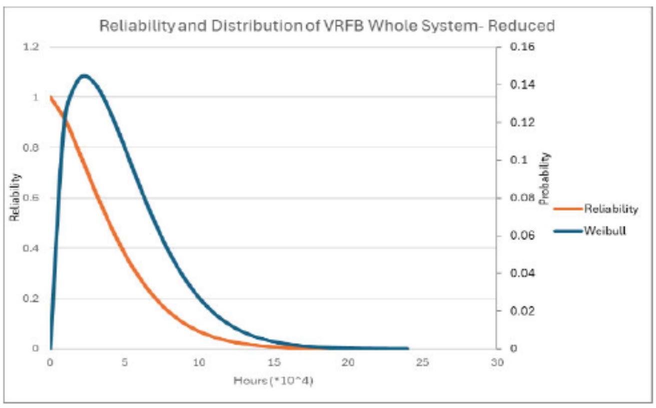
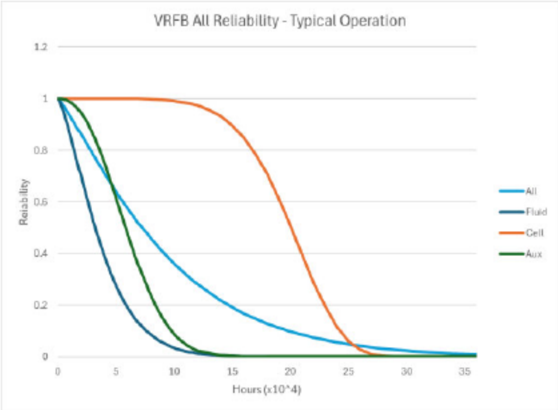
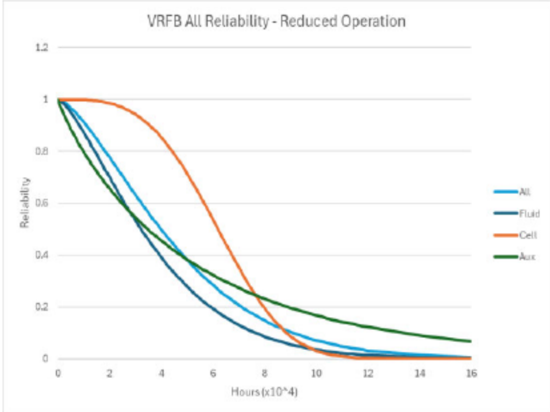
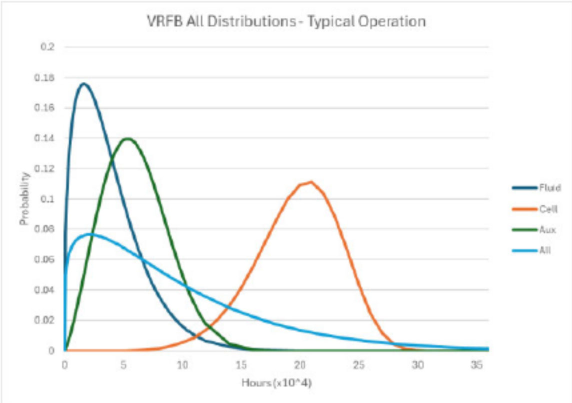
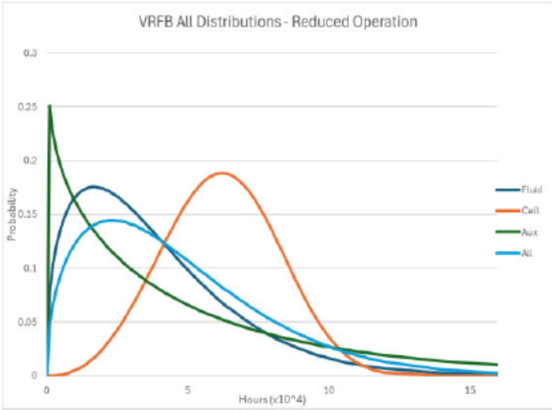
Fluid Circulation System		
Cell Stack		
Auxillary/ Support Systems		
All Systems Combined (Complete VRFB)		

Table 5-8: Graphical Comparison between Reliability and Distribution Density for Typical and Reduced Operation

Reliability		
Probability Distribution		

5.3.4 Discussion

This shift was found as representative towards what a worst-case scenario could result in by following the concept of a proliferative failure effect. The worst-case scenario that was interpreted follows a series of outcomes in order of failure:

1. Due to inefficient cooling from fouled heat exchanger parts leading to electrolyte precipitation, as well as eventual complete failure of the heat exchanger. Dust fouling has an approximate failure share for heat exchangers of 37%, making it an unlikely scenario but can be exacerbated by windy and dry conditions.
2. The electrolyte precipitation causes electrolyte imbalance leading to excess HER activity on the negative electrode leading to bipolar plate cracking.
3. The bipolar plate cracking then leads to copper contamination from the current collector.

4. The contamination then circulates through the electrolyte and over time can lead to membrane degradation.

By following this series of failures, there was a major difference for the reliability found for each subsystem and the total system as best compared in table 5-8 above. The calculated MTTF shift for each component and overall was dramatic however the main shift in reliability is from the degradation of components within the cell stack. Like the solution from Sumitomo, the manufacturer could realistically achieve a 20 plus year life expectancy for the full solution. Due to the possibility of high heat, the implementation of further temperature controls may be required to achieve this outcome. This is beneficial from the perspective of electrical reliability as well as financials. The implementation of controls may result in not having to replace a cell stack or the whole system in the instance of catastrophic failure, which requires finances and battery downtime to achieve.

The example conditions of increased dust were insinuated to occur in an area of regional Queensland, which is primarily comprised of Grassland and Desert land cover features (Perera et al.). Whilst dust may not be consistently present in these environmental conditions, consideration of their effects should always be made during project implementation or site selection stages. Dust can intrude small gaps and as such, unprotected areas such as the heat exchanger gap venting can lead to fouling. The OEM system design also appears to have a cover that can reduce some exposure to dusty conditions, however the overall effectiveness of this design would need to be tested to verify capabilities. This would be performed before implementing a solidified heat exchanger cleaning schedule. It could be assumed that filtration equipment can be utilised if required, however this would reduce the efficiency of the cooling through air flow reduction leading to a baffling effect. As for other equipment, they would primarily be unaffected by a dusty environment which is due to the shipping container exterior. The shipping container is far more resilient to dusty conditions than the others and may require some attention over time such as cleaning and repainted surfaces but remains otherwise unaffected in lower moisture areas.

The other failure implemented was bipolar plate failure leading to electrolyte imbalance. As has been identified, high heat operation can cause precipitation of the electrolyte as well as HER in the negative half-cell electrode, producing more heat and hydrogen gas. As such, extreme heat has the capacity to reduce lifetime of both moving and static components due to increased wear. The heat failure investigated resulted in the Bipolar Plate experiencing a failure rate 4.47 times faster than typical conditions, however, also comprises of additional elements of failure in electrolyte degradation such as imbalance or loss of capacity. Excessive H_2 gas production can also occur from copper contamination leading to decreased reliability. These conditions were modelled to emphasise the importance of controls, particularly for temperature and dust since Australia is renowned for a high heat climate and a large percentage of regional land cover.

Some elements in the fluid circulation system were found to be an interesting concept as the heat experienced here would not overly impact the PE components or glue. This is due to the sulfuric acid concentration being lower than 50%. Over time, degradation would be experienced but would be exacerbated mostly through inadequate installation such as improper plumbing materials or sealing adhesive. Cyclic use affects most components, particularly the pumps, cell stacks and heat exchange however valves are normally open and are only sealed during periodic routine maintenance leading to less cyclic impact. The moving part components within the fluid circulation and auxiliary systems face the highest levels of concern for failure due to reduced MTTF performance in non-optimal conditions.

One major interesting point was that of the support systems Weibull distribution, where the Auxiliary components faced a situation where a non-numeric value was not calculated rather returning a ‘divide by zero’ issue. This situation tends towards infinity, however in the context of this investigation, it was not possible to achieve that and not a reliable outcome to assume. Therefore, during construction, this value was altered to zero to ensure that a valid numeric distribution was found.

Most peaks in failure were found to occur within approximately 6 years of operation under either reduced or typical operating conditions. This meant that whilst the Auxiliary and Cell stack sections experience increased failures under atypical conditions, there would be failures that needed assessing through an appropriate maintenance schedule. System maintenance would lead to minimised downtime, increased equipment lifespan and ensuring efficiency promoting economic boost and electrical reliability (Salawu et al., 2023).

In the case of assigning the most impactful failure of all the failures investigated in the graphical manner, the heat exchanger was concluded as the most significant. Due to heat exchanger failure, the battery would face issues under warmer conditions as the impact is felt through the cell stack components. Battery discharge for example is non-optimal during heat events due to exothermic reactions, and its badly timed use could lead to excessive wear on components and in the electrolyte. This hints towards a fact that poor operational understanding of the system would most likely be the cause of reduced reliability for all components, and as such ongoing maintenance and cleaning is important.

Unfortunately, a completely thorough reliability analysis was not able to be undertaken due to the lack of certain risk conditions occurring in a relevant literature manner. The potential negative effects from shock impact, storm impact, and saltwater proximity were not able to be assessed however the literature review provided some basis for comprehension moving forward in the assessment of risk.

From the above outcomes, a base risk assessment was possible to determine based. Figure 5-2 is a typical risk matrix based off an impact vs likelihood scale. It provides a basic understanding of how the risks involved through processes and conditions can be applied through risk management approaches.

Impact →

Likelihood ↑	Negligible	Minor	Moderate	Significant	Severe
Very Likely	Low Med	Medium	Med Hi	High	High
Likely	Low	Low Med	Medium	Med Hi	High
Possible	Low	Low Med	Medium	Med Hi	Med Hi
Unlikely	Low	Low Med	Low Med	Medium	Med Hi
Very Unlikely	Low	Low	Low Med	Medium	Medium

Figure 5-2: Probability vs Impact Risk Matrix (Acebes et al., 2024)

From the above clarifications and discussions, impact ratings as per the above matrix impact categories can be assigned on a system exposed to the below risks in table 5-9.

Table 5-9: Risk Impacts Table

Risk	Impact	Reasoning
Minimal Maintenance Cyclic operation	**Minor**	Cyclic operation develops component wear over a long period. Typical operating life for components with an adequate maintenance and cleaning schedule would meet the 20-year projected equipment life expectancy.
Atypical Temperature Event	**Significant**	An atypical Temperature Event can cause precipitation and failure in other components over a set period.
Excessive Dust	**Significant**	Dust can fault cooling components leading to a abnormal temperature event
Electrolyte Precipitation	**Severe**	Caused by non-normal temperature events, leads to further damage in other components.
Storms	**Moderate**	Storms can damage exterior components such as the exception of electric cables and BMS.
UV Exposure	**Minor**	UV can only affect exterior components, all which have existing protections.
Saltwater Proximity	**Moderate**	Salt in the air leads to extreme decrease in time taken for corrosion.
Equipment Failure	**Significant**	Any form of equipment failure can result in further equipment failure, as well as in downtime for repairs.
Humidity	**Moderate**	Humidity can cause corrosion and rust over time, damaging electrical components such as metals as well as seals that are in contact.
Rain	**Moderate**	Can lead to corrosion over time or some potential for false trips.
Vandalism	**Significant**	A worst-case scenario for Vandalism could mean electrolyte leakage or other catastrophic failure.
Shock Impact	**Moderate**	Some shock impact can be absorbed by outer container as well as integrated seismic dampers on cell stack. Due to low possibility of impactful seismic activity, linked to vandalism, accidental hits and heavy projectiles from storms.
Harmful Electrolyte Leakage	**Severe**	Any manner of electrolyte leakage should be treated as an emergency as it can lead to various environmental impacts and harm if absorbed or consumed by a human. The risk of immediate harm can be affected by how quickly the waste falls away, i.e. if there's a nearby waterway.

Overall, the development of this system was not quite extensive enough to assume that all impacts would consistently have a similar reduction in MTTF. Too little is known about the complete interaction of the system components, particularly the significance that each probable failure has on complete system reliability. Further work on this area would be able to incorporate:

- Storm Impacts
- Shock Impacts
- Sea Salt Aerosol (SSA) Impacts
- Environmental leakage Impacts which may find some context through Life cycle assessments.

5.3.5 Limitations

The main limitation of the approach followed here was the lack of existing and consistent reliability information for the components within the VRFB. Established reliability modelling for each individual component would ensure not only a more complete model but would ensure further consistency and improved accuracy of the outcomes found. The identification of some final risk types would help round out the consistency issues found in this process.

Another limitation that stems from a lack of consistency is the different conditions that VRFB's operate in. In-field considerations range from environmental conditions, methods and materials used as well as installation processes. These all effect the overall resilience of components and consistency should be established on materials such as a national standard for material and processes used in the development of VRFB's.

Further work would be the achievement of a method of quantification for the reliability modelling to compare different scenarios. This could be achieved through similar processes above but using Monte Carlo modelling to find the most common ranges of failure to find best- and worst-case scenarios for failure rates.

6.0 COMPARATIVE RISK AND CONTROLS EVALUATION

As has been identified from the previous sections, the range of environmental conditions can alter the performance and life of the components that constitute a VRFB. Certain controls must be implemented to ensure minimal environmental impact and cost reduction through these decisions. The comparative controls analysis investigates set locations and identifies what controls may be included from the investigation undertaken so far. Whilst originally set out to be a comparative Life Cycle Assessment based on the reduced risk of conditions through controls, the methodology was altered to remain more suitable for the outcomes achievable. This was changed to a similar undertaking of a comparative risk matrix evaluation based on location and controls, with verification from the industry supervisor for further use towards an environmental controls framework. This verification proved to find minor alterations in logic approach. Controls were found to be implemented in a variety of ways, and further access to equipment and material impacts is also necessary for the development of controls. Some examples of relevant controls include sheds, other structures, filtration systems or sensor circuits. The necessary step for each location was followed as below:

1. Identified the locations and respective climate conditions which concluded what controls may be necessary to ensure operating conditions are ideal.

   This included identification of climate extremes and overall exposure of those extremes for the location. In addition to this was other considerations such as operating characteristics in grid usage, remoteness and social interaction. The combination of these factors described the potential conditions that the battery would experience from an operational perspective.

2. Identify a series of controls that would be useful in combatting certain operational conditions. This aimed to provide the more ideal solutions for each location, particularly identifying situations where controls may not be as suitable. This aimed to consider traditional and simple methods of these controls, as well as modern technologies to ensure that reliability is achieved in terms of simplicity and effectiveness.

3. Developed a series of risk matrices that consider for each location the potential risk found from the impact and likelihood found through risks from the stage two outcome risk table. It was performed in two separates for comparative purposes as below:

    - A non-control scenario
    - Control Scenario

4. This was then sent to the industry supervisor for feedback purposes to ensure alignment with future control outlooks before implementing decisions towards stage four. Any changes that were suggested to make were made to better align with future outlooks.

5. Documentation of final matrices that informed the development of the environmental controls framework.

6.1 Locational Context and Operating Conditions

Context is required for each location to propose certain controls to match environmental conditions. This context is typically provided through climatic conditions as below however some site-specific conditions are experienced as well. Conditional information used for all locations is listed below:

- The Bureau of Meteorology is the most extensive source of information for Australian weather and as such was utilised to gather information on temperature, rainfall, and humidity.

- The national map by the Queensland Government was found to contain relevant information for the renewable energy resources of Total Potential Rooftop Solar Photovoltaics presented as a power output. It was created through a combined effort between OMNILINK, Australian Photovoltaic Institute (APVI), University of New South Wales, and the University of Technology Sydney. The dataset identifies potential roof space and associates a PV output for each roof within Local Government Areas (LGA's). It was used to indicate usefulness of battery implementation from the perspective of offsetting local renewable energy exposure which could lead to low power demand issues.

- The national map also includes wind probability distribution files which are modelled wind files for Australia. They are unvalidated models and may be incomplete regarding wind profiles. They were utilised to infer the potential of dust build up and ventilation.

  The wind files are presented on a 12-sector directional basis as Weibull parameters. Equation 5.5 was used on all 12 sector Weibull curves and then all probabilities were combined using equation 6.1 for a single wind speed. Lastly, an average wind value was found to conclude a representative result using equation 6.2.

$$\sum_{n}^{n+x} Sectors = Sector_n + Sector_{n+1} + \cdots + Sector_{n+x} \tag{6.1}$$

$$\bar{u} = \sum(u_n * sector_n + u_{n+1} * sector_{n+1} + \cdots + u_{n+x} * sector_{n+x}) \tag{6.2}$$

$$Where\ \bar{u} = average\ wind\ speed\ in \frac{m}{s}$$

$$u_{n+\_} = wind\ speed\ for\ each\ sector\ in \frac{m}{s}$$

These wind files are called Wind Atlas and Analysis Program (WAsP) library files. They are supplied from the DNV GL Wind Mapping System (WMS) through the National Map service. For all locations, a surface roughness length of 1.5 meters and wind height of 10.0 meters was assumed for surrounding building and structure roughness and approximate ground height respectively.

Table 6-1: Relevant Location Climatic Conditions

Sources	Conditions	Berrinba	Blackall	Cairns	Unit
Berrinba – (Bureau of Meteorology, 2024d) Blackall – (Bureau of Meteorology, 2024a) Cairns – (Bureau of Meteorology, 2024b)	Maximum Temp (All Time)	41.9	44.6	42.6	°C
	Minimum Temp (All Time)	-0.5	-2.0	6.2	°C
	Mean Annual Days 40°C or above	0.3	10.6	0.0[1]	Days / Year
	Mean Annual Days 2°C or below	0.3	5.8	0.0[1]	Days/ Year
	Average Rainfall (Annual)	1089.2	526.1	2013.5	mm
	Mean Days with Rain (Annual)	130.7	51.2	156.1	Days
	Mean 9am RH	66	53	72	%
	Mean 3pm RH	53	32	62	%
(OMNILINK, 2024) LGA's: Berrinba – 34590 Blackall – 30760 Cairns – 32080	Potential Solar Output Total	2219	41	1159	MW
(DNV GL, 2024) WAsP LIB files Coordinates Berrinba – 27.771S, 152.996E Blackall – 24.371S. 145.485E Cairns – 16.896S, 145.727E	Average Wind Speed	1.87	1.78	2.74	m / s

[1]Minimal count of recorded instances in excess rounds to zero.

6.1.1 Event Tree Analysis

The event tree analysis was used to determine to develop relationships between concepts found in stage one and effect on reliability found in stage two. The main purpose of this section is to present a visual understanding of the investigated reliability reductions and their relationship to onsite conditions in a qualitative manner. The events analysis was broken down into two separate figures due to size and legibility.

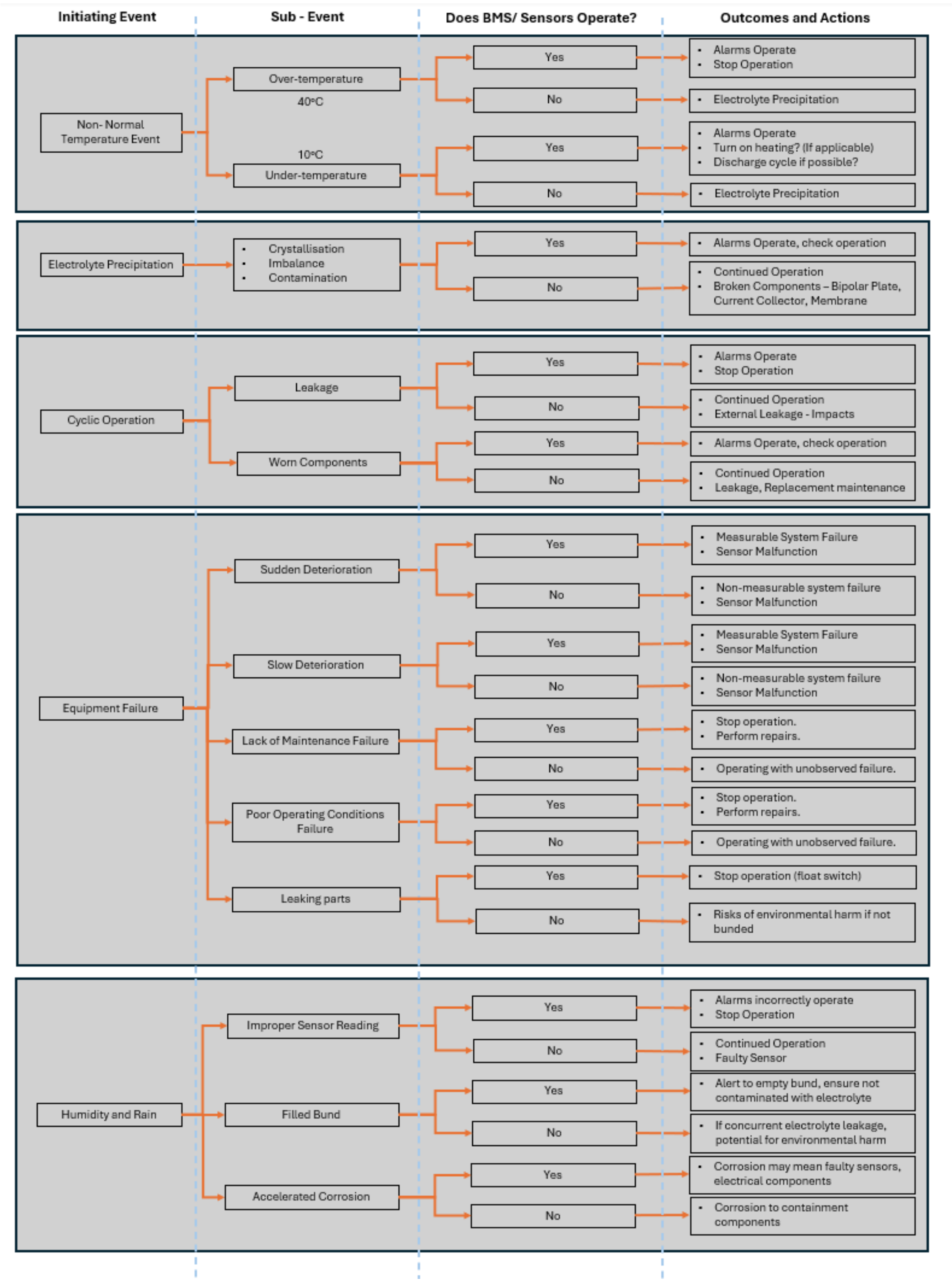


Figure 6-1: Event Tree Analysis for VRFB conditions part 1

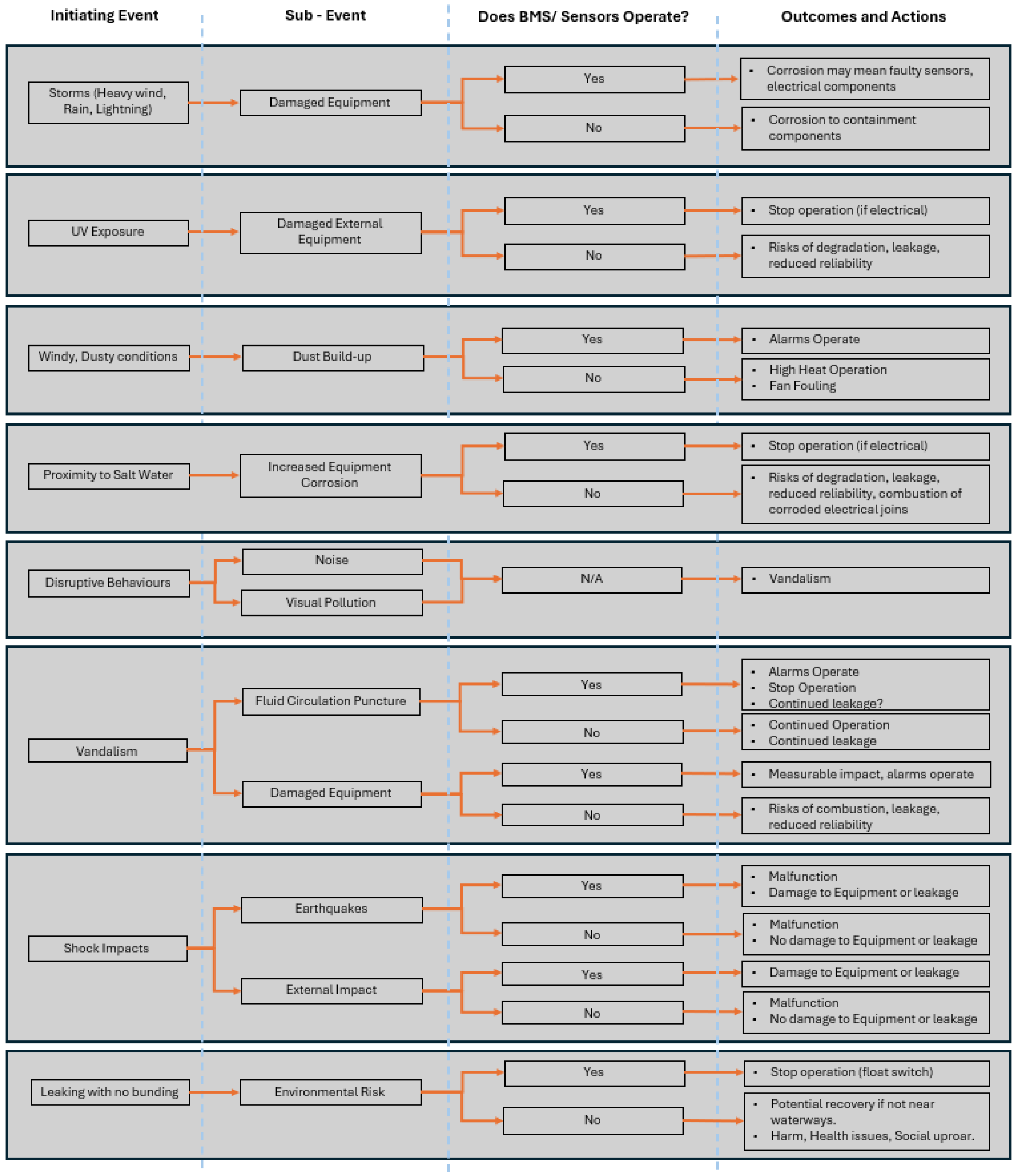


Figure 6-2: Event Tree Analysis for VRFB conditions part 2

6.1.2 Berrinba – Southeast Queensland

Berrinba was included for the climate conditions as a control scenario for verification with the industry supervisor. Due to the project pilot at Berrinba undergoing implementation and commissioning, this would prove relevant to relate the different locations together. The location was found to have benefits from proximity to other Energy Queensland or Energex Sites allowing personnel readily available for monitoring and emergency repairs, as well as storage sites for spare parts. Further benefits lie in its' positioning inside of an existing industrial depot, leading to less chance of complaints from surrounding businesses and residents. Thus, led to a realised lesser potential for issues to arise from vandalism, legal proceedings or disagreements. Although the location of the depot is in an industrial zone, it resides nearby the Berrinba wetlands meaning that lost electrolyte could more easily find its' way into water systems and cause environmental and health impacts.

The use of a battery system in a built-up area is to mainly provide load shifting capabilities to the network, complementing increasing levels of local renewable energy integration. Berrinba is in a section of network with large amounts of realised Solar generation as seen in the figure below meaning the location was found suitable for the local load shifting mentioned above.

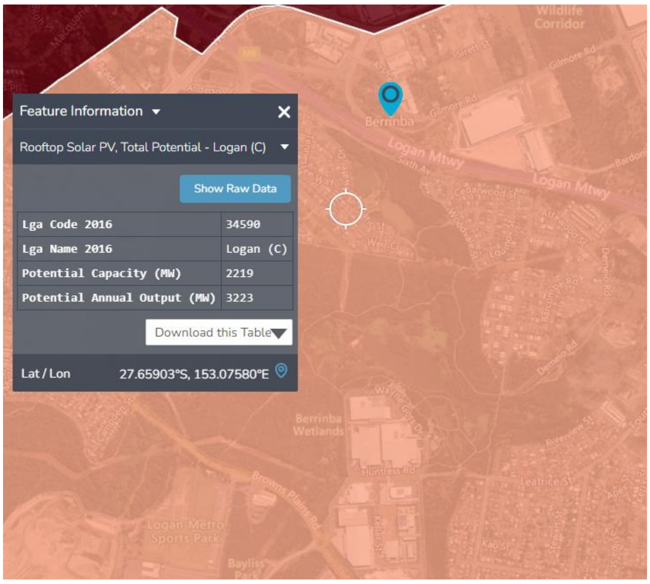


Figure 6-3: Berrinba Solar Potential (OMNILINK, 2024)

As can be seen from table 6-1 and the above figure, Berrinba has a large amount of Potential Solar Output due to the irradiance as well as available roof space in its' LGA. The potential for active power output means load shifting can be used to a great potential.

Other standout elements for the Berrinba site from table 6-1 were:

- The minimum and maximum temperatures experienced which are in excess to the recommended operating conditions of a VRFB, which are between 10°C and 40°C.
- On an average basis, 40°C is exceeded 0.3 days annually. A minimum of 2°C however is exceeded between the months of June through to September on an average temperature (Bureau of Meteorology, 2024c). It occurs rarely leading to an average of 0.0 annual

occurrences. Operation during this low temperature scenario should be regulated and a form of control introduced.

The main concern found for temperature operation is when the VRFB is operating or there is electrolyte separated from the main storage, allowing increased temperature change sensitivity. This was found to be somewhat offset due to:

- Operational characteristics that charging will be performed during the day, which undergoes endothermic reactions, thereby performing cooling in the cell stack.
- Charging through the day supports solar soaking tariff pricing for price reduction and reduces issues involved for the grids minimum demand (Ergon Energy Retail, 2024). Typical discharging during peak grid conditions would also be expected.

The cool temperature minimum for the case of Berrinba was found as less of an issue as it would not be utilised during minimum temperature conditions overnight, and as such issues in electron efficiency would not be experienced (Xi et al., 2016). The minimum temperature experienced also does not get close to -10°C which is a recommended minimum temperature for electrolyte storage to prevent crystallisation (Pan et al., 2016). To summarise, controls should only be necessary to ensure that the chance of precipitation for overheating is kept to a minimal.

- The last major consideration is expected annual rainfall which occurs approximately 35.8% of the days throughout the year leading to over 1000mm of rainfall. Annual humidity insinuates an overall percentage between 53% to 66%, particularly between the hours of 9am and 3pm. The increased moisture levels from rainfall and humidity have been identified to lead to corrosive impacts. There was also secondary concern found with open air bunding as a rainfall impact can reduce effective capacity.

6.1.3 Blackall – Central Queensland

Blackall was included in the controls assessment as one variation of controls for a different climate and contextual conditions. The township is small in both size and population, with the dominant industry being grazing. This gives rise to issues in locational limitations where the nearest depot is over 200 km away. This was found to translate into issues with access to spare parts as well as trained personnel for repairs. Furthermore, due to the large exposure of farmers culture, it was identified that there may be anguish and subsequent disputes over changes to the local industry and scenery leading to increasing instances in community disputes and legal proceedings. It was understood that this could be due to drawing attention to the object at hand or to get revenge for implementation without due public consultation (Bell et al., 2024) (Fuellgrabe, 1980). Vandalism is also important to consider as not only can extra expenses be involved but any loss of electrolyte from vandalism could lead to contamination in the nearby river and water source. Therefore, the identified strategy for implementing a battery is the development of a dispute management process or utilisation of community planning approaches.

VRFB's find advantage during cyclic usage, however some locations such as Blackall may find benefit in reactive compensation. The VRFB is presumably a four-quadrant inverter as per typical battery connections (Abdollahi Biroon & Pisu, 2020), meaning it can deliver or absorb varying amounts of active and reactive power according to network requirements. Reactive compensation finds benefit in voltage regulation scenarios. Voltage regulation is required at locations with low load conditions at remote locations at far ends of transmission lines like Blackall (Tharuka Lulbadda & Hemapala, 2022). However, it is only achievable through solving a major concern for the VRFB in this operating capacity. This concern is that the power cost of running auxiliary components is greater than the benefits in undertaking reactive compensation. More cost-effective outputs could be established through dedicated reactive compensation solutions. Despite not being entirely suitable for reactive compensation due to high auxiliary power requirements, different strategies for the VRFB battery usage should be considered for future use cases like Blackall.

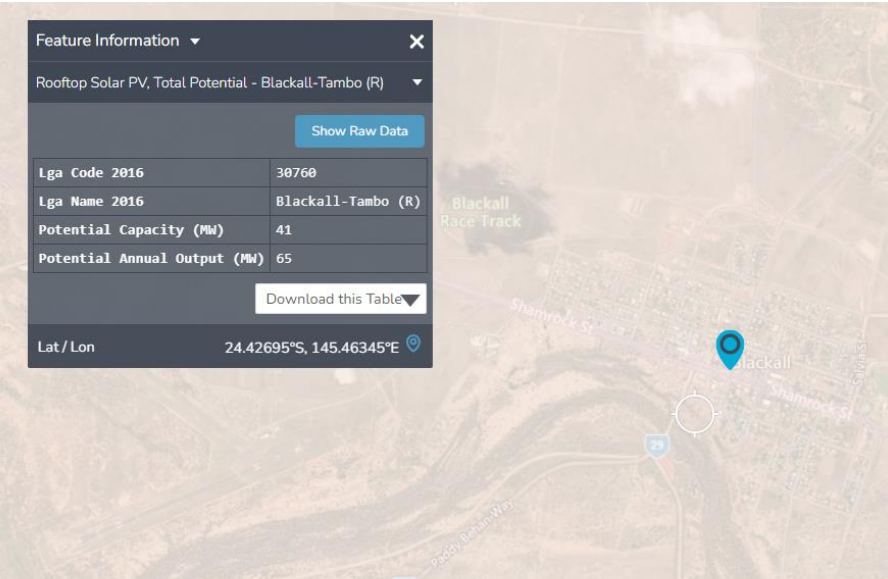


Figure 6-4: Blackall Solar Potential (OMNILINK, 2024)

As was confirmed from the above figure and table 6-1, the solar potential from rooftops is low however there is some benefit for renewable integration with nearby Renewable Energy Zones (REZ's), allowing some movement for energy shifting purposes.

As for the climate controls:

- Standout elements are the maximum and minimum temperatures of 44.6°C and -2.0°C respectively. To emphasis the potential for heat impacts, there are approximately 10.6 days per year where 40°C is exceeded meaning that heat impacts can be severe. Typical operational characteristics will mean that the battery will charge through the day, and discharge through peak afternoon or night conditions. The thermal characteristics of discharging (exothermic) would offset this issue however care should still be made to ensure safe and reliable operation, like daytime operation with charging.
- The minimum temperature was found to be below 0°C, leading to a bigger issue than Berrinba with temperatures less than 10°C experienced between June and August. Some consideration should be given to this, as reactive compensation may be a required solution of the VRFB, operating during the evening period. The temperature does reduce to less than 2°C an average of 5.8 days annually and thus operation and temperature controls should be considered.
- Due to this high inland heat, the humidity experienced is kept lower between 32% to 53% during the day over the course of a year, which complements lower rainfall compared to the other sites. The dry and hot conditions give rise to dust concerns as wind can exacerbate these conditions with an average of 1.78m/s experienced (6.41km/h at 10 meters above ground level).

Thus, the main climatic concerns are the high heat exposure and dusty conditions all year round. Due to the type of operation required of the battery, there should also be some consideration to ensuring the system does not get too cool during the evening to prevent lower efficiency operation during nighttime periods.

6.1.4 Cairns – Far North Queensland

The location of Cairns was included as it presented another variation of controls for different climate and contextual conditions. It more closely resembles Logan (Berrinba) than Blackall, being a city with over 100,000 in population with a focus in industries such as manufacturing and marine processing or logistics (Cairns Regional Council, 2024). As such, a variety of industrial zones were found where a battery installation could be included, leading to lesser anguish over a battery installation in Cairns. In extension, this leads to less visual pollution compared to the regional locations and the larger population centre also tends to mean that personnel and supplies would be more readily available. Especially as seasonal cyclonic weather could cause damage leading more spare parts required to address repair time reduction. Cairns is also located right on the coast meaning that salt in the air would be more prevalent, translating to increased corrosion rates for equipment from Sea Salt Aerosol (SSA) (Madani Sani et al., 2021).

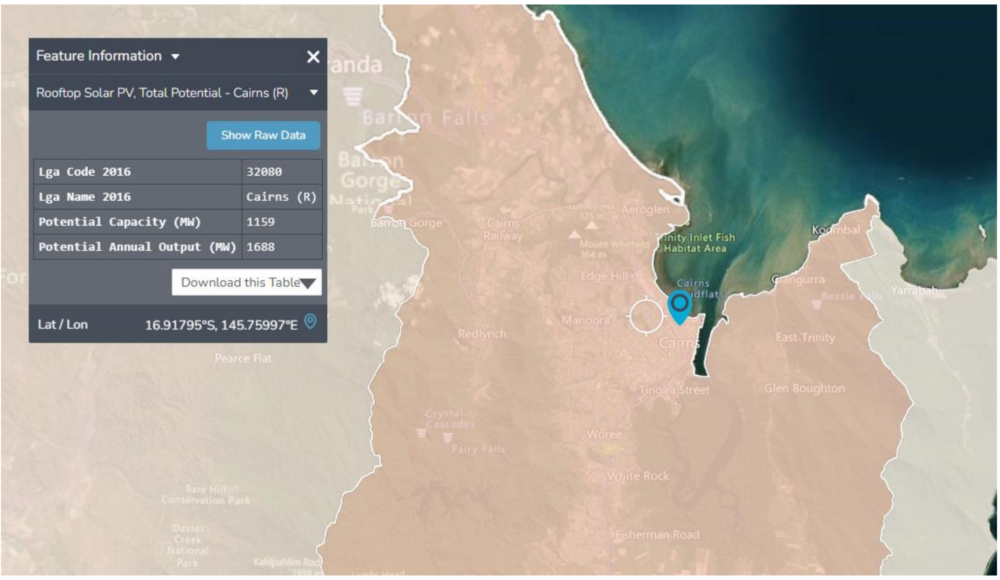


Figure 6-5: Cairns Solar Potential (OMNILINK, 2024)

For the Cairns LGA, it was seen above that the potential solar capacity realised supported the idea of standard charge and discharge cycling. In support of this idea was proximity to the North Queensland REZ, meaning that the usage of a battery would most likely benefit by assisting with demand shifting in the grid. One consideration against this concept is solar soaking which is performed by prosumers in the grid utilising their own power to achieve cost reduction and lesser impact from minimum demand concerns during times of peak solar generation. Whilst the charging period may vary, it can be said for discharging that late afternoon and evening periods is when the battery would be operating due to typical high demand.

The climatic conditions observed in Cairns:

- Regardless of day operating times, upper heat limitations need to be observed, and controls implemented for safe operation. However, Cairns temperatures above 40°C are not as common compared to the other locations. Lower temperatures are also a lesser issue with the lowest recorded value a comfortable 6.2°C and minimal late-night operation mean that efficiencies would not suffer greatly.
- If a shed is utilised, an important consideration for the battery is ventilation as there tends to be greater average humidity percentage between 62% and 72%, which can lead to

increased corrosion rates. Combining this with the salt air mentioned previously, can lead to further increased corrosion rates on components that are exposed to air.

- Cairns also has a high annual rainfall and an average of 42.8% days annually recording rain. These combined impacts serve to exacerbate corrosion rates and other impacts such as mould which flourishes in poor ventilation locations.
- Due to higher rainfall and the built-up location, the site would experience less issues from dusty conditions.

To summarise, the main issues expected are higher temperatures in summer as well as moisture content which combined with the proximity salty air can result in increased corrosion rates.

6.2 Initial Risk Matrices Development

The Development of risk matrices used the identified relationships and impacts assessment in stages one and two respectively, with the criteria as risks involved from each type of failure. The reliability assessment of the impacts performed during stage two and subsequent impact ratings were used in conjunction with locational conditions to determine the likelihood of risk occurrence. This approach allowed a range of risk matrix decisions to be made under varying conditions by altering the likelihood of that occurrence. The likelihood itself being determined by the conditions and what controls are implemented for those conditions. The life expectancy of these batteries is over 20 years and as such, most risks would be unlikely over a 20-year period in ideal circumstances. However, stage two has informed the potential for levels of exacerbation from these conditions and can effectively inform the likelihood variations.

It should be noted that most risk matrices are similar however not the same, and opinion can vary depending on areas of expertise. Collaboration with Energy Queensland is thus an important part for the development of an appropriate risk matrix system and appropriate controls. The table 5-9 was used for the determination of the impacts for the risk outcomes, and the likelihood of the risk was the variance provided by the different locations. By having an independent variable in the matrix development, logic was kept sound and consistent across the location samples. The combination of these components led to the determination of individualised risk outcomes for each location and risk type. Figure 5-2 is used as the risk matrix 'risk versus likelihood' determination and a scoring system on the same matrix was developed for the various risk outcomes implemented. By using the two-scale risk assessment matrix, it can be observed that the matrix skews towards impact as a bigger addresser of risk compared to likelihood:

Table 6-2: Risk Matrix Scoring

Figure 5-2 Scoring Adaptation		Impact				
		Negligible	Minor	Moderate	Significant	Severe
Likelihood	Very Likely	6	7	8	9	10
	Likely	5	6	7	8	9
	Possible	4	5	6	7	8
	Unlikely	3	4	5	6	7
	Very Unlikely	2	3	4	5	6

6.2.1 Control Location - Berrinba

The Berrinba location was included in this analysis as a control location, as it has an existing VRFB installation on site. By using Table 5-9, table 6-2 and considering the OEM package without further controls, the overall risk outcomes based on location likelihood were determined.

Table 6-3: Berrinba – No Controls Risk Matrix

	Berrinba – Without Controls			
Risk	**Impact**	**Likelihood**	**Risk**	**Score**
Cyclic operation	Minor	Very Likely	Medium	7
Non-normal Temperature Event	Significant	Possible	Medium High	7
Excessive Dust	Significant	Unlikely	Medium	6
Electrolyte Precipitation	Severe	Unlikely	Medium High	7
Storms	Moderate	Possible	Medium	6
UV Exposure	Negligible	Very Likely	Low Medium	6
Saltwater Proximity	Moderate	Unlikely	Low Medium	5
Humidity	Moderate	Likely	Medium	7
Rain	Moderate	Possible	Medium	6
Vandalism	Significant	Unlikely	Medium	6
Equipment Failure	Significant	Possible	Medium High	7
Shock Impact	Moderate	Unlikely	Low Medium	5
Harmful Electrolyte Leakage	Severe	Unlikely	Medium High	7
			Total	**82**

Ideally to remove the medium-high risks, a total risk reduction of one score for the non-normal temperature event, electrolyte precipitation, leakage control and equipment failure is required. The use of certain controls would adjust the outcomes of other risks as well, which may provide a benefit or detriment to certain risk ratings. The total risk came to 82 and a maximum allowable risk is 78 under the assumption that medium risk is allowable.

Below are the following risks for Berrinba, and subsequent controls that could be utilised for risk reduction purposes.

- Non-normal temperature event which can lead to electrolyte precipitation and excessive wear on moving parts. Potential controls implemented could be:
  - A roofed structure that stops direct heat however has adequate ventilation to stop heat buildup. Prior investigations in this report suggest that the roof shape and air ventilation play an important role of keeping an area cool. Evidently this would mean approaching civil structure designers to design a shed with a ventilation system capable of a maximum temperature of 40°C.
    It however does introduce other impacts of increased capital cost but would be found to have smaller reduction benefits in corrosion, UV exposure, and heat impacts on the shed material. Another impact such as basic maintenance can introduce further cost but over time is adequate for controlling these impacts to the structure and the battery.
  - Avoidance of a discharging period during hot temperature events. Even with the potential for BMS operation during this event, residual electrolyte would slowly leak from the cell stack veins back into the storage tanks. This time may be too long, and precipitates still occur.
  - Utilisation of a roofed structure also ensures that ventilation for humidity is adequate. It also can provide protection from major storm damage and rain causing false leakage trips inside the top container.
- Equipment failure was found as condition dependent in the event tree analysis, so achieving risk reduction was found to also assist in reliability purposes. The introduction of the roofed structure was also found to reduce the likelihood of other issues. However, recommendations can be made for spare parts provided in nearby containment centres or the system is integrated with redundancy components to ensure the risk of complete shutoff is kept low.

The controls utilised to develop the risk matrix:

- A shed with sealed sides which allows adequate ventilation through ceiling forced ventilation. This translates to minimal exposure to UV, rainfall whilst maintaining adequate heat reduction through thermal resistance and heat evacuation, as well as humidity management. Further benefits are for removal of rainfall buildup in bunding as the area is sealed from rain ingress.
- External bund of 110% for a single shipping container volume. It is assumed that the bottom tanks are sealed integrated secondary tanks (bunds), however the top container is not considered sealed and a scenario of continued pump operation under leaking circumstances could eventuate if safety detection systems failed. A single leak scenario is more probable than both electrolyte tanks leaking, and as such would lead to external leakage of a single tank capacity.
- A cleaning schedule that performs corrosion, rust and equipment checks should be implemented in conjunction with standard maintenance as recommended by the manufacturer.

Table 6-4: Berrinba - Controls Risk Matrix

	Berrinba – With Controls				
Risk	**Impact**	**Likelihood**	**Control**	**Risk**	**Score**
Cyclic operation	Minor	Unlikely	Maintenance Schedule	Low Medium	4
Abnormal Temperature Event	Significant	Unlikely	Sealed Shed, Ventilation	Medium	6
Excessive Dust	Significant	Very Unlikely	Sealed Shed	Medium	5
Electrolyte Precipitation	Severe	Very Unlikely	Sealed Shed, Ventilation	Medium	6
Storms	Moderate	Very Unlikely	Sealed Shed	Low Medium	4
UV Exposure	Negligible	Very Unlikely	Sealed Shed	Low	2
Saltwater Proximity	Moderate	Very Unlikely	Sealed Shed	Low	4
Humidity	Moderate	Likely	Sealed Shed – Sustained Impact	Medium	7
Rain	Moderate	Very Unlikely	Sealed Shed	Low Medium	4
Vandalism	Significant	Very Unlikely	Sealed shed	Medium	5
Equipment Failure	Significant	Unlikely	Maintenance, Cleaning Schedule	Medium	6
Shock Impact	Moderate	Very Unlikely	Sealed Shed, Bunding	Low Medium	4
Impactful Electrolyte Leakage	Severe	Very Unlikely	110% Single Tank Bunding	Medium	6
				Total	**63**

6.2.2 New Location – Blackall

Using the conditions table and the contextual understanding for the VRFB installation for this location, the following risk matrix is devised for a system without controls.

Table 6-5: Blackall - No Controls Risk Matrix

	Blackall – Without Controls			
Risk	**Impact**	**Likelihood**	**Risk**	**Score**
Cyclic operation	Minor	Likely	Low Medium	6
Non-normal Temperature Event	Significant	Possible	Medium High	7
Excessive Dust	Significant	Possible	Medium High	7
Electrolyte Precipitation	Severe	Unlikely	Medium High	7
Storms	Moderate	Possible	Medium	6
UV Exposure	Negligible	Very Likely	Low Medium	6
Saltwater Proximity	Moderate	Very Unlikely	Low Medium	4
Humidity	Moderate	Unlikely	Low Medium	5
Rain	Moderate	Unlikely	Low Medium	5
Vandalism	Significant	Possible	Medium High	7
Equipment Failure	Significant	Likely	Medium High	8
Shock Impact	Moderate	Possible	Medium	6
Impactful Electrolyte Leakage	Severe	Unlikely	Medium high	7
			Total	**81**

Blackall faces slightly worse maximum temperature conditions than Berrinba as well as more dust due to less rain and humidity. Vandalism can also be considered higher considering there may not be an existing depot that can house the installation meaning new developments causing unease among the populace. These areas need improvement to reduce all potential risks to medium, meaning the maximum allowable total risk score is 74. The main areas of improvement found to achieve this are:

- Non-normal temperature event and electrolyte precipitation which can be improved through the development of a structure with a roof and adequate ventilation like as discussed in the Berrinba section previously. There is more risk involved due to more days annually exposed to the higher temperatures, however forecast operation has meant that typical usage is not found during the hot part of the day for extended periods of time. Unless a typical usage pattern is effectively established, it can be identified that heat reduction controls should be utilised to reduce potential impacts.

Additionally, air-conditioning could be used sparingly by sealing ventilation and turning on when a certain interior temperature is reached. This ensures that residual electrolyte is not warmed up and precipitates, and that the containers with the electrolyte don't warm up majorly which can shift temperature long term swings in the large amount of fluid.

- A completely sealed structure also provides an extra layer of protection from vandals, reduces UV exposure and reduces dust particles in the VRFB system. There is also added benefits in reduced potential impacts from storms.
- Excessive dust impacting the heat exchanger fans could lead to increased parts failure as well as increased temperature issues. In turn, this can lead to not only electrolyte precipitation but also increased required maintenance. Thus, addressing excessive dust should be done in a manner that aligns with typical maintenance schedules so the remote location of Blackall can operate for extended periods of time without failure.

  As previously mentioned, dust filters in similar installations experience cleaning or replacement periods of roughly three months. This ensures that air flow is kept to a maximum for heat reduction but also keeps most particulates from fan blades and other components inside the shipping containers.

  In the event of a dust storm and a concurrent control of a sealed structure, it could be that filtering the structures ventilation system would ensure that dust does not affect the VRFB inside. Downsides would include less simple maintenance for filter replacement, as well as the filter being exposed to more environmental conditions which could unpredictability reduce the effectiveness over time. It does however have benefits for ensuring other parts of the installation such as a bunding float valve or other external VRFB moving parts and sensors do not experience faulty readings from dust buildup. It is recommended that dust cleanup is a part of a maintenance schedule for areas with increased dust.

In terms of parts failure, dust and heat both play major factors but as found in stage two and the event tree analysis in stage three, the dramatic reduction in reliability for the VRFB system is dramatic through excessive dust exposure. Dust failure can lead to heat related failures and as such needs to be minimised. To conclude, the sealed structure provided major benefits for some climatic conditions as well as for vandalism reduction however usage must be kept in mind as operation will warm up the interior of the structure. Atypical non-cyclic usage and interior cooling would answer this issue but would experience higher capital expenditure and less efficiency when cooling is required. Thus, the final controls recommended for use in this example are as follows:

- Fully Insulated Shed.
- High Temperature activated Air Conditioning.
- Dust filter at VRFB. This may not be required with use of the shed but ensures that dust is not infiltrating the installation, slightly increases risk for temperature events due to lower flow rate for evacuating air. A more effective alternative than a dust filter at the buildings ventilation.
- Bunding is achieved for bottom tanks using self-contained integrated secondary tank solution. Bunding for top tank like Berrinba at 110% single container capacity for plausible outcomes, provides protection in the case of leaks for the slower response times from crews.
- Cleaning of all ventilation fan blades and components of dust in maintenance schedules. Dust can attract moisture which can cause more focused corrosion if rain events do occur.

Table 6-6: Blackall - Controls Risk Matrix

	Blackall – With Controls				
Risk	**Impact**	**Likelihood**	**Control**	**Risk**	**Score**
Cyclic operation	Minor	Unlikely	Maintenance Schedule	Low Medium	4
Abnormal Temperature Event	Significant	Very Unlikely	Sealed Shed, Ventilation, air conditioning	Medium	5
Excessive Dust	Significant	Unlikely	Sealed Shed, dust filter	Medium	6
Electrolyte Precipitation	Severe	Very Unlikely	Sealed Shed, Ventilation, air conditioning	Medium	6
Storms	Moderate	Very Unlikely	Sealed Shed	Low Medium	4
UV Exposure	Negligible	Very Unlikely	Sealed Shed	Low	2
Saltwater Proximity	Moderate	Very Unlikely	Sealed Shed	Low Medium	4
Humidity	Moderate	Unlikely	Sealed Shed – Sustained Impact	Low Medium	5
Rain	Moderate	Very Unlikely	Sealed Shed	Low Medium	4
Vandalism	Significant	Very Unlikely	Sealed shed, Fenced Boundary	Medium	5
Equipment Failure	Significant	Unlikely	Maintenance, Cleaning Schedule	Medium	6
Shock Impact	Moderate	Very Unlikely	Sealed Shed, Bunding	Low Medium	4
Impactful Electrolyte Leakage	Severe	Very Unlikely	110% Single Tank Bunding	Medium	6
				Total	**61**

6.2.3 New Location – Cairns

Table 6-7: Cairns - No Controls Risk Matrix

	Cairns – Without Controls			
Risk	**Impact**	**Likelihood**	**Risk**	**Score**
Cyclic operation	Minor	Very Likely	Medium	7
Non-normal Temperature Event	Significant	Unlikely	Medium	6
Excessive Dust	Significant	Very Unlikely	Medium	5
Electrolyte Precipitation	Severe	Unlikely	Medium High	7
Storms	Moderate	Likely	Medium	7
UV Exposure	Negligible	Very Likely	Low Medium	6
Saltwater Proximity	Moderate	Very Likely	Medium High	8
Humidity	Moderate	Very Likely	Medium High	8
Rain	Moderate	Possible	Medium	6
Vandalism	Significant	Unlikely	Medium	6
Equipment Failure	Significant	Possible	Medium High	7
Shock Impact	Moderate	Possible	Medium	6
Impactful Electrolyte Leakage	Severe	Possible	Medium High	8
			Total	**87**

Cairns humidity and yearly rainfall are major factors in the control development process as they lead to the development of other issues that can cause decay in structural strength or operating lifetime of components.

- The salt in the air from nearby seawater causes increases to corrosion rates and would need to be addressed. This can be achieved through less exposure to moisture or with protection layers. The protection layers could be exterior paint and materials to be corrosion proof is necessary for the proposed installation life expectancy of 20 years. This coating would have to be reapplied as an additional part of the maintenance schedule for the VRFB installation.
- Due to the high moisture content all year round, implementation of a structure for the purpose of temperature reduction may result with moisture trapped even with normally adequate ventilation. A rooftop only structure with corrosion resistant components may be more beneficial to stop rainfall and would be rated to a particular cyclonic wind rating dependent on site conditions. This structure would also address the temperatures experienced in Cairns through removal of indirect irradiance.

- Due to the seasonal cyclonic conditions, the introduction of a set of checks on shed structural integrity and rust would be necessary to ensure safety. This would be undertaken during typical maintenance inspections before the major storm season approaches.

The final controls used for matrix development were:

- A rooftop only shed with Cyclone rating (assumed C4) provided protection for the components from UV, heavy rain and cyclonic weather which can cause objects to become projectiles.
- Scheduled protective coating maintenance inspections to achieve corrosion prevention on fixtures and fittings on top of typical maintenance recommended by the manufacturer. Scheduled assessments could also be undertaken for structural reliability on shed, this would ensure the structure remains resistant during a storm event.
- Additional 110% single tank capacity secondary bunding for a top tank leak scenario.

Table 6-8: Cairns - Control Risk Matrix

	Cairns – With Controls				
Risk	**Impact**	**Likelihood**	**Control**	**Risk**	**Score**
Cyclic operation	Minor	Unlikely	Maintenance Schedule	Medium	4
Abnormal Temperature Event	Significant	Very Unlikely	Cyclone rated Carport style Shed	Medium	5
Excessive Dust	Significant	Very Unlikely	N/A	Medium	5
Electrolyte Precipitation	Severe	Very Unlikely	Cyclone rated Carport Style Shed	Medium	6
Storms	Moderate	Unlikely	Cyclone rated Carport Style Shed, structural assessment	Low Medium	5
UV Exposure	Negligible	Unlikely	Cyclone rated Carport Style Shed	Low	3
Saltwater Proximity	Moderate	Possible	Protective Coatings and Maintenance Schedules	Medium	6
Humidity	Moderate	Likely	Protective Coatings and Maintenance Schedules	Medium	7
Rain	Moderate	Unlikely	Cyclone rated Carport Style Shed	Low Medium	5
Vandalism	Significant	Very Unlikely	Fenced Boundary	Medium	5
Equipment Failure	Significant	Unlikely	Maintenance, Cleaning Schedule	Medium	6
Shock Impact	Moderate	Very Unlikely	Cyclone rated Carport Style Shed, Bunding	Low Medium	4
Impactful Electrolyte Leakage	Severe	Very Unlikely	110% Single Tank Bunding, Observations to ensure no water ingress	Medium	6
				Total	**67**

6.3 Feedback and Control Adjustments

Further consultation with Energy Queensland indicated adjustments should be made to the conditions mentioned in the above risk matrix assessment. An outcome of this is to be achieved before further discussions with a specialised risk assessment team is undertaken (not in the scope of this research). This ensured that further action taken would be less subject to major changes. The main point of actions addressed are removal of a shed as a control and removal of the secondary external bund as a control.

6.3.1 Consequences of shed control removal

The shed was removed as a control due to the manufacturers product capability for outdoor usage. Neglecting a shed control translates to less capital expenditure however the cost of replacing individual parts or fluids more frequently may offset this benefit.

The potential consequences of not using shed control could include:

- UV exposure is not a major part of VRFB reliability issues however direct sun contact will mean that the container and the equipment inside warm up more quickly. This outcome would lead to intermittent operation of VRFB and equipment or electrolyte damage.
- Rain exposure meant that bunding would fill up with water after rain events, which in a worst-case scenario would mean that a single tank electrolyte leakage would mix with the water and overflow. This overflow can lead to waterways causing water toxification, or grasslands causing environmental toxification or direct human contact leading to major health impacts.
- Storm exposure for impacts and other wind damage particularly from cyclonic weather.
- Dust impacts as a wall of a shed would provide protection from dust ingress.
- A sealed shed with effective ventilation can mean humidity reduction or control as well.

Constant exposure to elements will mean the VRFB will face higher humidity concerns, particularly during rain or storm events.

6.3.2 Consequences of external bunding control removal

The removal of a secondary external bund invited more issues into consideration than not utilising the shed. The main purpose of the bund was to perform containment of the top tank in the unlikely event of BMS and installed float switch failure for direct pump tripping during a leakage event.

The consequences involved are major in the event of this occurrence including:

- Environmental impact from failure of VRFB components and lack of bunding leading to chemical leachate in earth or waterways.
- Social impact from chemical leachate in earth or waterways causing environmental harm, injuries or death. Backlash from a business perspective would mean a complete loss of trust from consumers and community stakeholders.
- Legal impact from the chemical leachate, as it could be argued that duty of care was not reasonably undertaken.

6.4 Alternative Control Solutions

The benefit of the shed solution was addressing multiple conditions at once, and it was not found that any one control beyond that could perform that well. Combined with the bunding, there is very minimal opportunity for issues to arise during operation. Thus, the choice of alternative solutions to maintain similar outcomes was important.

6.4.1 Alternative UV and Heat Control

UV exposure and direct heat reduction could be achieved using shade sails that need replacement at standard points of time. Some degree of rain reduction can be achieved as well.

The use of shade sails would be dramatically cheaper and provide the UV and heat reduction however would be prone to major storm damage especially in the cyclonic climates. It would allow some degree of water retention into the existing bund if bunding was installed. A preparation process could be implemented to ensure that the battery was secure before a storm event, and without faults. Additional controls would be the removal of the shade sail to ensure it does not become a projectile. Shade sails are quite light however mounting components such as metal clips could also stay attached to the shade sail when detached leading to damage.

A downside to this would be for large VRFB installations, as ensuring that all shade sails are in good condition and need to be taken down before storms means that more personnel would be needed to complete the task within a period.

A regular cleaning period for the shade sails would also be required to ensure the material doesn’t become compromised leading to rips or more.

6.4.2 Alternative Vandalism, shock and dust Control

A potential control for vandalism, shock impact and dust reduction would be in a dust suppression fence. It is essentially a specialised, small gap mesh fence that performs a main purpose of wind break purposes and achieves subsequent dust control. The small gaps allow some dust through but ensures that there is no pressure difference either side of the fence minimising large blow over of dust.

Due to the nature of being a fence, it also has some applicability towards vandalism and impact likelihood reduction as it made of perforated metal sheeting in some cases and as such can provide sturdy protection.

Potential vandalism reduction could be found from attempting to access the site and the assailants could be moderately inhibited in gaining access. Due to the difficulty from access, it could also completely ward off less ambitious offenders.

Choosing this option, however, may face increased capital expenditure and should only be chosen for sites that face increased dust exposure. The colour of the material should also be carefully chosen to not face social anguish from an installation, insinuating that public consultation would be important for this outcome.

6.4.3 Alternative Humidity Control

A humidity control could be implemented using reusable desiccant bags that can sit inside of the VRFB, absorbing moisture. Calcium chloride is a common and effective industrial desiccant solution due to high absorption properties in high humidity environments (Bouzenada et al., 2016). Calcium chloride is non-combustible, and non-flammable however can give off toxic fumes when heated in a fire. It would also be reusable as when heated a sensible temperature, the water would evaporate from the desiccant which can be achieved at temperatures above 40°C.

6.4.4 Alternative Leakage Solutions

The final major concern for controls is the leakage solution, where an ideal control has been found to not utilise any form of external bunding to prioritise cost reduction as well as physical footprint reduction. It was understood that employing traditional open air bunding would be difficult to achieve successfully without the shed control, and as such it is ideal to remove the need for the bunding requirement entirely through system risk reduction. As per the Workplace Health and Safety Act 2011, including bunding was found to not a legal requirement however duty of care for chemical containment processes is paramount and as such AS 3780 is normally adhered to. Bunding is therefore beneficial in most cases for chemical containment but is not a complete necessity, including this situation with multiple system redundancy failures occurring before leakage can occur.

To provide context again, the system already has been established with using secondary integrated units for the bottom electrolyte storage containers and as such would face minimal issues. It could encounter a rare leaking scenario that may be possible if the BMS does not communicate correctly, and float pump switches do not cease pump operation. This can lead to the unsealed top container leaking out either the positive or negative electrolyte fluid circulation lines. This scenario would be very unlikely due to multiple redundancy systems including float switches for immediate pump stoppage but could still occur.

6.4.4.1 Assess complete system redundancies

The first option would be to understand the complete detail of the OEM package without making assumptions to assess reliability of accurate components. This is one alternative solution through complete comprehension of the system at hand and would be a vital step before undertaking further risk control measures. The components included in the detail of the manufacturers accurate system could include:

- Sensors.
- BMS controls diagrammatic layout.
- Back-up control systems and Structure.
- Physical redundancies.
- BMS electrical diagrammatic layout

6.4.4.2 Alternative Bunding Solutions

Other solutions lie in implementing physical controls rather than process controls. Whilst the avoidance of bunding has been found as the most ideal outcome, there are two major solutions exist for alternative bunding. Choosing either would ensure that each of the tanks have protections employed for higher chance of chemical containment than traditional bunding:

1. Sealed Bunding Solution

Develop sealed bunding equivalent to 110% of a single electrolyte tank that is directly connected to the bottom of the top container. It could normally be closed and opens when enough weight from the top fluid pushes down on it or be activated through a float switch level system.

This solution does face some design problems including if the top container is sealed adequately to keep rain external (and thus not cause increased contamination of the electrolyte). It also means that float leak detection in the top container would not operate as originally intended and would need modification to detect and activate the valve to the sealed bunding tank.

There is also an issue of where the storage container can go, the left solution on the below diagram insinuates putting the sealed bund underneath the installation, but the mass of the containers could be excessive and not viable. This may then suggest that the bund should alternatively be another container off to the side of the OEM solution as discussed in option two. Option two may also have opportunity to be expressed as a single bunding container instead however two containers may offer some redundancy in the case of a puncture etc. Furthermore, the packages would also need to be puncture proof which is determinant of material and thickness during acquisition. It would also need to be condition resistant for the location at hand, inferring another container made of Corten steel like the ISO shipping containers.

Legend:

1: Catholyte Storage
2: Anolyte Storage
3: Cell stack and Auxiliary storage

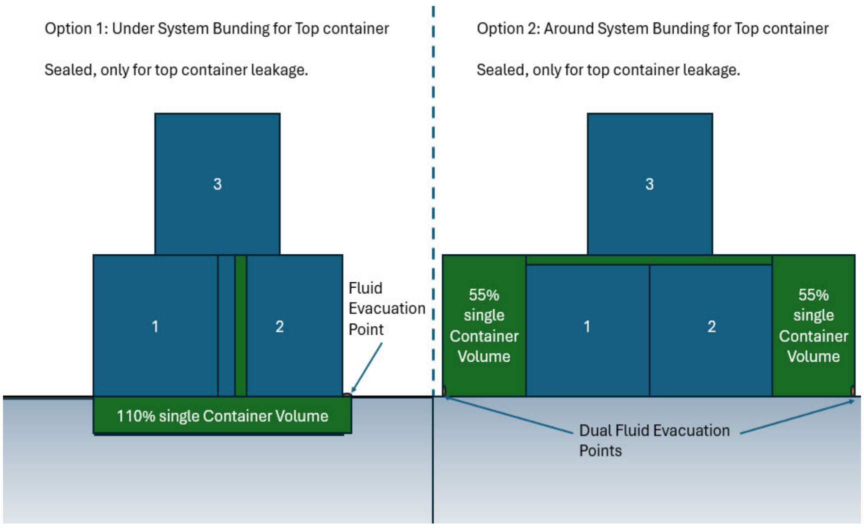


Figure 6-6: Proposed Sealed Bunding System

Table 6-9: Advantages and Disadvantage of 1st bunding alternative

Advantages	Disadvantages
The system ensures complete bunding for all three containers, providing no chance for leakage beyond complete destruction.	It is a more expensive solution, requiring sealed containers to meet bunding requirements.
Minimal impact means it is most suitable for remote locations with poor personnel response times.	Has a physical footprint beyond the manufacturers' package
Under correct installations, it is unaffected by climatic conditions.	Replicating for a large installation or various installations would force difficulties in acquisition.

2. High Surface Area Bunding

Another method for bunding could take less capital expenditure but have higher risk of electrolyte loss, as well as environmental impact. Using a high surface area bund would ensure that evaporation of water stored within the bund can occur at a faster rate and thus minimise the chances of excess water containment under a top container leakage scenario. The scenario itself relies on simultaneous failures in leakage and pump communication and therefore likelihood is lower and as such the bund required may not have to necessarily be constantly water-free but can evacuate at a fast rate.

Legend:

1: Catholyte Storage

2: Anolyte Storage

3: Cell stack and Auxiliary storage

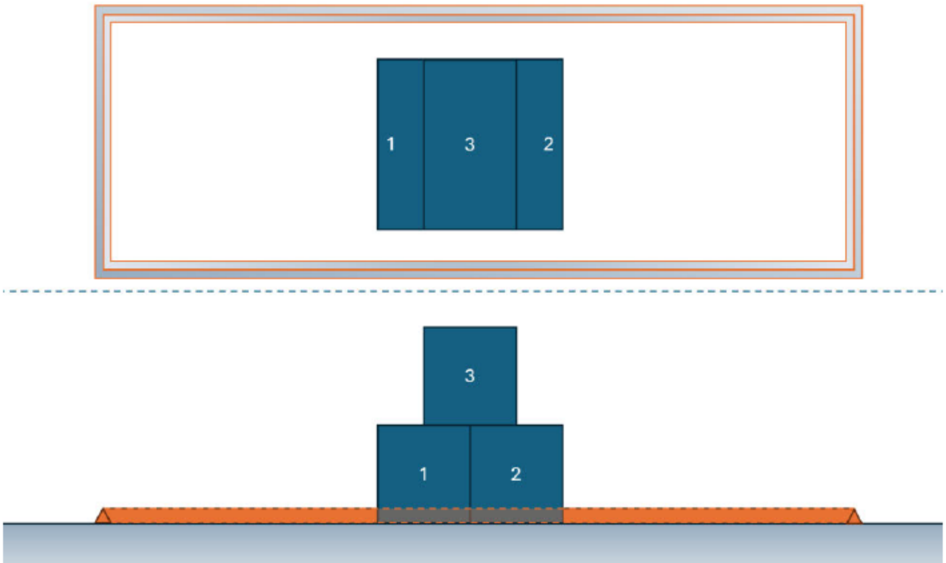


Figure 6-7: Proposed open-air bunding system

The system is to be designed to meet AS 3780:2023 requirements of 110% the largest tank within the compound. It is also able to be safely evacuated through use of chemical handling PPE and compatible pump equipment. The containment barrier should be made of a heavy-duty rubber such as Ethylene Propylene Diene Monomer (EPDM) which allows resistance to climatic conditions and vehicle drive-overs in the case of an accident or requirement for vehicle access.

There was one major limitation of this design found which may not completely meet requirements of section 6.5.2 of AS 3780:2023 which is to ensure there are no increased chances of environmental harm and further condition deterioration during an emergency. A leakage and concurrent rain event may lead to conditions that allow electrolyte leakage from the bunded area, which is a possible event in the case of a leakage emergency.

A positive to this system is a lower capital expenditure with benefits in achieving reduced environmental impact and has previous exposure with fuel station bunding for leakage events. Previous exposures however utilise a grate with lower bunding due to not having great capacity for surface containment and a roof overhead that inhibits most rain ingress.

Table 6-10: Advantages and Disadvantage of 2nd bunding alternative

Advantages	Disadvantages
Cheaper solution for meeting potential bunding requirements.	Less effective containment compared to the proposed sealed bunding system, leading to higher chance for environmental impacts.
Has UV exposure and shock impact resistance.	The requirement for implementing other engineering controls for an emergency spillage scenario.
Long life, easily removable.	Requiring faster responses from chemical handling teams.
-	Accumulated rainwater that has not evaporated within a period may be considered as contaminated and disposed through correct means (Environment Protection Authority South Australia, 2016). This could be prevented if bunding cleaning preparation processes are followed a spill event.

6.4.4.3 Alternative Non-Bunding Solutions

As mentioned, the ideal outcome is that no sheds or bunding are utilised in the development of controls. Devising the system without shed and bunding controls means that system response must be considered firm or utilise controls that perform system response firming. This had been identified as beneficial towards minimal opportunity for leakage conditions.

Diversification has been identified as a main methodology for ensuring system resilience for renewable energy integration however it also has applicability in ensuring equipment control in the VRFB. For typical operation, the failure of parts in the OEM package is not backed up by redundant components meaning that a single failure may stop complete operation of the system so long as the failure is detected. The main issue for this scenario is thus, ensuring that the detection of the failure is observed by the BMS for internal cell stack and fluid circulation protection.

It has been established that leak control for the bottom electrolyte storage containers is adequate with float level sensors and ground fault detection systems forming the basis for an initial alert of leakage. It also has the secondary integrated bund which contains the leak inside of either bottom tank respectively. This means for a leak would occur through:

- Two layers of electrolyte storage tanks. These are the internal PE corrosive resistant tank and a lined Corten Steel shipping container respectively.
- The the ground fault detection system would immediately alert once fluid has contacted the Corten Steel shipping container.
- The fluid level sensors would also sense the leak and alert.

This is essentially a triple redundant system and would stop all but catastrophic cases.

For the context of the top containers, the electrolyte is pumped upwards from the bottom electrolyte storage containers through piping. A burst or leaking pipe has multiple controls implemented for leakage control such as differential pressure system for the cell stack that would identify a sudden change in pressure on either side of the cell stack. Further leakage in the top container would encounter float level switching and when activated would cease pump operation. In the case of further leakage however, this is only contained as well as how the container is sealed. The Gildemeister solution has an ingress protection rating of IP 54 (Gildemeister Energy Storage GMBH, 2015) which outlines that dust ingress is not entirely protected and that water splashed against the machine shall have no harmful effect (Fantech, 2008). This limited ingress protection would mean that leakage occurrence would be possible in the event of float level and differential pressure sensor failure. This design was determined as a dual redundancy system, evidently one layer removed from the bottom container redundancies.

Inhibiting fluid leakage in the top tank can then be summarised into two methods:

- The stop of liquid flow into the top tank by means of disabling the pump. There are two ways of achieving this, through the float level switch tripping method and through lowering or complete inhibition of the flow rate through the pump.
- The containment of liquid flow in the top tank by means of increased ingress protection. This method is not viable as the equipment stored in the top container would be majorly affected by rising liquid levels. The most likely cause would be catastrophic failure for the electrical equipment within the top container. Furthermore, complete ingress protection is not viable due to venting requirements for heat exchanger operation.

Evidently, the viable solution in this capacity is through pump power and flow control systems. It was deemed advisable to check with the manufacturer to ensure that modifications made do not inadvertently cause harm to the integrity of the original solution and redundancy systems. Below are solutions that could achieve this purpose after these checks are made.

1. Pump Trip - Additional Redundancy

A potential solution to this was concluded to be the implementation of additional separate redundancy systems to switch off the pumps. The proposed design consists of a float level switch with a trip controller that is disconnected from the main VRFB management system. It adds the third layer of redundancy to the pump which is the component that is the most influential to ongoing leaks. Both pumps would need to be switched off in this event to remove the risk of membrane rupture leading to a two-container leakage scenario.

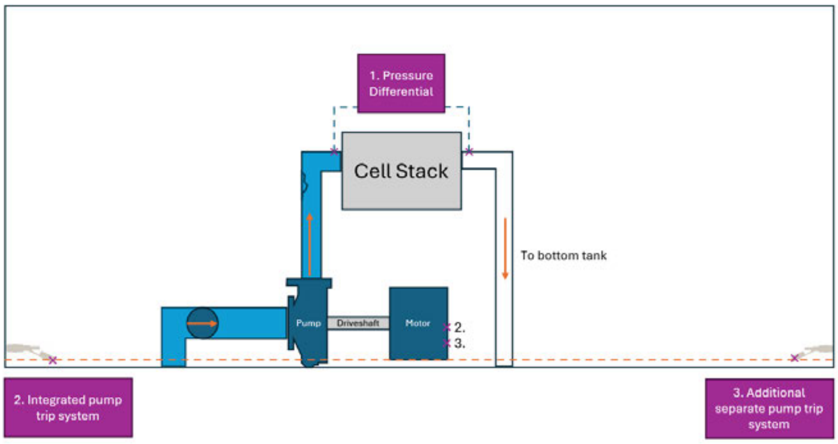


Figure 6-8: Option 1 - Pump Trip Redundancy System

One consideration for the trip system is to ensure that operation is not too quick, as this was identified to cause velocity to suddenly drop in the pump which leads to a large delta change in pressure. This causes a phenomenon called water hammer which can cause damage to the pump or other parts of the fluid circulation system (Zhang et al., 2010). A pump trip controller with a simple human interface and control system would best ensure that the risk of this outcome is heavily reduced.

Table 6-11: Advantages and Disadvantage of Pump Trip Redundancy System

Advantages	Disadvantages
Low-Cost System	Slight Modification to existing OEM package
Simple for Integration	Potential for pipe, pump and motor damage if not controlled.
Triple Redundancy	In the extremely rare event of triple redundancy failure, electrolyte leakage possible

2. **Intentional Pump Starvation or Inhibition**

Intentional pump flow restriction can be achieved using a fluid circulation valve that could be operated from a float level switch that closes the suction side of the pump to reduce or stop flow completely. The butterfly valve assumed to be used in this system can perform some flow rate reduction and as such is viable to achieve this outcome, otherwise a ball valve could be utilised.

The use of a system like this can lead to pump failure and potential explosions through increased use in a single period due to cavitation and starvation. Further implications are dry running and temperature spikes, therefore complete flow rate inhibition would be dangerous. Flow rate reduction would still lead to cavitation however the major effects would be reduced. Flow rate reduction is therefore more desirable however maintenance response crews would have a limited time before leakage from the top container does occur.

A similar system could be utilised using the discharge side however similar results are achieved, and a solution connected on the discharge side allows more leak failures through pipe joins. A sacrificial system such as this would better to operate as close as possible to the intake from the electrolyte storage tank.

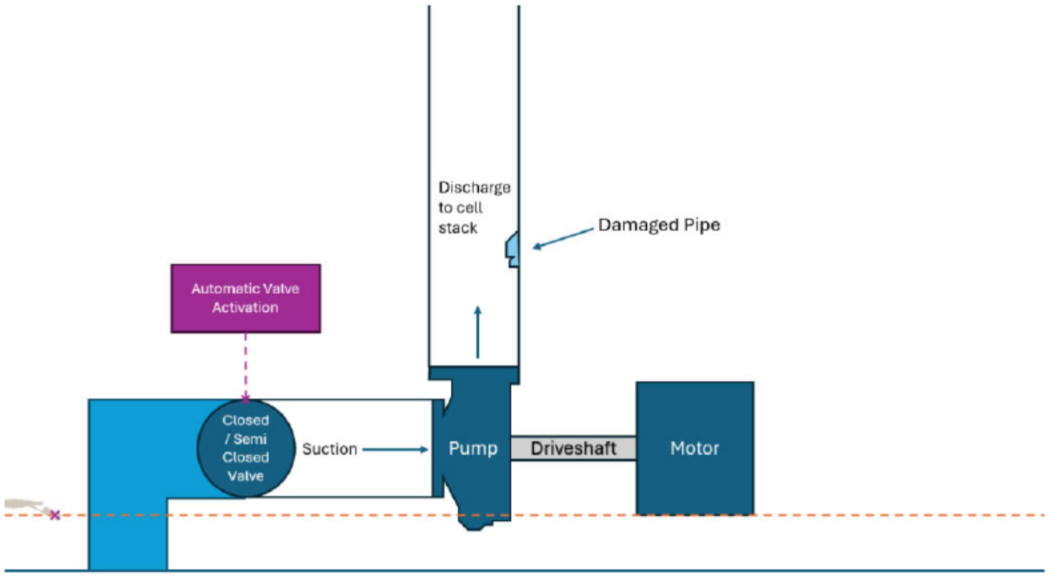


Figure 6-9: Option 2 - Intentional low flow solution

Restriction on the discharge side is called 'deadheading' a pump and can produce disastrous results dependent on fluid or vapours contained within (Simon, 2018). Dependent on the pump, there is a short period of time where long term damage can be prevented allowing time for other control enablement or repairs. In the event of flow restriction rather than complete flow loss, some risk is exacerbated however pump cavitation would remain prevalent as identified in (Xu et al., 2021).

Table 6-12: Advantages and Disadvantages of Low Flow Solution

Advantages	Disadvantages
Low-Cost System	Moderate modification to existing OEM package
Basic Integration, requires plumber and VRFB downtime for completion.	Potential for pipe, pump and motor damage if not controlled adequately. Higher risk than pump trip solution due to pump remaining active
Triple Redundancy	In the extremely rare event of triple redundancy failure, electrolyte leakage possible

6.5 Revised Matrices

The revised matrices were completed based on the main EQL requirements of:

- No shed structures on site for the containment of the VRFB solution.
- No additional external bunding, meaning any leak should be contained or appropriately solved through the controls implemented internal to the manufacturers package.

6.5.1 New Location – Blackall

For the location of Blackall, new controls are to be implemented in alignment with the intended direction of operation for future VRFB installations.

Table 6-13: Blackall - With New Controls

	Blackall – With Controls				
Risk	**Impact**	**Likelihood**	**Control**	**Risk**	**Score**
Cyclic operation	Minor	Unlikely	Maintenance schedule	Low Medium	4
Abnormal Temperature Event	Significant	Unlikely	Shade Sail, non-peak temperature discharge	Medium	6
Excessive Dust	Significant	Unlikely	Dust fencing, dust filter, Cleaning Schedule	Medium	6
Electrolyte Precipitation	Severe	Very Unlikely	Shade Sail, non-peak temperature discharge	Medium	6
Storms	Moderate	Unlikely	Shade Sail – Limited	Low Medium	5
UV Exposure	Negligible	Possible	Shade Sail – Limited	Low	4
Saltwater Proximity	Moderate	Very Unlikely	N/A	Low Medium	4
Humidity	Moderate	Unlikely	N/A	Low Medium	5
Rain	Moderate	Possible	Shade Sail – Limited	Medium	6
Vandalism	Significant	Very Unlikely	Dust fence with agreeable colour and appearance	Medium	5
Equipment Failure	Significant	Unlikely	Maintenance, Cleaning Schedule	Medium	6
Shock Impact	Moderate	Very Unlikely	Dust fence, local consultation	Low Medium	4
Impactful Electrolyte Leakage	Severe	Very Unlikely	Top Container Additional pump redundancy	Medium	6
				Total	**67**

Compared to the original controls assessment for the Blackall area which had a total risk score of 61, the new risk score is 67. This insinuated that more risk was present in the design which is mostly due to the lack of shed, air conditioning usage and dedicated external bund.

The lack of bunding systems led to a review of redundancy layers to achieve chemical leak prevention. It was identified that an extra redundancy to stop the operation of pumps was most suitable for this task to inhibit fluid leakage in the top container and subsequent leakage externally.

Other operational conditions were addressed through cheaper solutions such as:

- The shade sail for addressing direct UV exposure, storm impact reduction, rain reduction, and heat events leading to electrolyte precipitates forming due to heat.
- Temperature is also addressed on days with major heat events, where operation should not continue in the exothermic discharge manner and through shade sail usage.
- Dust, vandalism and subsequent shock impact are addressed by the inclusion of a dust fence which performs inhibition and prevention purposes. Further dust controls include the dust filter.
- Equipment failure, cyclic operation and excessive dust should all be addressed through a typical manufacturers maintenance schedule, as well as a form of a cleaning schedule focusing on dust ingress on moving parts.

6.5.2 New Location – Cairns

For the location of Cairns, new controls are to be implemented in alignment with the intended direction of operation for future VRFB installations.

Table 6-14: Cairns – With New Controls

	Cairns – With Controls				
Risk	**Impact**	**Likelihood**	**Control**	**Risk**	**Score**
Cyclic operation	Minor	Unlikely	Maintenance Schedules	Low Medium	4
Abnormal Temperature Event	Significant	Very Unlikely	Shade Sail	Medium	5
Excessive Dust	Significant	Very Unlikely	N/A	Medium	5
Electrolyte Precipitation	Severe	Very Unlikely	Shade Sail	Medium	6
Storms	Moderate	Possible	Shade Sail – Limited	Medium	6
UV Exposure	Negligible	Possible	Shade Sail	Low	4
Saltwater Proximity	Moderate	Possible	Protective Coatings and Maintenance Schedules	Medium	6
Humidity	Moderate	Possible	Protective Coatings and Maintenance Schedules, Desiccant Bags	Medium	6
Rain	Moderate	Unlikely	Shade Sail – Limited	Low Medium	5
Vandalism	Significant	Unlikely	Boundary Fence	Medium	6
Equipment Failure	Significant	Unlikely	Maintenance, Cleaning Schedules	Medium	6
Shock Impact	Moderate	Unlikely	Shade Sail – Limited, Boundary Fence	Low Medium	5
Impactful Electrolyte Leakage	Severe	Very Unlikely	Top Container Additional pump redundancy	Medium	6
				Total	**70**

Compared to the original assessment for the Cairns area which had a total risk score of 67, the new risk score is 70. This slightly higher risk is present mostly due to the lack of solid overhead protection, however, finds improvement in humidity through usage of desiccant bags.

Like Blackall, the lack of bunding systems led to a review of redundancy layers to achieve chemical leak prevention. It was identified that an extra redundancy to stop the operation of pumps was most suitable for this task to inhibit fluid leakage in the top container and subsequent leakage externally.

Other operational conditions were addressed through cheaper solutions such as:

- The shade sail which addressed direct UV exposure, storm impact reduction, rain reduction, and heat events leading to electrolyte precipitates forming due to heat.
- Temperature is also addressed on days with major heat events, where operation should not continue in the exothermic discharge manner and through shade sail usage.
- Humidity and SSA effects were dwindled through usage of protective coatings and calcium chloride desiccants.
- Vandalism and subsequent shock impact are countered through the inclusion of a boundary fence.
- Equipment failure, cyclic operation and humidity (corrosion) should all be addressed through a typical manufacturers maintenance schedule, as well as a form of maintenance schedule focused on reapplication of protective coatings and general cleaning.

6.6 Incomplete LCA Comparison

The initial scope of this segment was the inclusion of a comparative LCA analysis based on unique and varying locational conditions. It was to be based on two locations, with multiple variations investigated over the 20-year life expectancy including:

- Life cycle Assessment according to presumed controls implemented:
  - VRFB components with effects of maintenance over time but would find minimal replacement according to MTTF calculated previously.
  - Valuation of the controls implemented (e.g. Shed, dust fence, etc)
- Life cycle Assessment according to no controls implemented:
  - VRFB components with more required maintenance and replacements based on MTTF with reduced life.

Upon initial undertaking, it was identified that this was a thorough task that should only realistically be completed with access to more correct data through Energy Queensland or reliable databases. The accessible software provided a starting point, but the databases utilised were not up to date and it was concluded to not prove effective for a solution. Through this identification of not enough suitable information, the LCA was not undertaken. The settled outcome is from above, which was an in-depth review of controls and risk on a multi locational basis. This included an event tree analysis with some identification of significance of certain controls based on risk probability previously undertaken in stage 2.

Further research in this section for the LCA may consist of:

- Working with the manufacturer to either obtain an Environmental Product Declaration or assist in the development of one. Using this on a standard basis for the various Vanadium Redox Solutions would assist in the streamlining of environmental assessments for more in depth and effective communication.
- Completion of LCA is recommended for the development of a more thorough Environmental Controls Framework, it would allow sufficient means to evaluate controls usage.
- Considering the above points, it will be pertinent to either perform this LCA comparative analysis in one of two ways:
  - Through a heavily redacted Undergraduate/ Postgraduate student thesis in future years.
  - Through an internal document for internal usage only.

One of the most important points of undertaking a risk assessment is to have full appreciation for the context at hand. Regarding the effectiveness of environmental controls for Energy Queensland, more context is required to avoid making assumptions about the system that may point towards opposite outcomes than what would be achieved in a typical system.

6.7 Discussion

The controls identified here aimed for variance in approach, providing potential alternative solutions as well as the risks mitigated through their usage. Since the LCA alternative for this method proved difficult to correctly assess, it was thought that utilisation of an environmental risk matrix for the evaluation of risks and inherent reductions through controls was a next best solution.

The assessment of risks, relationships and reliability previously utilised helped towards the development of the matrices as was the goal of the stage one and two investigations. The main helpful terminology from stage one for the development of controls was the pairing of ‘battery’ and ‘systems’ which identified that the VRFB is not only made up of multiple systems, but each control assisted those systems in different ways. This approach of breaking down controls into different effects was helpful in finding both benefits and limitations. As can also be seen, the reliability assessment of stage two assisted with the qualitative event tree analysis development for logical outcomes based on separate major conditions.

Particularly from the first round of risk matrices, it was found that the various combinations of controls had to be implemented to complement one another, and not detract from other controls or conditions without due cause. Ultimately, planning processes of these projects will find that the capital expenditure will be a major issue that needs investigation before future implementation. An example of this was the implementation of an enclosed structure with dust filtration even when the VRFB has the capacity for dust filtration as an option. Using dust filters on the structure would reduce the effectiveness of the ventilation causing moisture buildup and higher internal temperature for the structure which was the issue the fans attempt to solve initially. This example explained how overcompensation can be a problem, causing issues in operation and financial outcomes.

Feedback from Energy Queensland highlighted some stages where considerations were not in alignment with what the VRFB package may be best suited for. The two-stage matrix assessment thus proved to be an important factor to evolve thinking for controls utilised in the field.

The second round of risk matrices proved to require more outside thinking of what types of controls should be implemented and their overall effectiveness in achieving that risk reduction. Too many different types of controls can also lead to complicated and unnecessary maintenance schedules if they don’t align with each other temporally.

7.0 FRAMEWORK DEVELOPMENT FOR RISK TREATMENT

The framework was developed to mainly assist business decision making through simplicity, and as such was required be designed in a way to reflect that concept. The framework in this section is aimed towards VRFB however with further development, it may be found that it supports solutions for other battery technologies.

Ultimately the main goal of the framework was to assist in the deciphering of locational conditions based on the effects of each condition on operation. Through the previous research stages, it needed to consider climatic, operational and legal considerations towards the development of a list of controls. Some controls are straightforward and inclusive of any site but thoroughness was found important for maintaining a consistent solution process for all sites.

7.1 Framework Structure

Whilst risk management processes as found already in ISO 31000 are relevant for the development of concepts behind the framework, the structure required for business implementation was found to be more reminiscent of concepts discussed in the COSO internal controls framework. The COSO framework utilises the principles as below to develop a business's internal controls system. There is applicability towards the development of other frameworks using these conceptual ideas. The literature review, Stage one and Stage two assessments performed an assessment of risks finalised during the event tree analysis. This is particularly reflective of objectives six and seven below.

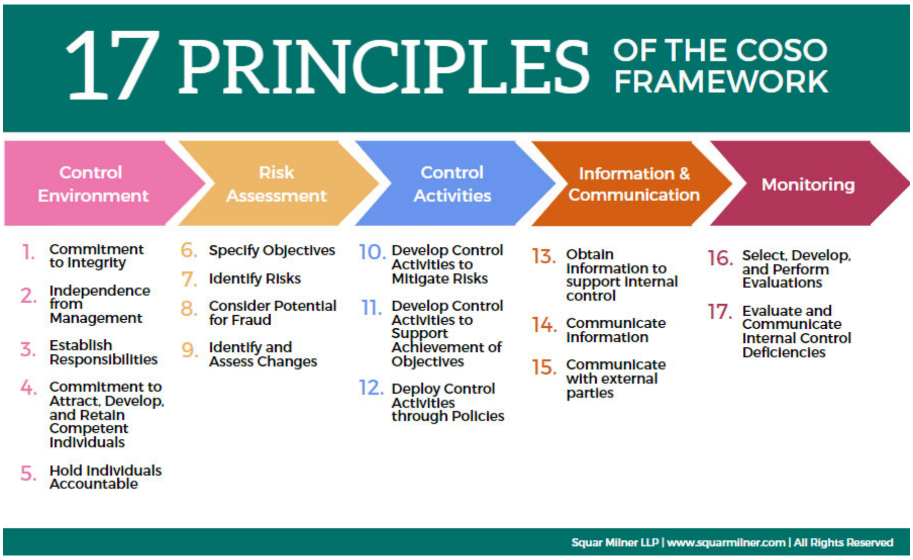


Figure 7-1: COSO Framework Principles (Committee of Sponsoring Organizations, 2013)

However, the main goals for the framework concept draft are to provide a control framework concept that achieves objectives ten, eleven and twelve whilst remaining simple ensuring that operational effectiveness is maximised. Further development of the framework will be necessary to ensure that business or risk management goals are achieved successfully and on a continuous basis. This will become more important as there are more projects and project types introduced into the environmental controls framework. Summarising the relevant objectives of the environmental controls framework:

- Objective 10 is 'Develop control Activities to mitigate risks' which was identified through developing a streamlined control selection process relevant to the project at hand.
- Objective 11 is 'Develop control activities to support achievement of objectives' which was found as best achieved using initial risk assessments of a unique installation and checking them against established business risk assessment procedures for the same project type. The risk assessment procedures consist of modified approaches to the risk assessment criteria utilised in stage three.
- Objective 12 is 'Develop Control Activities through Policies' was found to be the least addressed of the three through the development of the controls framework. Ideally, the implementation of the environmental controls framework as an internal business policy would support this cause, however additional work after this research would be necessary to achieve this principle.

The development of the controls framework was designed to address risk in a simple manner to reduce required work output through readily designed risk assessments and control contributions. Limitations identified that reduce the effectiveness of a controls system in some instances are (Owusu-Ansah, 2019):

- Unforeseen circumstances
- Human error
- Established control procedures are not followed (if deemed mandatory to follow)
- Other overriding processes

However, the implementation of set control procedures with flexibility can reduce the elements above that are present in other ways such as human error in judgement whilst performing risk assessments (Owusu-Ansah, 2019). Whilst considered a limitation, the overriding of set controls may be done so for the matter of implementing sound engineering thought for a successful, ethical and safe design. The environmental controls framework proposed here represents a small segment of the internal controls COSO framework, so for better understanding of complete procedures and optimisations then it is recommended to purchase the complete eBook if financial resources permit.

The assessment of all risks associated with the VRFB from the literature review, as well as stages one, two and three inform the approach for the framework. For the VRFB, it was deduced that the three major conditions associated with successful operation were those of climatic, operational and legal as seen through the diagram below.

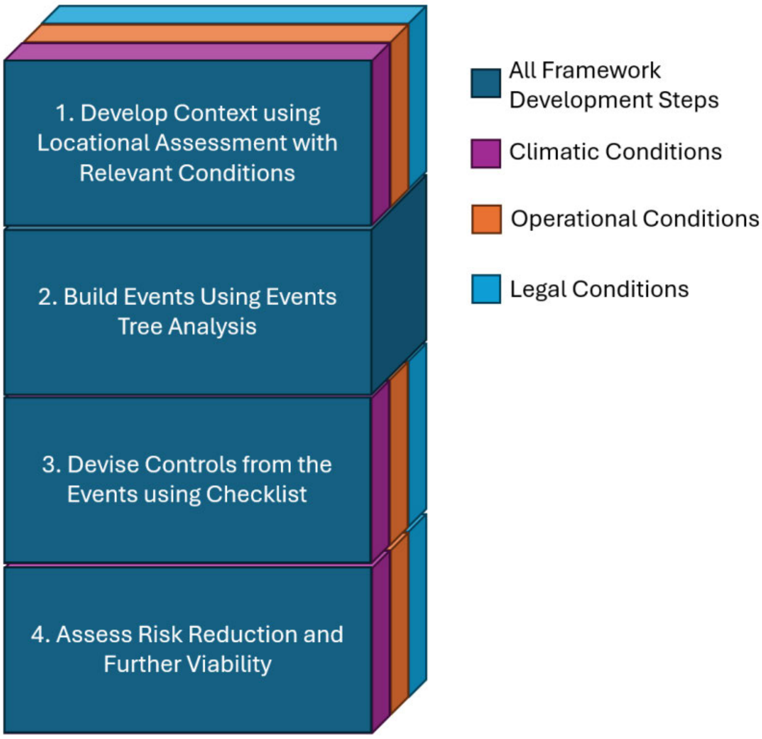


Figure 7-2: Controls Framework Layout

1. Step one includes the development of context for the project. This means performing a risk assessment of all potential conflicts as well as understanding the project at hand including climatic, operational as well as legal standpoints.
2. Step two is building events that could occur through operation. This helped develop the understanding of how one risk may cascade down to numerous other risks and should be mitigated at one point rather than another. This performed the outcome of identifying weak single failure points as well as multi-failure points.
3. Step three is the unique section for the project at hand which consists of a checklist for the project at hand which ensured that the risks involved with a project at a minimum are achieved and subsequent controls for the system are included. For the context of the VRFB, this constitutes the environmental, operational and legal considerations discussed in this thesis. See section 7.2 for a sample of basic mechanisms.
4. Step four constitutes further risk assessment for clarity of final risks and controls. This is undertaken after control selection to ensure that other preliminary discussions such as design and costings have been included in thought processes.

Further explanation of this framework sample is as below for the context of a VRFB which includes numerous relevant concepts covered in the development of risks and controls:

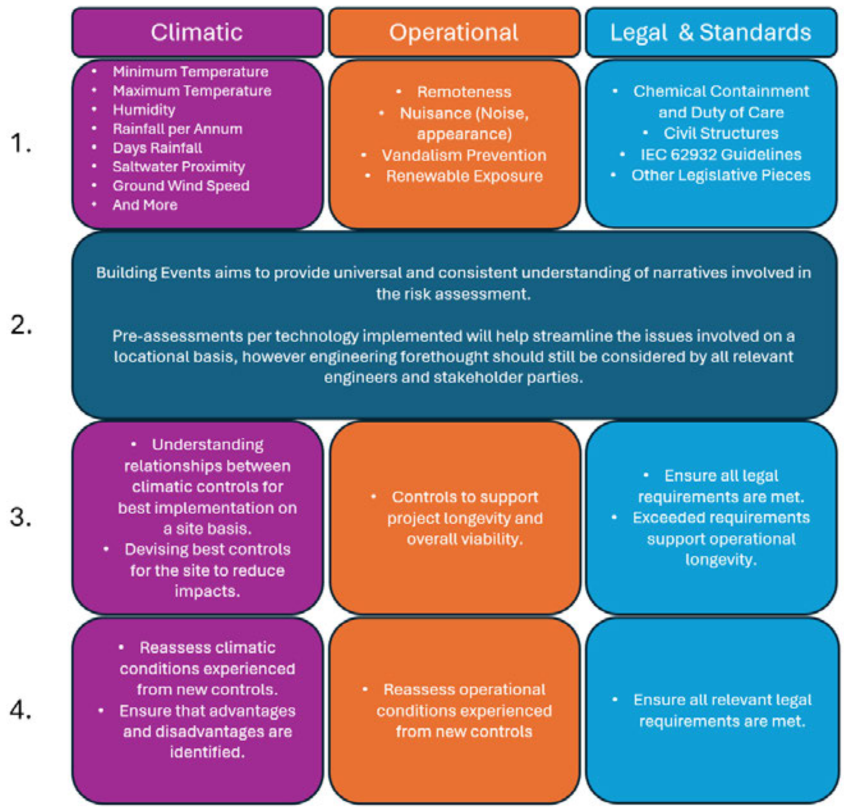


Figure 7-3: Controls Framework Layout Description (Step 1 - VRFB Project)

The main benefits achieved for following these steps is that the user has:

- Addressed all concerns for the operation of a VRFB.
- Deduced a best-case scenario to control its operation and promote reliability for environmental impact reduction.
- Assessed these scenarios for viability and impact reduction.

And from the basis of designing the framework, it has:

- Ensured that the framework is easily explained and replicable from a business perspective.
- Provided the option to maintain accurate and convey useful information for business implementation.

7.2 VRFB Checklist

Steps one, two and four are separately undertaken by the user. Steps one and two both consider risk assessment and contextual building in a global scale which is an idea that should be undertaken for any new installation of any technology. Step four concludes with re-evaluation and other measures of viability including financial limitations. These components are thus more reliant on the engineering knowledge and processes undertaken by a risk management team. Step three however, should use a standardised checklist that calculates risk, implements controls and re-evaluates the residual risk.

7.2.1 Checklist Development

Step three develops a checklist system for unique project scenarios whilst remaining simple. There are multiple benefits for choosing this approach:

- Including an initial risk assessment and cross checking against a developed risk and controls checklist ensured thoroughness.
- Utilising an existing internal document for the development of controls using relevant risks helped streamline the controls process while ensuring a multitude of considerations have been made.
- For problem solving, human behaviour inherently follows a ‘problem, solution, outcomes’ approach. Utilising a checklist that follows this behaviour will ensure simplicity is reached. Since the final solution was a simple checklist, it can be utilised with numerous software including basic entries such as excel, or other programs that can create automated digital workflows.

7.2.2 Checklist Sample

Elements of the checklist includes elements that have been included such as the implementation of:

- Risk Impacts
- Risk Controls
- Risk Residuals

The utilisation of these is found to form the basis of risk management which has been informed by the work so far in the project.

7.2.2.1 Matrix Logic

The checklist utilises system conditions and conditional formatting to visually represent risks involved with the impact, as well as selection of certain controls to perform risk reduction. This risk reduction thus aims to present a final risk outcome that is reflective of the risk matrices above.

The first step is the declaration of matrix weighting, which mimics that which was established in stage three of this report.

	Risk By Value				
	Negligible	Minor	Moderate	Significant	Severe
Very Likely	5	6	7	8	9
Likely	4	5	6	7	8
Possible	3	4	5	6	7
Unlikely	2	3	4	5	6
Very Unlikely	1	2	3	4	5

	Risk By Category				
	Negligible	Minor	Moderate	Significant	Severe
Very Likely	Low Medium	Medium	Medium High	High	High
Likely	Low	Low Medium	Medium	Medium High	High
Possible	Low	Low Medium	Medium	Medium High	Medium High
Unlikely	Low	Low Medium	Low Medium	Medium	Medium High
Very Unlikely	Low	Low	Low Medium	Medium	Medium

Figure 7-4: Risk Matrices used for checklist Development

7.2.2.2 Site Conditions

Next was found to be the determination of a risk outcome based on site conditions, where varying the conditions based on a drop box will cause the likelihood of occurrence to fluctuate dependent on the selection made. An example is found below for the cases of two temperature events:

- 'Unlikely' for conditions of over 40°C for less than 10 days per year
- 'Possible' for conditions of over 40°C for more than 10 days per year
- The 10 days per year was identified by the site conditions explored through stage three of this research.

Risk Description	Impact	Site Conditions	Likelihood
Minimal Maintenance Cyclic operation	Minor		
Atypical Temperature Event	Significant	Over 40°C, more than 10 days per year	Possible
Excessive Dust	Significant		
Electrolyte Precipitation	Severe		
Storms	Moderate		
UV Exposure	Minor		
Saltwater Proximity	Moderate		
Equipment Failure	Significant		
Humidity	Moderate		
Rain	Moderate		
Vandalism	Significant		
Shock Impact	Moderate		
Harmful Electrolyte Leakage	Severe		

Maximum between 10°C and 40°C
Over 40°C, less than 10 days per year
Over 40°C, more than 10 days per year
Under 10°C, less than 10 days per year
Under 10°C, more than 10 days per year

Risk Description	Impact	Site Conditions	Likelihood
Minimal Maintenance Cyclic operation	Minor		
Atypical Temperature Event	Significant	Maximum between 10°C and 40°C	Very Unlikely
Excessive Dust	Significant		
Electrolyte Precipitation	Severe		
Storms	Moderate		
UV Exposure	Minor		
Saltwater Proximity	Moderate		
Equipment Failure	Significant		
Humidity	Moderate		
Rain	Moderate		
Vandalism	Significant		
Shock Impact	Moderate		
Harmful Electrolyte Leakage	Severe		

Maximum between 10°C and 40°C
Over 40°C, less than 10 days per year
Over 40°C, more than 10 days per year
Under 10°C, less than 10 days per year
Under 10°C, more than 10 days per year

Figure 7-5: Temperature Site Conditions Comparison

The determination of the Likelihood and the Impact previously identified through Stage two work meant that the total risk is thus able to be calculated for the same example of 'Over 40°C, more than 10 days per year'.

VRFB Controls Checklist Draft

Risk Description	Impact	Likelihood	Total Risk
Minimal Maintenance Cyclic operation	Minor		
Atypical Temperature Event	Significant	Possible	Medium High
Excessive Dust	Significant		
Electrolyte Precipitation	Severe		
Storms	Moderate		
UV Exposure	Minor		
Saltwater Proximity	Moderate		
Equipment Failure	Significant		
Humidity	Moderate		
Rain	Moderate		
Vandalism	Significant		
Shock Impact	Moderate		
Harmful Electrolyte Leakage	Severe		

Figure 7-6: Total Risk from location conditions

The benefit of presenting the risk here allows the understanding that risk reduction needs to be undertaken to achieve a maximum of a 'medium' risk.

7.2.2.3 Controls Reduction

The Total risk is then reduced through the decision process of selecting certain controls that are included. They are included as the team who has deduced the final controls for a technology has included them for the case of risk reduction.

The controls act both as a suggestion for implementation as well as a tool to determine the outputs of risk assessments.

VRFB Controls Checklist Draft

Risk Description	Impact	Impact Risk	Likelihood	Total Risk	Controls Implemented?	Residual Likelihood Risk
Minimal Maintenance Cyclic operation	Minor	2				
Atypical Temperature Event	Significant	4	Possible	Medium High	No Control	Possible
Excessive Dust	Significant	4				
Electrolyte Precipitation	Severe	5				
Storms	Moderate	3				
UV Exposure	Minor	2				
Saltwater Proximity	Moderate	3				
Equipment Failure	Significant	4				
Humidity	Moderate	3				
Rain	Moderate	3				
Vandalism	Significant	4				
Shock Impact	Moderate	3				
Harmful Electrolyte Leakage	Severe	5				

Sealed Shed with Ventilation
Shade Sail, Charge at peak
No Control

VRFB Controls Checklist Draft

Risk Description	Impact	Impact Risk	Likelihood	Total Risk	Controls Implemented?	Residual Likelihood Risk
Minimal Maintenance Cyclic operation	Minor	2				
Atypical Temperature Event	Significant	4	Possible	Medium High	Shade Sail, Charge at peak	Unlikely
Excessive Dust	Significant	4				
Electrolyte Precipitation	Severe	5				
Storms	Moderate	3				
UV Exposure	Minor	2				
Saltwater Proximity	Moderate	3				
Equipment Failure	Significant	4				
Humidity	Moderate	3				
Rain	Moderate	3				
Vandalism	Significant	4				
Shock Impact	Moderate	3				
Harmful Electrolyte Leakage	Severe	5				

Sealed Shed with Ventilation
Shade Sail, Charge at peak
No Control

Figure 7-7: Controls Reduction Comparison

Finally, the Controls reduction can be presented in the final risk outcome, with the example below utilising the relevant elements of:

- Initial Risk: Atypical Temperature Event
- Risk Impact: Significant
- Site Conditions: 'Over 40°C, more than 10 days per year'
- Risk before Reduction: Medium High
- Controls: 'Shade Sail, Charge at peak temperature'
- Final Risk Outcome: Medium

VRFB Controls Checklist Draft

Risk Description	Impact	Residual Likelihood Risk	Final Risk Outcome
Minimal Maintenance Cyclic operation	Minor		
Atypical Temperature Event	Significant	Unlikely	Medium
Excessive Dust	Significant		
Electrolyte Precipitation	Severe		
Storms	Moderate		
UV Exposure	Minor		
Saltwater Proximity	Moderate		
Equipment Failure	Significant		
Humidity	Moderate		
Rain	Moderate		
Vandalism	Significant		
Shock Impact	Moderate		
Harmful Electrolyte Leakage	Severe		

Figure 7-8: Risk Reduction Outcome

Since the design has been determined as a medium risk then the use of the control is suitable for business integration.

7.2.2.4 Final Design Outlook and Further Work

All elements explored above are tied together and thus the final checklist draft was achieved. The design approach aimed to implement elements that present risk and offer a solution to achieve risk reduction. Whilst a basic tool, it can form the basis for other projects with similar risks if combined with the rest of the environmental controls framework above.

It should be noted that it was not designed to replace Engineering thought processes and due cause but rather supplement risk management through the controls framework devised above.

The below figure represents the overall outlook of how the excel spreadsheet is set up for clarity purposes. Numerical risk categories are hidden and are associated with the risk matrices explored above.

VRFB Controls Checklist Draft

Completion	Risk Description	Impact	Impact Risk	Site Conditions	Likelihood	Total Risk	Controls Implemented?	Residual Likelihood Risk	Final Risk Outcome
	Minimal Maintenance Cyclic operation	Minor	2						
Completed	Atypical Temperature Event	Significant	4	Over 40°C, more than 10 days per year	Possible	Medium High	Shade Sail, Charge at peak	Unlikely	Medium
	Excessive Dust	Significant	4						
	Electrolyte Precipitation	Severe	5						
	Storms	Moderate	3						
	UV Exposure	Minor	2						
	Saltwater Proximity	Moderate	3						
	Equipment Failure	Significant	4						
	Humidity	Moderate	3						
	Rain	Moderate	3						
	Vandalism	Significant	4						
	Shock Impact	Moderate	3						
	Harmful Electrolyte Leakage	Severe	5						
Typical Standards for Operation									
UL 1973									
:C 62932-1:2020									
:C 62932-1:2020									

Figure 7-9: Final Outlook for the Controls Checklist Draft

Further work would be the implementation of various standards that incorporate the elements of remediation for each type of risk. For example, this could include the utilisation of standard IEC 60529 which forms the basis for Ingress Protection. Ingress protection would be found particularly in the rain, humidity and dust-based risks as remedial measures there are applicable towards achieving a higher IP rating.

Further work before business implementation would be the determination of likelihoods through team-based assessments of risk outcomes, current risk conditions reflect those determined through the stage three process and may not effectively align with the thoughts that could extend from team-based conclusions.

8.0 CONCLUSIONS

8.1 Final Findings and Discussions

Effective project implementation can be affected by numerous impacts, and for the context of the VRFB, they can suffer from a limited exposure to practical operational systems. The operating conditions have been found to have a major effect on the reliability of the system, which ultimately has the potential for major environmental harm through electrolyte leakage. To this end, the risk management was performed to find a balance of operating cost through risk controls whilst ensuring that risk reduction is achieved to a satisfactory degree. The most important aspect to tie the risk outcomes together, was the application of risk matrices and satisfactory controls through the industry supervisor. The general direction of risk reduction controls was identified to be of a minimalistic approach to achieve cost reduction whilst ensuring adequate risk reduction was achieved. Thus, the three original project aims can be reiterated:

- **Are all operating behaviours and impacts of the Vanadium Redox Flow Batteries known?**

  Through Risk identification of relevant existing literature and the establishment of a systematic process of quantitative analysis, there were minimal high impact new relationships between terms that could be identified. It can be concluded that technology is established from a research perspective, however, lacks knowledge of in-field implementation.
- **What is the significance of these impacts towards operation?**

  The risk analysis and evaluation portions assisted in the understanding the magnitude of these impacts, particularly from an equipment reliability perspective from variance in environmental conditions. Just as important is the understanding achieved through operational conditions such as chemical containment and limitations set by financial and legal means. By assessing the battery from the perspectives of 'impacts from the environment' and 'impacts to the environment', it can be concluded that the assessment of impacts and potential controls has been thoroughly undertaken.
- **How can these impacts be controlled to best inform business decisions?**

  The risk evaluation section and the treatment sections provided the best investigation as to how this outlook can be visualised. It has been understood that elements in risk management approached here are not final and any further implementation would likely face alterations, or adjustments to evaluation processes. A potential business application was achieved that was designed for simplicity and scalability.

8.2 Further Work and Final Comments

However, further work is needed to effectively how these impacts are conveyed for the business perspective. One potential solution to this has been mentioned which the development of a Life Cycle Assessment solution internal to EQL to ensure equipment acquisition is correctly considered. By utilising this solution and knowledge of operational characteristics explored in this report, environmental impact can be more easily understood without the need for further reliability investigations.

The identification of risks was performed through a vast literature review from many sources which is since standard Flow Battery implementation is not an established literature piece. The further development of the technology will flourish with a set approach for the integration of the Flow battery technology. Whilst elements of the environmental controls framework worked on in this thesis do establish safety in operation, consistency is also needed on a national scale. This would mean at the bare minimum, the formal adaptation of a single standard that clarifies installation requirements. At the very least, this standard would consist of information derived from a flow battery international standard such as IEC 62932:2020 which outlines operating requirements. It would also consider the establishment of minimum safety requirements towards the development and operation of these installations. This may utilise elements considered within the framework developed here, however clear minimum requirements for installation will help harmonisation between the manufacturers and Australia's operating contexts. To that end, the work that has come out of this thesis is steps towards:

- Further clarity on the framework for business implementation based on supplementing existing internal business procedures. This refers mostly to the risk management procedures.
- The determination of a set series of controls that reduce the risk incurred from environmental impacts relevant to the Queensland context. Evidently this may also have applicability for other locations, however locational assessment for these installations is paramount. This will help engage risk management processes for chemical related projects at the very minimum.

The research undertaken captured a broad scope at environmental risk management processes for the Vanadium Redox Flow battery, supporting integration at Distribution and Transmission scale installation solutions whilst promoting future research in risk control alternatives.

APPENDICES

Appendix A: UniSQ Risk Assessment Register

5585	RISK DESCRIPTION	STATUS	TREND	CURRENT	RESIDUAL
	ENP4111 Thesis Risk Assessment	Awaiting Approval		Low	Very Low

RISK OWNER	RISK IDENTIFIED ON	LAST REVIEWED ON	NEXT SCHEDULED REVIEW
Luke Brandt	26/08/2024	29/08/2024	29/08/2025

RISK FACTOR(S)	EXISTING CONTROL(S)	CURRENT	PROPOSED CONTROL(S)	TREATMENT OWNER	DUE DATE	RESIDUAL
Work Station setup, including chair comfortability, monitor height causing eye strain	Control: Frequent breaks and stretching, as well as adjusted equipment to match body preference.	Low	Swapped an old non-ergonomic chair for one that provides support, allowing easier and more comfortable work		26/08/2024	Very Low
Site visit to VRFB; a safe building with development in final stages, has walkways with completed and adequate hand rails. No toxic electrolyte on site, controlled personnel access only. Brief walk across approximately 5 meters for vehicle and pedestrian interaction.	Control: Ensuring follow in house risk management and hazard plan assessed by EQL site supervisor. Ensure following directions of the personnel in charge and taking care of surroundings to ensure no injuries when in depot confines.	Very Low	No Control:			Very Low

Appendix B: Literature Jupyter Notebook Code

```
correl = df2.corr()
arr = correl.to_numpy()
counti = 0
indexlist = []
for i in arr:
  counti+=1
  countj = 0
  for j in i:
    countj +=1
    if j > 0.8:
      if counti !=countj:
        #print(counti)
        #print(countj)
        #print(j)
        indexlist.append([counti, countj, round(j,2)])
      #countj +=1
  #counti+=1

######Dissertation Table
#data = np.array(indexlist)
#shape = [len(indexlist),3]
#freq1 = data.reshape(shape)
#pd.DataFrame(freq1, columns = ['x','y','value'])
#At this point Top_Freq_List contains the 100 most frequented words and their frequencies that can be used later to create instances of usage.
"""
This section of code performs file conversion from .pdf to .txt


It utilises the functions involved in 'PyPDF2' library
"""
```

```
pdf_folder = r"C:\Users\Luke\Documents\BENH\ENP4111\BibLitAnalysisCode\PDFFiles"
txt_folder = r"C:\Users\Luke\Documents\BENH\ENP4111\BibLitAnalysisCode\OriginalTextFiles"
i = 0
for fle in os.listdir(pdf_folder): #For each file in the folder
    print(fle) #Print File name / path
    if __name__ == "__main__":
      with open(pdf_folder + '//'+ fle, 'rb') as pdf_file: #Open pdf file
        pdf_reader = PyPDF2.PdfReader(pdf_file) #Read Pdf File
        text = '' # Initialize an empty string to store the text

        for page_num in range(len(pdf_reader.pages)): # For each page
          page = pdf_reader.pages[page_num] # Read the page
          text += page.extract_text() #Extract text from the page


      # Write the extracted text to a text file
      with open(txt_folder + '//' + str(i), 'w',encoding = 'utf-8') as txt_file: #For each file read
        txt_file.write(text) #Write the text to a .txt file and Encode

      print("Conversion Complete!")
```

""""

Main code for the determination of literature cleaning and frequency counts.

This includes filtering for digits, stop words, word length in order to develop a 100 most frequented words list

Some potential issues in consideration is issues encountered in pre-processing through the file encoding phases. This

has resulted in some issues as evident by the term 'ï¬ow' being present in frequented terms however no visibly incorrect

characters present in the source .txt files. This alludes to an encoding problem when bringing in the code.

"""

nonincludes = ['can','may','ee','ï¬ow','al','et','table','figure','fig','results','also','kg','data','due','therefore',

'two','gwp','one','two','etâ','kwh','however','use','used','however','using','found','will','well','based','considered',

'respectively','values','groundwater','amf','dhe']

#This list was developed and adjusted according to review of results, ensuring irrelevant or nonhelpful terms were removed.

#It can be noted that due to the file processing step, some encoding errors have been recognised that could skew performance

word_count = {} #Develop, initialise empty word count dictionary to store words and frequencies

Top_Freq_List =[] #List for storing the top frequented words in

filepath = r"C:\Users\Luke\Documents\BENH\ENP4111\BibLitAnalysisCode\New Files"

file_freqcount = 0 #Initialise file count

for fle in sorted(os.listdir(filepath)): #For each file in the file path

with open(filepath+'//'+fle,'r',encoding = 'unicode_escape') as curr_file:

#print(curr_file)

```
      sorted_words1=[]
      for rows in curr_file: # For each in row in the current file
        rows = rem_punc(rows) #Remove punctuation from the row
        words = rows.split() #Split the row into words
        for word in words: #For each word in the words list
          word = word.lower() #Convert words to lower format for consistency
          if any(letters.isdigit() for letters in word):
            continue #If any of the characters in a string are digit then remove from suggestion
          if word in get_stop_words('english') or word in nonincludes:
            continue #If any stop words or other identified non-inclusive words.
          if len(word) == 1: #If the length of the term is equal to 1
            continue
          freq_count(word)#Frequency count function for words

  file_freqcount += 1 #File frequency count used later for list building based on number of files brought in.

#From this point is to calculate total frequency of words over all files
sorted_words_total = []
for index in word_count: #For each instance in the word_count iteration, append to the sorted words list
  sorted_words_total.append((word_count[index],index))
  sorted_words_total = (sorted(sorted_words_total))[::-1] #And then sort the words from largest value to smallest

# At this point, sorted words contains the ALL word frequencies from ALL literature pieces
# To get 100 most popular, bring out 100 instances of word of the list
Freqs = [] #List for dissertation table

i =0
for sep_freq in sorted_words_total: # for instance in the sorted_wods
  while i <100: #For the hundred most popular words
```

```
        [count, word] = sep_freq #separate into numerical and term variables
        #print("{0:15}{1:3}".format(word, count)) #Visible testing
        Top_Freq_List.append(word) #Word Frequency list
        sep_freq2 = [word,count, colcount[i]] #Used to build a table in the dissertation file for easier viewing
        Freqs.append(sep_freq2) # Same as above
        i+=1
        break
#print(Top_Freq_List)
 ######Dissertation Table
data = np.array(Freqs)
shape = [25,12]
freq1 = data.reshape(shape)
pd.DataFrame(freq1, columns = ['Word', 'Frequency', 'Distribution','Word', 'Frequency','Distribution','Word', 'Frequency', 'Distribution','Word','Frequency', 'Distribution'])
#At this point Top_Freq_List contains the 100 most frequented words and their frequencies that can be used later to create instances of usage.


finalwordlist=[]
filepath = r"C:\Users\Luke\Documents\BENH\ENP4111\BibLitAnalysisCode\New Files"
for fle in sorted(os.listdir(filepath)):
    with open(filepath+'//'+fle,'r',encoding = 'unicode_escape') as curr_file:
        #print(curr_file)
        word_count = {} #Reset dictionary each iteration
        sorted_words = [] #
        for rows in curr_file:
            rows = rem_punc(rows)
            words = rows.split()
            # print(words)
            for word in words:
                #print(word)
                word = word.lower() #Convert words to lower format for consistency
                if any(letters.isdigit() for letters in word):
                    continue #If any of the characters in a string are digit then remove from suggestion
```

```
        if word in get_stop_words('english') or word in nonincludes:
            continue
        if len(word) == 1:
            continue
        freq_count(word)#Frequency count function for words
    for index in word_count: #For each instance of word conut
        sorted_words.append((word_count[index],index)) # Append to a list to sort
        sorted_words = (sorted(sorted_words))[::-1]  #Sort from largest value to smallest
  finalwordlist.append(sorted_words) #Append the sorted words to the final list after each file
iteration


"""
Code provides list for development and arrangement for the top 100 terms and their frequencies
for each file.


It compares the 100 most frequent list entries compared to all entries and for each file, appends
the count for
each of the most 100 frequent words only.
"""
zerolist = [0] * 100 #Used to build a list with same dimensions as the final word list
listlength = list(zip(Top_Freq_List, file_freqcount*zerolist)) #Same dimension list ensures sorted
words are applied the correct value
a=[]


for j in listlength: #For all instances in listlength
  #print(j)
  [word1, count1] = j #Split up values in each instance of list length to derive word and count
separately
  for i in finalwordlist: #For each file instance in the list (list inside list)
    for k in i: #for each word in each file
      #count = 0
      [count,word] = k #Derive its word and respective count
      if word == word1: #If the word from the 100 frequency list and the current entry are the same
        count1 = count #Make the count for this instance equivalent
```

```
    a.append(count1)  #Append the count variable value to the list

    count1 = 0 #The count variable for set to zero and stays at zero until a matching word was found in the list


data = np.array(a) #Turn the list into a numpy array object

shape = [100,1*file_freqcount] #Reshape according to 100 most frequent words adn the amount of files. Stays dynamic

ab = data.reshape(shape) #Reshape the data array according to the

#print(ab)

ab=np.transpose(ab) #Transpose the data, puts each word as a column and file count as a row.



"""

The conversion of data to use in a word cloud presentation format



Utilises array conversion, dictionary building and word cloud generation utilising the dictionary frequencies

Finally the Word Cloud is plotted and visualled

"""

Top_100_Array = np.array(sorted_words_total) #Convert data to a numpy array

Top_100_Shape = [len(sorted_words_total),2] #Reshape for name and frequency

Top100_WC = Top_100_Array.reshape(Top_100_Shape) #Reshaped data



dict_WC = {}



for i in Top100_WC: #For each entry in the array

  [count,word] = i #Assign variables to the word and count

  dict_WC[word] = float(count) #Add the count to the dictionary with the word
```

```
wordcloud = WordCloud(max_font_size=50, max_words=100, background_color="white").generate_from_frequencies(frequencies=dict_WC)
    #Generate a WordCloud by counting the frequency of the word in the dictionary
plt.figure() #Plot options
plt.imshow(wordcloud, interpolation="bilinear")
plt.axis("off")
plt.show()
"""
Conversion of data to a dataframe for use in tools below.
As the code is below, the non-commented dataframe code visualises the output on a per word format.
The first chunk of commented out code represents the transposed list which visualises the output in a per file format.
This is done in separate manner as on per file format as it is a computationally intensive process, and thus outputs
needed to be separated.
"""
df1 = pd.DataFrame(ab, columns = Top_Freq_List) #Create a dataframe from the numpy array
df2 = df1.T #Transpose the values in the dataframe dependent on word or file basis


# df1 = pd.DataFrame(ab,columns = Top_Freq_List) #Create a dataframe from the numpy array
# df2 = df1.T #Transpose the values in the dataframe dependent on word or file basis
colcount = np.count_nonzero(df2, axis=0)  #Used to calculate the top 100 frequency file variance count, to be used in earlier code ^^
```

```
"""

This is the calculation of adequacy using the Bartletts test for sphericity.

Notes:

The chi Square statistic was found using a matrix determinant, meaning with a determinant of 0, the statistic will tend to infinity (log of 0)

This also affects the p value

"""

chi_sq,p_sq = calculate_bartlett_sphericity(df2) #Chi2 calc, p calc

chi_sq,p_sq

"""

This section of code reflects the correlation matrix for either a per-file or per-file input

"""

ticklist = list(range(1,25))

print(ticklist)

f = plt.figure(figsize=(17, 15))

plt.matshow(df2.corr(), fignum=f.number,cmap = 'viridis')

plt.xticks(range(0, 24),ticklist,fontsize=7.5, rotation=90)

plt.yticks(range(0,24),ticklist,fontsize=7.5)

#plt.xticks(range(df2.select_dtypes(['number']).shape[1]), df2.select_dtypes(['number']).columns, fontsize=7.5, rotation=90)

#plt.yticks(range(df2.select_dtypes(['number']).shape[1]), df2.select_dtypes(['number']).columns, fontsize=7.5)

cb = plt.colorbar()

#cb.ax.tick_params(labelsize=14)
```

```
plt.title('Correlation Matrix - Per File', fontsize=16);


"""

HCA mapping that includes all words from the investigation. Highlights all cluster as most important at 5 ward lengths away from eachother.

This implies some significance to their relationship.

Other instance is all files from the investigation.

Changed using the transposed dataframe section.

"""

linked = linkage(df2.corr(), method = 'ward', metric = 'euclidean') #Measuring linkage distance using euclidean method

np.shape(linked)

plt.rcParams["figure.figsize"] = (8.3,11.7)  #Change plot size to suit A4 sheet

abc = dendrogram(linked, #Setting up dendrogram)

        orientation = 'right',

        distance_sort ='descending',

        leaf_font_size= 8,

        color_threshold=2,

        show_leaf_counts = True,

        labels=ticklist)

plt.xlabel('Wards Distance') #plotting with axis labels etc.

plt.ylabel('Files')

plt.title('HCA - Per File',fontsize=16)

plt.grid(which = 'major',axis = 'x')
```

Appendix C

Table 0-1: Hazard and Precautionary Codes for Vanadium Electrolyte

Hazard Classification Code	Prevention	Response	Storage	Disposal
H290	P234	P390	P406	-
H302	P264 P270	P301+P317 P330	-	P501
H314	P260 P264 P280	P301+P330+P331 P302+P361+P354 P363 P304+P340 P316 P321 P305+P354+P338	P405	P501
H318	P264+P265 P280	P305+P354+P338 P317	-	-
H335	P261 P271	P304+P340 P319	P403+P233 P405	P501
H361	P203 P280	P318	P405	P501
H370	P260 P264 P270	P308+P316 P321	P405	P501
H372	P260 P264 P270	P319	-	P501
H400	P273	P391	-	P501
H402	P273	-	-	P501
H410	P273	P391	-	P501
H412	P273	-	-	P501

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