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MASTER IN ENVIRONMENTAL ENGINEERING AND SUSTAINABLE ENERGY

Modeling and Simulation Analysis of Flow Battery for Microgrid Applications

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Dedication

This thesis is dedicated to the memory of my beloved grandmother, Fatima Bushnak, may God have mercy on her, who passed away before I start my master's studies. I had promised my grandmother to achieve this academic goal and I hope that I have fulfilled that promise.

Acknowledgment

This work would not have been possible without the help and support of many people. Many thanks to my supervisor Prof, Marc Maric, who supported me, guided me, and had numerous meetings with me. Also many thanks to Carlos Olalla, Dieter Boer, Joan Salvado Rovira, Luis Francisco Garvi, and all URV professors who helped me to establish a deep knowledge in renewable energy technologies. And special thanks to the coordinator of the master department, Prof Sandra Contreras Iglesias, whose support was generous and offered me many chances to succeed.

Lastly, my family deserves endless gratitude, special appreciation to my mother for keeping me motivated and confident. My Deepest thanks to my aunts who believed in me. Because of them, my accomplishments and success wouldn’t happen.

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Nomenclature

AC	Alternating Current
CSP	Concentrated Solar Power
DC	Direct Current
DMA	dimethylacetamide
DoD	Depth of Discharge
ESS	Energy Storage System
EV	Electric Vehicle
Hz	Hertz
kWh	Kilo Watt hour
LCOE	Levelized Cost of Energy
LI	Lithium
MWh	Mega Watt hour
ORFB	Organic redox flow battery
PV	Photovoltaic
RES	Renewable Energy Source
RFB	Redox Flow Battery
SoC	State of Charge
VRFB	Vanadium Redox Flow Battery
Wh	Watt-hour

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Summary

The need for energy demand of human society is progressively growing and is expected to continue increasing for the coming decades. Using fossil fuels in power generation made impacts that raised environmental concerns. Consequently, integrating renewable sources of energy is rising in the modern electric grid which has lowered emissions, new improvements in producing technologies of solar panels and wind turbines made them cheaper and more efficient which helped in boosting their usage instead of the polluting power plants. However, wind and solar sources of energy suffer from intermittency which makes their power generation unreliable and unpredictable. Therefore, energy storage systems are necessarily required to add stability and resilience to the grid that has its power generation from intermittent renewable energy sources. This thesis will focus on redox flow battery as an energy storage solution that is cheap, long-living, and sustainable. The flow battery is continuously improved by scientists until it reached a stage that can compete against Lithium battery which is at the top of modern battery technology. These enhancements in flow battery designs lowered the production costs that reached as low as $200 per kWh, because of using common earth-abundant materials such as Iron, Zinc, and salts. With the aid of computer simulation, this work will evaluate the integration of flow batteries in a micro-grid, and study the performance of three well-developed types of flow batteries. The simulation analysis shows that all flow batteries had a life cycle of more than 20 years, while Lithium batteries although were the most expensive, they had less than 6 years of the life cycle. Finally, integrating the Iron flow battery with wind and solar energies had successfully lowered the usage of generators for an islanded microgrid to less than a 4% fraction of generation with a cost of energy as low as 0.21 $/kWh.

1. Introduction/Background

In order to achieve a great usage of renewable energy sources (RSS), energy storage systems (ESS) are essentially required to make the grid more stable and reliable. This happens when the excess electricity being generated by RSS is stored, and when the electrical generation is too low or when the load is too high, the stored energy in ESS is dispatched filling any energy shortages. Some RSS suffers from intermittency by nature, an intermittent source of energy means that one or more circumstances can affect the stability of the power supply. Electricity generated from photovoltaic (PV) modules may fluctuate a lot in power delivery if the day is cloudy. In this case, ESS can be one of the solutions to fix the fluctuations by storing energy when the sun was shining, and dispatching the stored energy when a cloud passes by. This way, the PV systems become more reliable. Wind turbines also suffer from the same issue, a steady windless day can stop wind turbine's electrical generations completely, leading to shortages which can affect the stability of the grid. Again, ESS fills the energy gaps by dispatching the stored energy generated from wind turbines when the wind velocity was high enough to generate electricity.

Peak shaving is another advantage of implementing ESS, during times of high electrical demands the utility price is usually high which can make it difficult for industries that depend on electricity which can cause a low profit. ESS can charge during lower electricity rates when the demand is low, and discharges when the electricity prices are at their most avoiding peak prices. This way industrial operations can proceed without cutting profits.

Usually in most grids, alternating current (AC) is used instead of direct current (DC) in power lines because of the capability of converting voltage levels with simple transformers, this will make electrical power transportation much easier across big distances. One of the important AC properties is the frequency, frequency measured in hertz (Hz) is defined as the number of wave cycles per second. In Europe, frequency is 50 Hz, while North-American countries are 60 Hz. A stable grid should always maintain a constant frequency to avoid electrical damages, especially when frequency drops which can lead to a severe failure to most devices attached to the grid. When the load is low and the power generation is high, this can lead to a substantial increase in the frequency. For example, if a sunny day comes with low demand, PV modules will generate maximum power making the frequency increase. In contrast, the frequency drops if the load is high and the power generation is low which can create many problems with the stability of the grid. In this scenario, ESS plays an important role in maintaining a constant frequency by storing the excess generated electricity lowering the frequency if it is high, or releasing energy when the frequency drops making it stable again.

1.1. Microgrid System

A microgrid is defined as a group of electrical sources and loads that can be either connected to the city's interconnected grid or work in island mode and function autonomously. Power sources can be from renewable sources such as wind, solar, etc., or can be from non-renewables such as generators that use fossil fuels. The load could be residential, commercial, or industrial as shown in figure 1.1. The microgrid has many advantages such as the security of electricity supply in case of any failure to the main grid. Moreover, it can be more efficient because the power sources are close to the load which cut the power loss when transmitting energy to long distances.

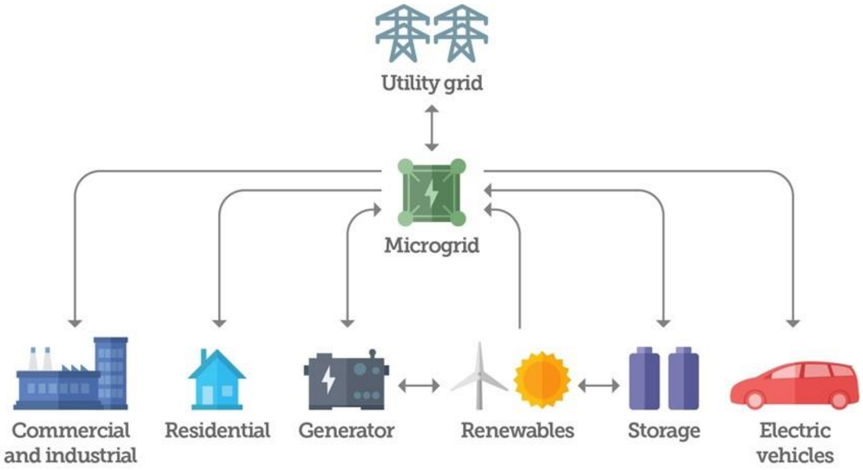

Figure 1.1 Typical microgrid components (Villarreal, 2016)

1.2. Why Use Battery Storage Systems

Batteries are not the only form of energy storage systems. Many ESS take several forms such as mechanical energy e.g., Flywheel, potential energy e.g., Pumped hydro, thermal energy e.g., concentrated solar power (CSP). However, not all cities have access to big amount of water which is required by pumped hydro, and not all countries have vast land areas to be covered by mirrors in case of CSP. This is why the battery is a great choice because a battery can be installed almost in every city independent of geographical position, weather, and resources access.

1.3. The Working Principle of Battery

A battery which is an electro-chemical type of energy storage works based on oxidation-reduction reactions of an electrolyte with metals, a basic battery consists of two different metals known as electrodes and is placed in a diluted electrolyte as shown in figure 1.2. Based on the electron affinity of the electrode’s metals, oxidation-reduction reactions take place in electrodes creating differences in charges. The electrode in which an oxidation reaction took place is negatively charged and known as an anode. Whereas the electrode in which a reduction reaction took place is positively charged and known as cathode. the medium where ions transfer between the two electrodes is the electrolyte. Electrolytes can take liquid or solid physical form and they can be water or other solvents combined with dissolved salts, alkalis, or acids which are required for ionic transmission.

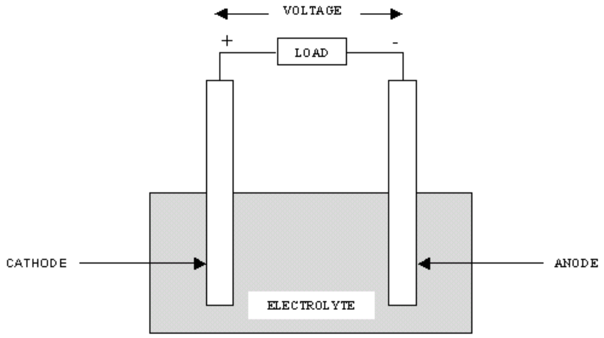

Figure 1.2 Basic battery elements (Acker,2017)

Battery types are used according to their application and need. The lead-Acid battery is one of the oldest batteries that have been invented by Gaston Plante in 1860, it is used mostly in cars to help to start the engine, and as a PV energy storage device. This type of battery has two lead electrodes submerged in an electrolyte consisting of sulfuric acid and water. One of the biggest disadvantages of these batteries is low specific energy density 25 Wh/Kg, (dong,2011).

Nickel Metal Hydride (NiMH) is another common battery found in many devices, this battery uses a rare earth mixture of lanthanum, cerium, neodymium, praseodymium, (dong,2011), these batteries have a higher specific energy density than lead-acid batteries (100 Wh/Kg) and are thermally stable, the complexity of charging is one of the major cons of using NiMH battery.

Lithium batteries have both high specific energy density and volumetric energy density compared to other common batteries as shown in figure 1.3, which means that the battery has a high energy content with minimal size. Moreover, a high nominal cell voltage of 3.7 V with a high cycle life makes it ideal to use in many applications, such as consumer electronics, electric vehicles (EV), energy storage for PV, and many more. Lithium is in the group of alkali metals and the is lightest of solid elements. The most common type of lithium battery uses metallic lithium as the anode, whereas manganese dioxide is the cathode, and the salt of lithium is the electrolyte.

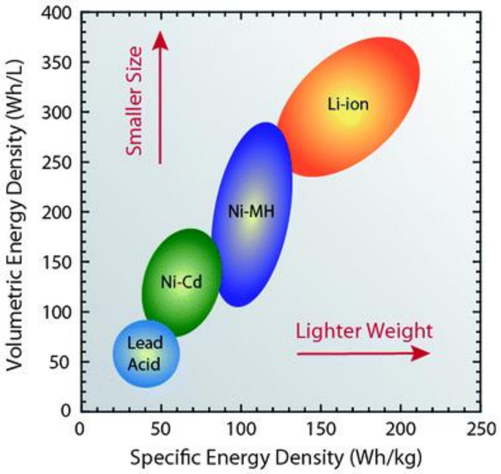

Figure 1.3 A comparison of battery energy densities (King,2018)

Since lithium-ion batteries have proved to be a transformational technology not just for the current electronic devices but progressively for home energy storage, and of course for EVs, engineers have made an attempt to scale them up to use them as grid energy storage. For example, the Tesla Li-Ion installation in Hornsdale Australia is the world's first and biggest grid scale Lithium battery. With a capacity of 130 MWh, it provides essential grid-support services such as frequency regulations and load balancing (Neoen, 2021). However, this application is pushing the limit of what Li battery batteries can be a feasible or cost-effective method of storing energy. Moreover, Li battery loses capacity over time which is seen with devices like cellphones that use the same battery type, this means that the battery installations lifetime gets shorter and requires replacements.

Furthermore, lithium metal is dangerous and toxic for living creatures and the environment, "Lithium mining from salt brines in South America is associated with concerns of contaminating local water basins and the salinization of freshwater needed by local communities. Cobalt mining in Democratic Republic of Congo has widely reported issues with child labor, environmental damage and toxic pollution leading to birth defects in the local population." (Whiteaker, 2021). For all these reasons, redox flow batteries as will be discussed later, show a growing interest in using them as a better solution than Li batteries in grid-level energy storage. Also, the emerging types of redox flow batteries use all organic materials instead of using hard to find polluting metals such as Lithium.

1.4. Flow Battery

A flow battery is a rechargeable battery that involves pumping two liquid electrolytes one negative and the other is positive from two tanks into one or more electrochemical cells or cell stacks but kept separated by a membrane as shown in figure 1.4, it is a hybrid system between a battery and a fuel cell. The main difference between a flow battery and a common battery is that the active chemical specious are dissolved in the electrolyte, whereas a typical battery has its electrodes as the active chemical specious. In figure 1.4, specious A oxidizes and release electrons to be picked by the electrode, the electrons travel to the load then to the positive electrode and specious B, which receives the electron and change to the reduced form and the ions in the electrolyte are allowed to transfer through the ion-selective membrane. A flow battery is also called a redox flow battery (RFB), after the reduction-oxidation process.

The main advantages of flow battery are the scalability, by simply increasing the size of the tanks and adding more electrolyte, energy capacity measured in Watt-hour (Wh) can be increased to cover many houses using a single battery, while power capacity measured in Watt can be increased by adding more cells in the stack. Moreover, the life cycle of a flow battery is among the highest and can last for up to 30 years before needing replacements, making them a promising future goal towards powering micro-grids.

The main types of flow batteries are:

- Classical: These batteries have all reactants in solutions such as All-Vanadium battery
- Hybrid: At least one reactant is insoluble and deposited as a solid layer on the electrode. E.g., Zinc-Bromine
- Organic: Using organic materials as active chemical specious. E.g., Organic redox battery that use quinone

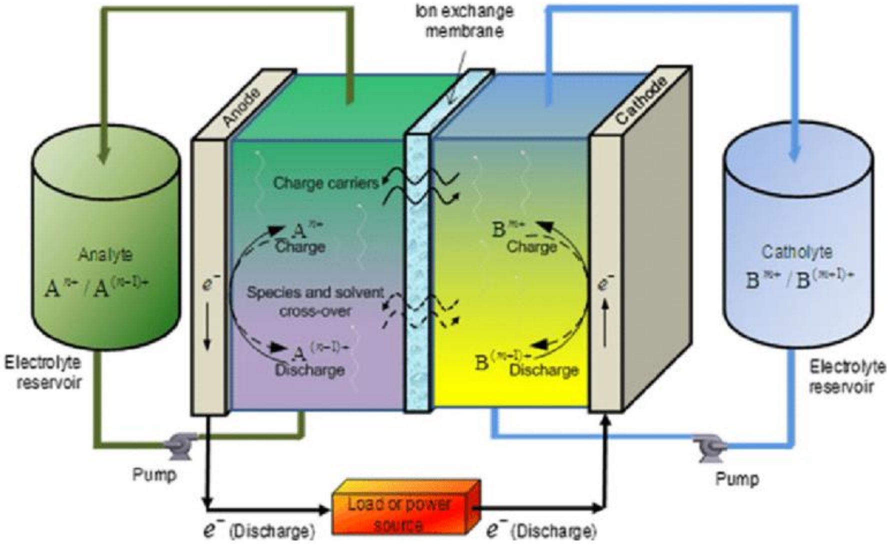

Figure 1.4 Illustration of a typical RFB (Weber et al, 2011)

1.5. Vanadium Flow Battery

Vanadium redox flow battery (VRFB) consists of two electrodes, positive and negative accompanied by a membrane that permits ion exchange. Vanadium ions mixed with electrolyte are kept in two tanks, a mechanic pump circulates the fluids into a set of cells as shown in figure 1.5. reduction and oxidation reactions occur in the cell, the electrodes capture the free electrons and are transferred to the circuit, while the hydrogen cations are passed through the membrane

The reaction that is happened in the cell is shown below:

$\mathrm{VO_2^+ + 2H^+ + e^- \rightleftharpoons VO^{2+} + H_2O}$ Positive-side (1.1)

$\mathrm{V^{2+} \rightleftharpoons V^3 + e^-}$ Negative-side (1.2)

$\mathrm{VO_2^+ + V^{2+}2H^+ \rightleftharpoons VO^{2+} + H_2O + V^3}$ Cell overall reaction (1.3)

VRFB main advantages:

- Can be left completely discharged without any capacity losses
- Safe, electrolytes are non-flammable and mixing them does not cause any damage
- High range of working temperature
- Low Levelized cost of energy (LCOE)

The main disadvantage of VRFB is that it uses Vanadium which is not commonly found in nature, therefore Vanadium prices are high. Moreover, Vanadium oxides are toxic and can lead to toxicity hazards.

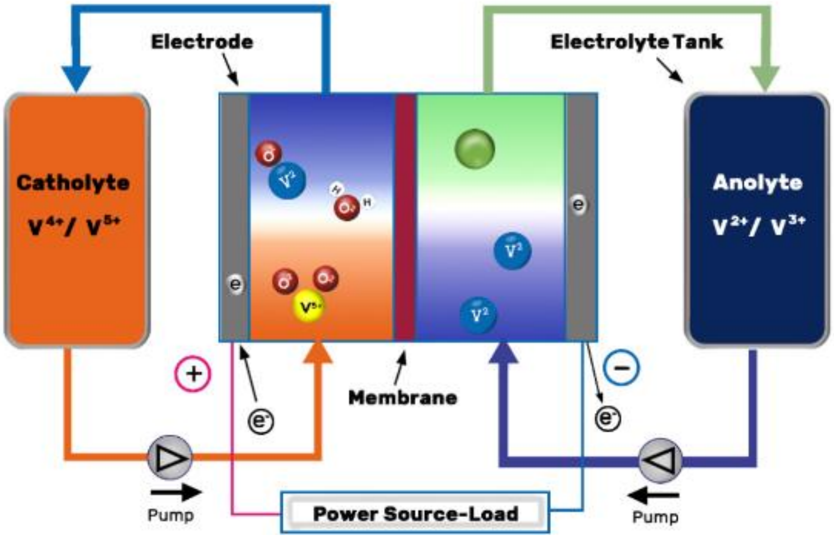

Figure 1.5 VRFB basic components (Weber et al, 2011)

1.5.1 Main Components of Vanadium Flow Battery

There are two important parts that each vanadium flow battery must include, storage tanks that contain the electrolytes where energy can be stored, and cell stacks which contains several cells assembled in a manner to convert chemical energy into electricity in a reversible way, the main elements of vanadium batteries are listed bellow

- **Electrolyte**

Many vanadium batteries use Vanadium ions dissolved in sulfuric acid. Vanadium is a d-block transition metal, its color is silver, and is placed first of long period of periodic table between titanium and chromium. Vanadium can take several oxidation forms ranging from 2+ until 5+ and each oxidation form makes the metal change in color as shown in figure 1.6

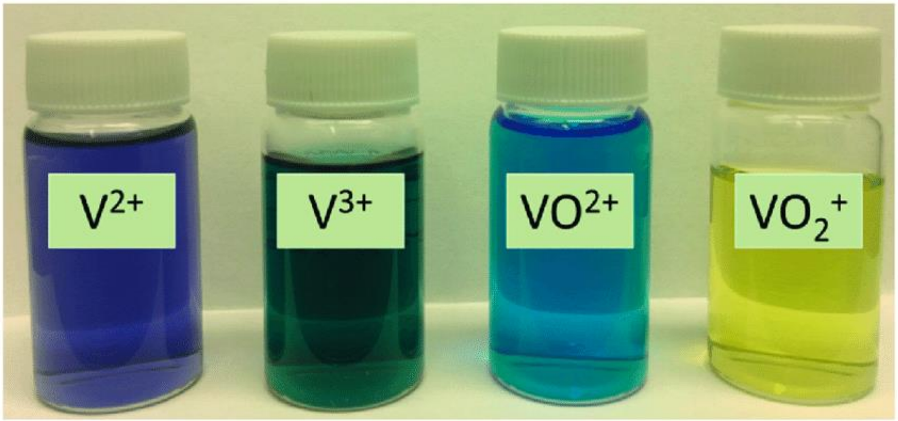

Figure 1.6 Vanadium color change due to Oxidation (Jing et al, 2019)

Ideally, it is desirable that the redox couple offers a high nominal voltage and high reversible redox kinetics (Aramendia,2020). Also, it is preferred that the electrolyte is stable enough to permit a high depth of discharge (DoD), a high DoD means that the battery can be discharged until a very low energy content is left, also the electrolyte should retain the energy content as much as possible when the battery is not used keeping the loses minimal.

- **Electrodes**

The electrodes are responsible for capturing the free electrons coming from the chemical reactions, also they work as a passage of electric current during the charging/ discharging process. Some important aspects should be considered when designing electrodes for flow batteries as follows:

- To withstand the highly acidic environment in the electrolytes and be chemically stable
- To be built from a material that has good electrocatalytic activity
- Operates as designed in the voltage range of the flow battery
- Must have good electrical conductivity, or have a low resistance to prevent the slower rate of charge/ discharge process
- Preferably built with low cost

1.6. Zinc-Bromine Flow Battery

It is a type of hybrid redox flow battery, this type of battery also requires storage tanks and pumps to operate, the battery is made from a Zinc anode, and Bromine as cathode, plus a membrane or porous separator. the solution of Zinc Bromide $ZnBr_2$ is pumped to the cell stacks as shown in figure 1.7, in the charging process as the electricity causes a reaction with Zinc Bromide which creates zinc plating on the negative electrode, whereas at the positive electrode, bromine is formed. In the discharging process, Zinc dissolution occurs, and Bromine is reduced to Bromide for the Zinc Bromide solution again as shown in the equations below:

$$\mathrm{Zn_{(s)}} \rightleftharpoons \mathrm{Zn^{2+}_{(aq)}} + 2\mathrm{e^-} \quad \text{Negative-side} \tag{1.4}$$

$$\mathrm{Br_{2(aq)}} + 2\mathrm{e^-} \rightleftharpoons 2\mathrm{Br^-_{(aq)}} \quad \text{Positive-side} \tag{1.5}$$

$$\mathrm{Zn_{(s)}} + \mathrm{Br_{2(aq)}} \rightleftharpoons 2\mathrm{Br^-_{(aq)}} + \mathrm{Zn^{2+}_{(aq)}} \quad \text{Cell overall reaction} \tag{1.6}$$

Main advantages of Zinc-bromine RFB:

- A complete discharge of the battery is possible and can be done on daily basis, this means that usable capacity is the same as the nominal capacity
- High cycle life because of little degradation
- The electrolyte is not flammable, which make the battery have a low fire risk
- The battery can be operated without cooling systems
- Cheap materials used to build the battery
- Recyclability, existing technologies can successfully recycle end of life Zinc Bromine batteries

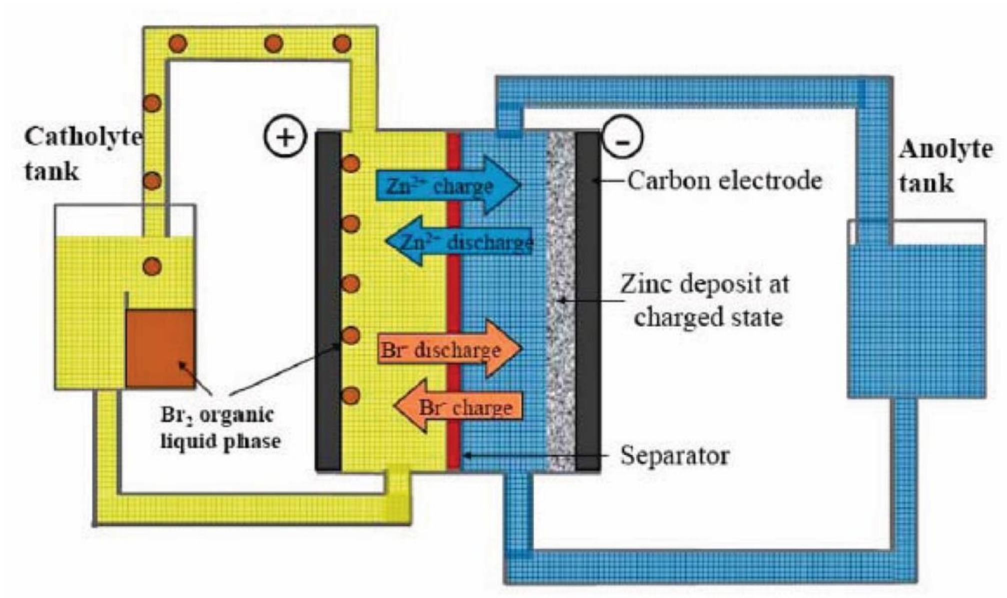

Figure 1.7 Elements of Zinc-Bromine RFB (Alighieri, 2017)

1.7. Iron Flow Battery

The All-Iron redox flow battery uses iron (2) chloride/ iron (3) chloride as a positive electrolyte, whereas iron (2) chloride is used as a negative electrolyte with Iron platting at the negative electrode. During discharge, Fe^3 reduces to Fe^2 which happens after gaining electrons given by the positive electrode as shown in equation (1.7). whereas, the metallic form of Iron dissolves to form Iron chloride (2) after losing electrons to be picked up by the negative electrode as shown in equation (1.8). in charging mode, all the reactions are reversed and the metallic form of Iron forms again at the negative electrode as shown in figure 1.8.

$$2FeCl_3 + 2e^- \rightleftharpoons 2FeCl_2 + 2Cl^- \text{ Positive-side} \tag{1.7}$$

$$Fe + 2Cl^- \rightleftharpoons FeCl_2 + 2e^- \text{ Negative-side} \tag{1.8}$$

$$Fe+2FeCl_3 \rightleftharpoons 3FeCl_3 \text{ Overall cell reaction} \tag{1.9}$$

Thanks to the battery chemistry, it does not use rare-earth minerals such as Lithium or Vanadium. Instead, it uses earth-abundant iron, water and salt which make the battery among the safest, easiest to operate in the market. Moreover, it does less harm to the environment in obtaining the materials and producing the battery. This battery suffers from a hydrogen problem, which is a parasitic evolution of hydrogen gas that happens at electrodes during charging, this can affect the performance of the Iron RFB (Bellini, 2020).

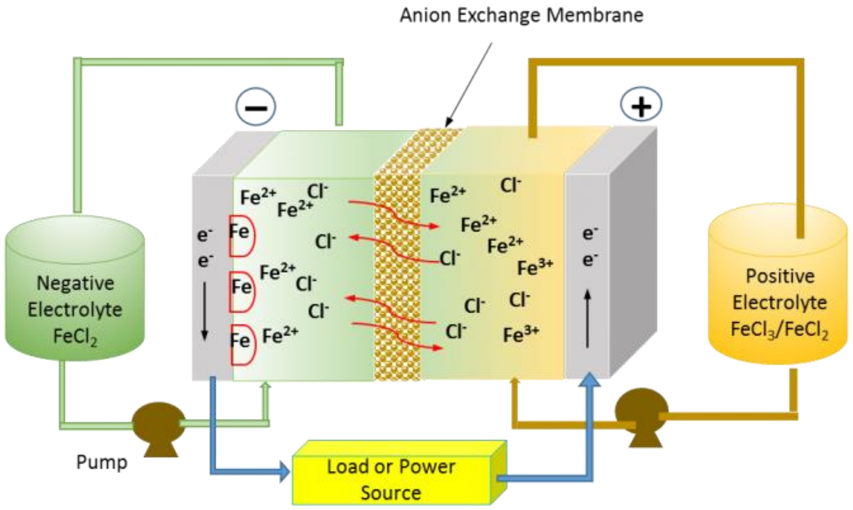

Figure 1.8 Components of Iron Redox Flow Battery (Dana and David, 2018)

1.8. Organic Flow Battery

As discussed earlier, most classic flow batteries depend on the exchange of transitional metal ions such as Vanadium and Vanadium oxides, VRFB is the most popular and developed kind of flow battery because of its high cycle life and the ability to be easily scaled up. However, the downsides of using VRFB are two. Firstly, Vanadium is considered to be rare in nature and few countries produce it, which translates to the high cost of obtaining the metal. Secondly, Vanadium oxide is corrosive and toxic which poses environmental risks in case of a spill from the electrolyte tanks. For these reasons, organic redox flow battery (ORFB) replaces all the precious metals with earth-abundant organic compounds such as carbon, hydrogen, oxygen, nitrogen, and sulfur (Liu et al., 2021). Organic RFB offers a very safe and cost-effective method for storing energy.

Mainly, there are two types of organic RFB based on the electrolytes, Non-Aqueous ORFB, and Aqueous ORFB. In non-aqueous ORFBs, organic electroactive molecules are dissolved in organic solvents with other supporting electrolytes, e.g., dimethylacetamide (DMA). non-aqueous ORFBs have a higher nominal cell voltage than the 1.24 Volt limit of aqueous ORFB (Zhong, 2020), a high cell voltage is always favorable in any battery as it increases the energy density and occupies less physical space. Aqueous ORFBs on the other hand have greater viable potential because of the minor solvent cost, high conductivity, and more safety than non-aqueous ORFB.

The organic flow battery is a truly sustainable battery that is made completely from non-toxic, cheap materials. Even electrodes are made from conducting organic materials such as shrimp shells as mentioned in the MIT study. The team at Linköping University designed an organic flow battery that has PEDOT electrodes, PEDOT is an organic and conducting polymer poly (3,4-ethylenedioxythiophene). The team claims, the “device is very cheap, entirely recyclable and perfectly safe, opening up the possibility of installing such a battery in homes to act as a power bank for electric vehicles.” (Nick Lavars, 2020).

2. Objectives/Scope of the Project

The main goals of this work are to enhance the knowledge of redox flow battery by studying the working principle, performance, and advantages/disadvantages of common RFBs. Since Lithium (Li) battery is currently the most reliable and popular battery storage, RFBs will be simulated using HOMER PRO software and compared against the performance of Li battery to clearly demonstrate how RFBs perform. Moreover, this work will provide a design of a microgrid system that uses a flow battery with minimum costs.

Specific goals are listed as follows:

- Give a brief explanation of RFBs, and explain their working principle
- By using simulation analysis, the study will illustrate the performance of RFBs under a typical community load
- Illustrate the ability of RFBs to be deeply discharged and show why this ability is important in the system operation
- Perform economic and environmental analysis
- Design a model of an optimum microgrid system PV, Wind turbines, generator, and a flow battery.

3. Methods/Approach

In order to achieve the project aims, HOMER PRO computer software will be used to simulate and model RFBs, this will be done according to the two steps:

1. Energy storage sensitivity analysis with one source of renewable energy:

To have a clear idea about the performance, the simulation will examine with only one renewable source to avoid complications. The analysis will study the behavior of the energy storage device on a typical day in the peak month according to the annual load profile. This will be done by:

- Creating a model on HOMER PRO software, this model will represent a typical microgrid load. This model will also include PV or Wind turbines as a renewable source. Finally, a generator as a backup system
- The model will have Lithium battery storage and the simulation data will be gathered and analyzed
- The Li battery will be swapped with RFBs. In this analysis, the following RFBs will be simulated respectively: Vanadium RFB, Zinc-Bromine RFB, Iron RFB.

2. A system design that uses a flow battery with integrating wind and solar energies:

After assessing the performance of flow batteries, the best performing flow battery will be used to design a system that uses typical wind and solar sources of energy.

3.1. Modeling the Electrical Load

According to the Center for Climate and Energy Solutions 2017, microgrids can serve a load starting from a single building to an entire community, ranging in size from 100 kW to multiple megawatts. For simplicity, the microgrid is islanded and the size will be set to a generic community load of 2000 kW requiring a daily energy budget of 48000 kWh per day, and peaking in summer months reaching almost 24 kW according to the modeling of the load as shown in figure 3.1, the electrical demand rise in the evening then peaks just before midnight, then starts dropping till the next day. Mainly, electrical demand increase in the summer months because of cooling demands, HVAC is heavily used to maintain good temperature/ humidity levels for human beings, animals, and equipment. Whereas in winter, many devices can be used for heating that does not rely on electricity such as biomass which lowers the demand in winter.

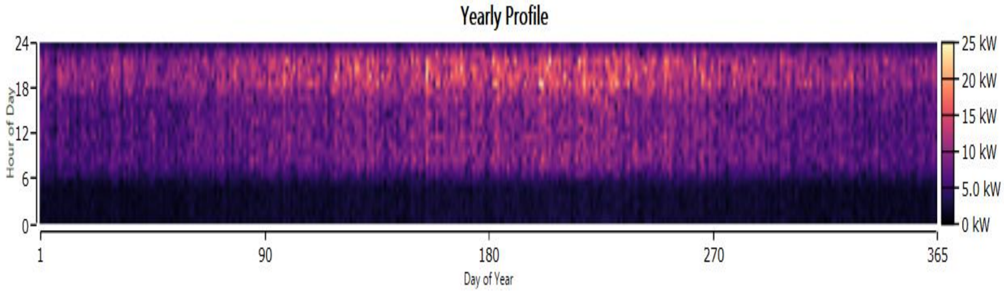

Figure 3.1 Yearly profile of the electrical load as simulated by HOMER PRO

3.2. Modelling Renewable Energy Sources

Since RES are an essential element of a microgrid, this simulation analysis will study the two most common renewable energy sources: Photovoltaic (PV), and wind turbines. Both systems suffer from intermittency, and they have different generation profiles that affect energy storage performance.

3.2.1 PV

For simplicity, the simulation will set PV size to 6000 kW generic flat PV modules loaded from HOMER PRO PV library with a cost of 2500 $ per kW and a lifetime of 25 years, the simulation of PV as shown in figures 3.2, A.1 and table A.3 was conducted with a solar profile of the city of Tarragona, Spain.

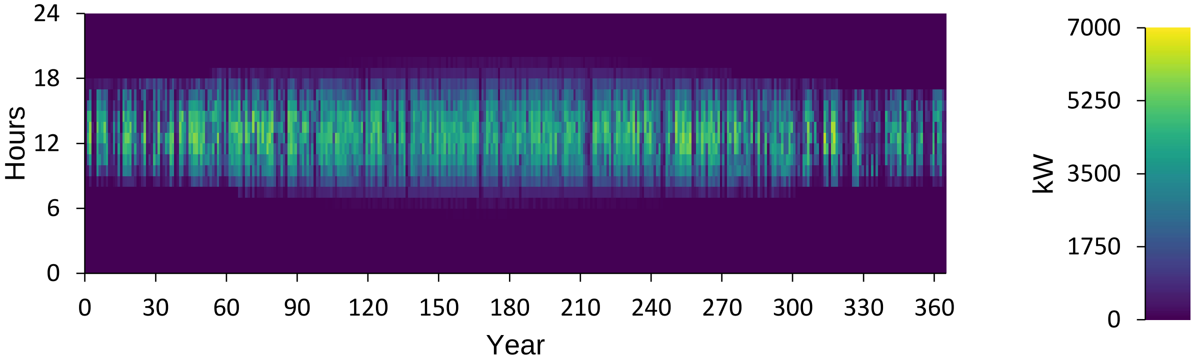

Figure 3.2 Simulated PV Power Output

3.2.2 Wind Turbines

A generic 1.5 MW wind turbine model with a hub height of 80 meters and a projected lifetime of 20 years will be modeled. In this simulation, the wind turbines number will be set by HOMER PRO according to the load needs, wind profile was again considering Tarragona, Spain. Figures 3.3 & A.2, and table A.3 show the expected energy generation.

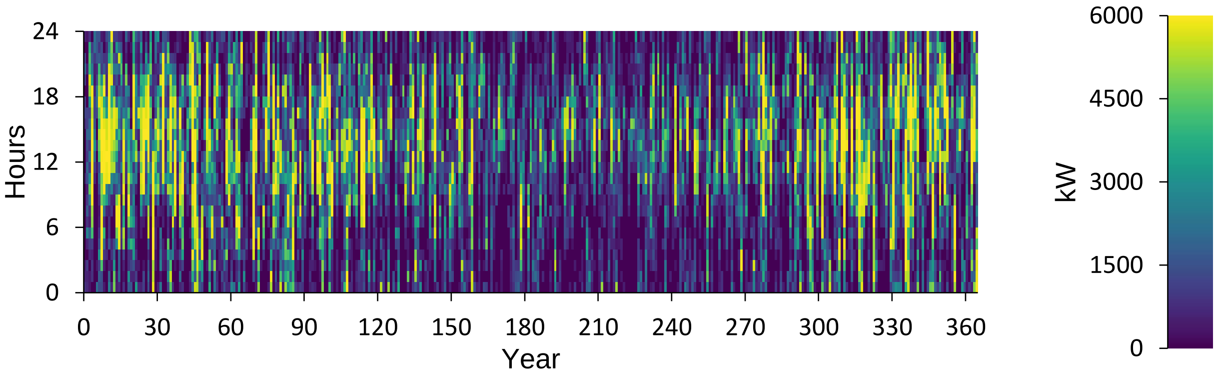

Figure 3.3 Simulated Wind Turbines Power Output

3.3. Modeling Generator

Since fossil fuel generators are mandatory to be used as backup power systems to energize the load in case of, for example, the storage device energy content is low, a sudden increase in the load, or a malfunction in any of the RES operations. A model was created to represent such types of generators in which a diesel generator was simulated with a capacity set according to the load needs. It is always desirable to lower the operation time of the generator to lower the emissions and save fuel cost, this can be done by choosing better energy storage that holds the most of the renewable energy.

3.4. Modeling AC-DC Converter

An Inverter is required to convert direct current (DC) to alternating current (AC) which is a vital element in converting DC power from the battery storage bank and PV to feed the AC electrical grid load, whereas a rectifier is used to convert AC to DC and is required in case of wind turbines charging the battery bank. Both Inverter/Rectifier can be modeled using the HOMER PRO-provided AC-DC converter model having an efficiency of both Inverter/Rectifier 97 %.

3.5. Simulation Limitations

In every simulation study, there are always inaccuracies in the simulating conditions that can affect the reliability of the obtained results. In this simulation study, some limitations are summarized as follows:

- Inability to scale up the flow battery, since one of the big advantages of RFBs is the simplicity of creating a battery on a grid-scale, the simulation considered RFBs from datasheets but there was no ability to change the battery electrolyte tank sizes, this could be a source of power losses since the system architecture will be made from several RFB batteries instead of one big battery. The solution can be adding the ability to change the size of the electrolytes tank when building the energy storage model.
- The model assumed a constant Ac/Dc efficiency, with increasing electrical loads, semi-conductors found in the system converter heat-up which will decrease the conversion efficiency. The model should include correlations to calculate the conversion efficiency at any load and electrical current.
- Load community assumption, the model made the load profile based on the simulation software algorithm. Instead, the model should import a load profile that is based on historic data that was collected from a real micro-grid.
- Parasitic loads such as cooling systems and pumps that circulate the electrolyte are not included in the simulation model. Results could be more accurate by calculating the parasitic loads and over-sizing the storage device to meet the load needs
- Power losses, the model did not consider voltage level conversions, nor transformers efficiency and power line losses when transferring power from the micro-grid elements.

4. Results and Discussion

4.1. Battery Storage Sensitivity Analysis

For simplicity, the simulation model as shown in figure A.3 was allowed to have PV modules as the only renewable source because of the ease of predicting the expected power generation from PV as shown in figure A.1. This means that the longer the battery can store the power from PV and deliver it after the sunset the better is the battery.

4.1.1 Lithium Battery Storage

A simulation based on a 100-kWh lithium battery storage model shows that almost 100 batteries are required to cover the load as shown in table A.1. Unlike RFBs, Li-battery usable capacity is not equal to the rated capacity, this is because a Li battery life cycle will be heavily shortened if deeply discharged. In table A.1, the usable percentage of the battery capacity can be calculated by dividing usable nominal capacity by rated nominal capacity, which is 80% in this case, this translates that the desired battery storage capacity should be oversized to avoid a shorter life-cycle. Another important parameter obtained from the simulation is the expected life which is less than 6 years and it is considered very short when compared to RFBs.

Figure 4.1 shows a typical day in the peak month of July, the load is drawn against all power sources to demonstrate the share of the generation that each hour has, while figure 4.2 shows the energy content of the battery in percent, also called the state of charge (SOC) with the battery charging power on the same day in July. As shown in figure 4.2 the PV modules start charging the battery starting from 7 in the morning and finish charging at 10. Until 16 o’clock, the load is getting totally served by PV modules, and the demand increased substantially starting from 16 o’clock causing a decrease in the energy content of the battery. At 19 o’clock, the generator fires with a power of more than 5000 kW although the battery had more than 70 % of charge, the reason is that the battery couldn’t produce power that can hold against the growing demand which made the generator take over and charge the battery while serving the load. After fully charging the battery, the battery then continues to serve the load starting from 22 o’clock until almost completely discharged (29 % SOC) at 4 in the morning which makes the generator work again to support the load until the sunrise.

Both figures 4.1 and 4.2 show that in order to lower the generator operation time and save fuel, the battery must be capable of delivering high output power that can serve the load at its highest. This feature is as important as having a battery that can be deeply discharged below 20%.it is also noticeable that the battery storage system is kept fully charged most of the time (10 hours) which means that the battery is lightly used. Moreover, even with this low usage the battery life was only 5.5 years as shown in table A.2, which is very low.

In this simulation analysis, it was shown that the lithium battery technology although it has the highest specific energy density, it still has drawbacks that make it harder to integrate with microgrids, the high cost, fire hazard, short life cycle, and inability to be deeply discharged proves that Li technology is not necessarily the best technology for storing energy on a grid scale.

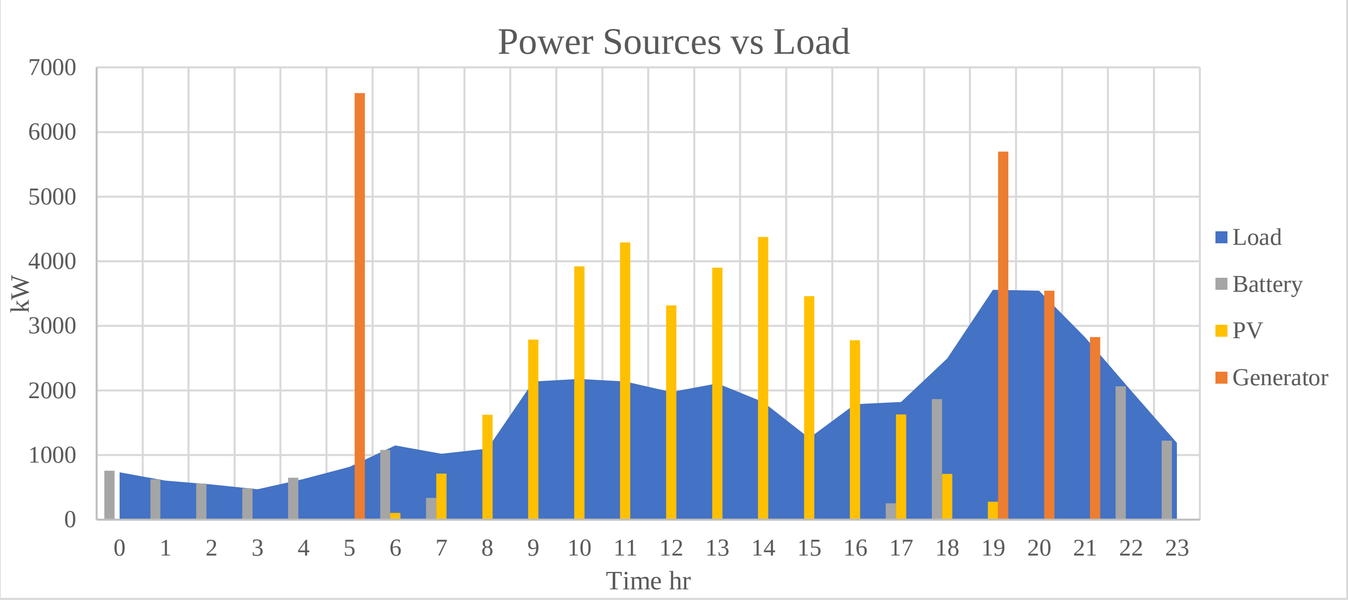

Figure 4.1 Simulating a typical day in July with Lithium battery, Power Sources vs Load

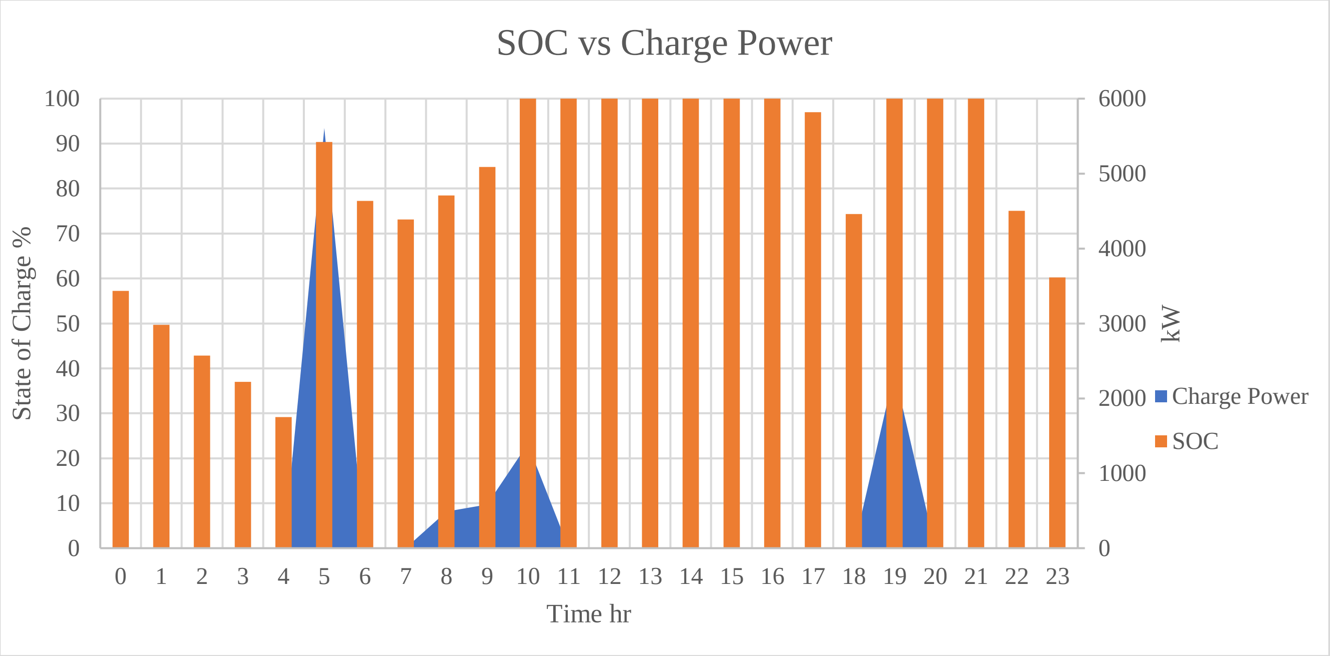

Figure 4.2 Simulating a typical day in July with Lithium battery, SOC vs Charging Power

4.1.2 <u>Vanadium RFB</u>

To model the Vanadium redox flow battery (VRFB) accurately, a datasheet (see appendix B) was required to obtain important parameters such as capacity, maximum depth of discharge (DOD), etc. The parameters were imported to build the model and simulate with those same conditions that the Li battery was simulated against. From figures 4.3 and 4.4, VRFB showed a much better performance when compared to Li battery, VRFB was able to deliver more than 3000 kW of power when the load was at its highest and did not require the intervention of the generator, just after the end of the load peak, the generator kicked in operating for two hours to supply the load and charge the battery. After the battery is fully charged, it continues to supply the load throughout the night without any intervention of the generator until the sunrise making PV modules charge the battery and supply the load. Unlike Li battery, VRFB did not reach a critical state of charge that require immediate generator intervention to stabilize the grid. Table A.2 shows that VRFB is expected to function for 25 years according to the simulation, which is very long when compared to the five years of Li battery. Also, the nominal capacity is similar to the usable nominal capacity, which means that the battery can be discharged completely to zero % SOC, without causing any effect on the battery health. VRFB demonstrates good performance in delivering high power when needed. Furthermore, VRFB had a very high life cycle and was able to be deeply discharged. VRFB is much safer, scalable, and Vanadium metal is more found in nature than Lithium. For those reasons, the Vanadium flow battery is the most well-known and popular in the RFBs family. However, the expensive extraction of Vanadium metal made the commercialization of VRFB difficult.

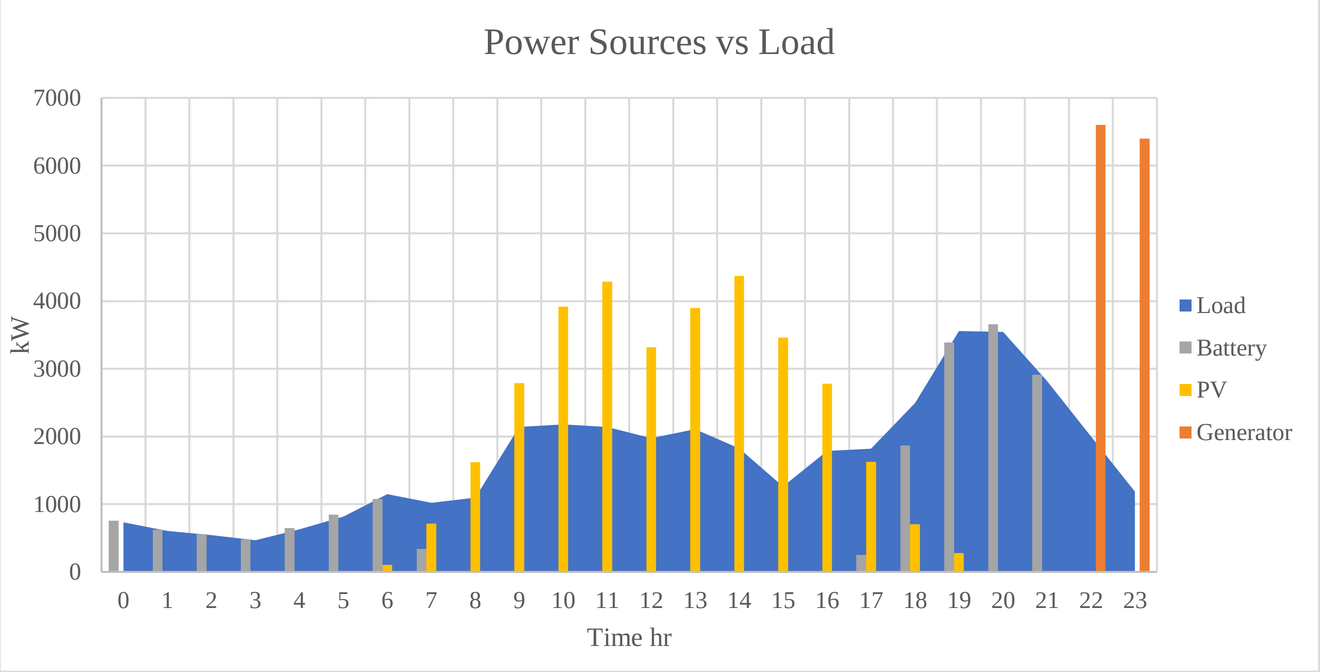

Figure 4.3 Simulating a typical day in July with VRFB, Power Sources vs Load

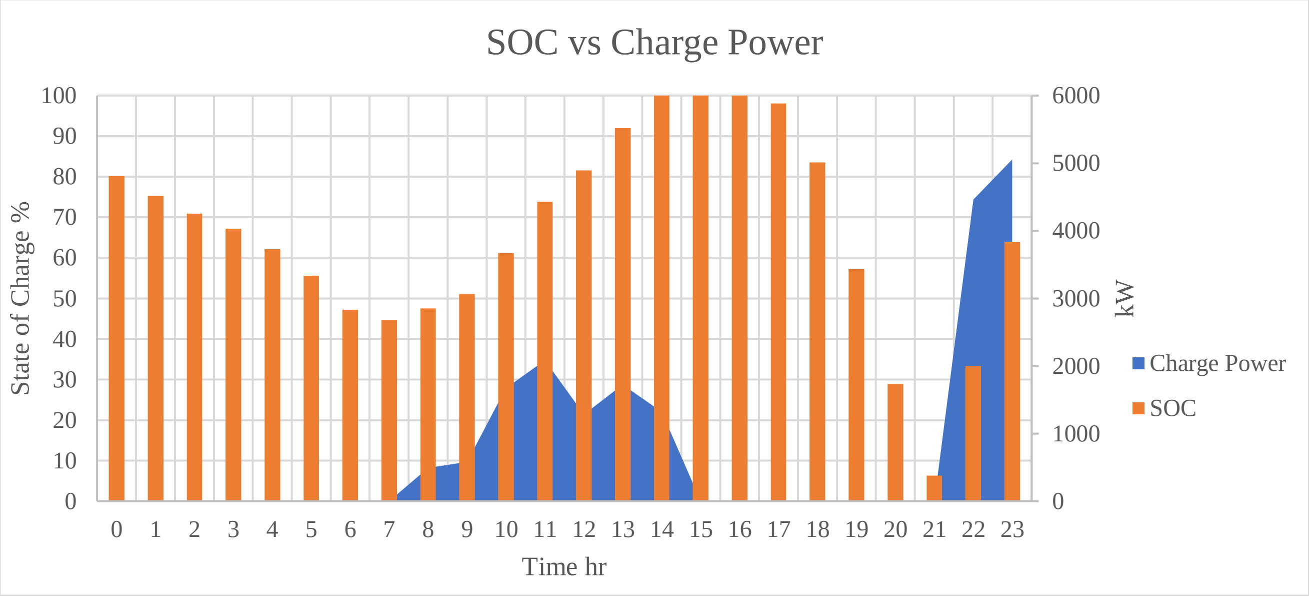

Figure 4.4 Simulating a typical day in July with VRFB, SOC vs Charging Power

4.1.3 <u>Zinc-Bromine RFB</u>

A datasheet (Appendix B) was taken to build the battery model from a leading company in producing zinc-bromine RFB. In figure 4.5, it was clear that the Zn-Br RFB delivered a big amount of energy starting from 17 at noon and lasting until 22 just before midnight. It is also clear that the battery was almost fully discharged at 22 o'clock, this means that the battery starts discharging from sunset until just before midnight almost covering the high load peak alone. The generator starts as shown in figure 4.5 & figure 4.6 after a complete discharge of the battery for a period of three hours producing power and burning fuel less than VRFB and Li battery simulations because the generator was mostly charging the battery while covering a low electric demand. VRFB discharged just after the peak hour, and the micro-grid controller turned on the generator covering the remaining high electrical demand and also charging the battery. This is why having a storage device that can cover almost the entire period of load peak can cut the fuel consumed by the generator and lower emissions. the only problem with the Zinc-Bromine model is that the battery was too small in capacity and had a low nominal voltage because the grid scale Zn-Br RFB was not commercialized yet. However, this did not affect the simulation results.

Zinc-Bromine RFB shows an improved performance than VRFB, and also this battery does not require expensive materials such as Lithium or Vanadium and can be built from earth-abundant materials. Finally, the battery can take a very small size as shown in the datasheet, which means that it can be used in residential applications.

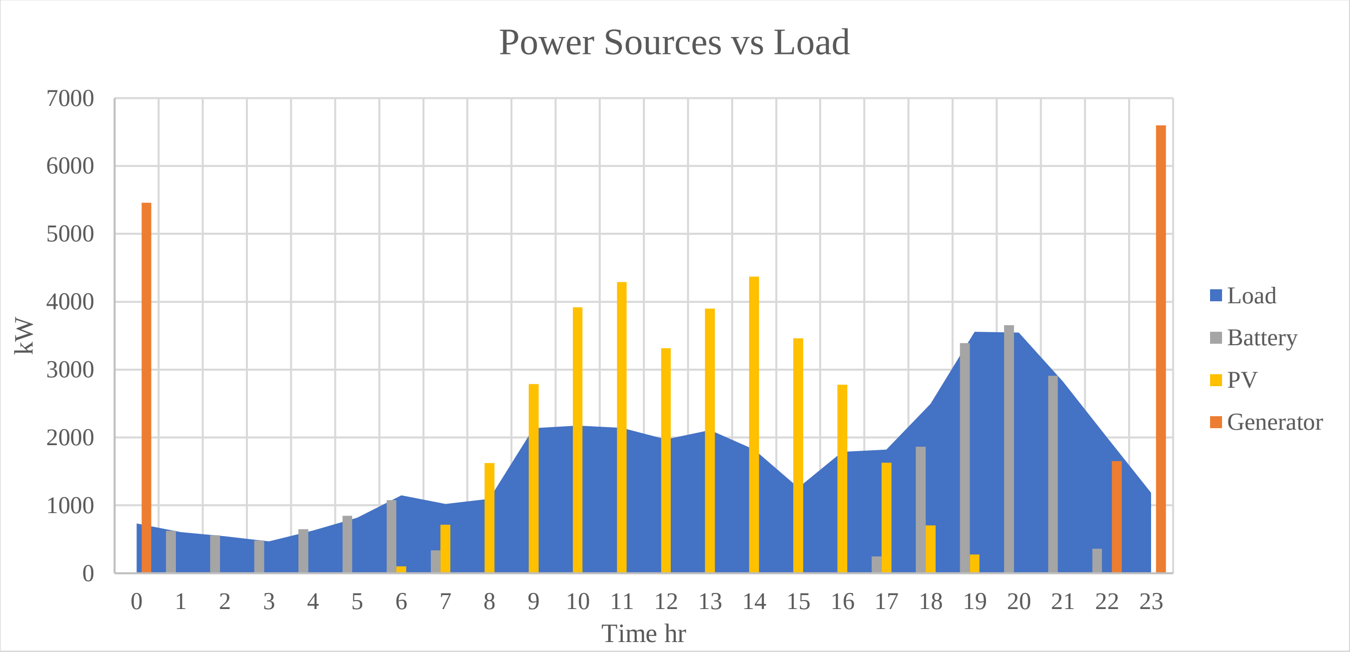

Figure 4.5 Simulating a typical day in July with Zn-Br RFB, Power Sources vs Load

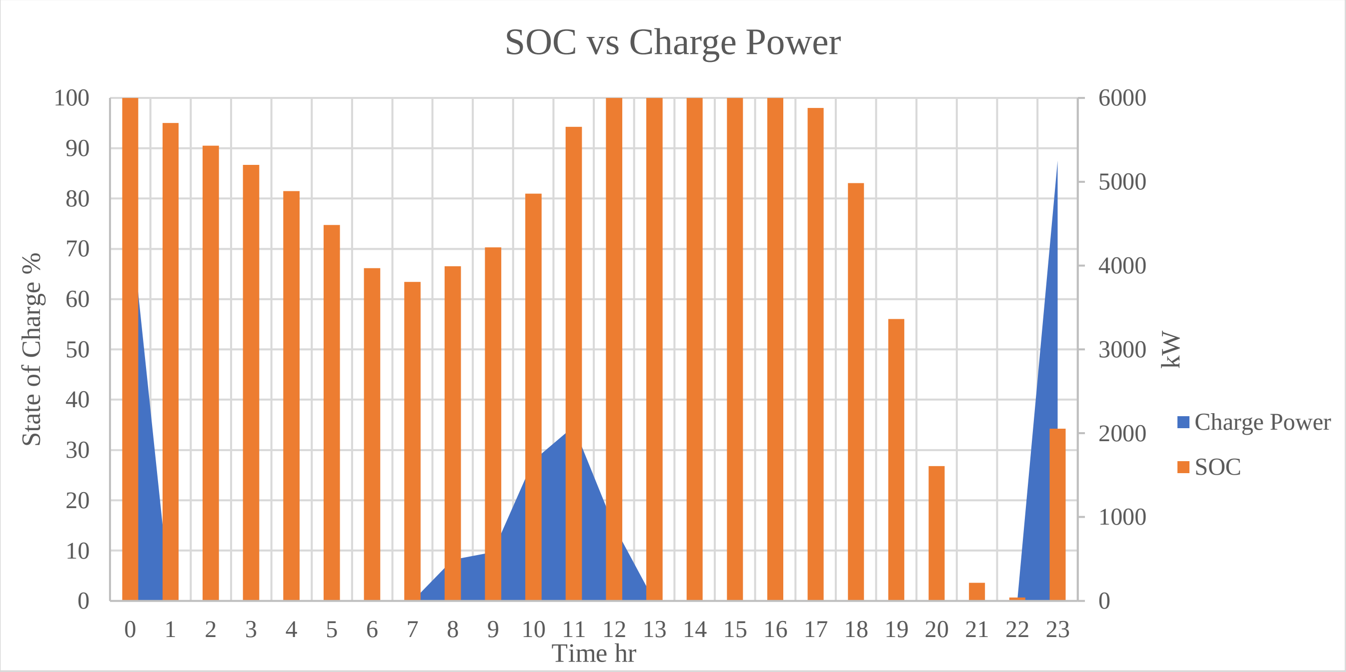

Figure 4.6 Simulating a typical day in July with Zn-Br RFB, SOC vs Charging Power

4.1.4 Iron RFB

Iron RFB showed a similar performance to the Vanadium flow battery simulation as shown in figure 4.7, the battery almost covered all the peak period until the generator started at 22 as shown in figure 4.7 & figure 4.8. It is also observable that the battery didn't charge until its maximum capacity, this is because the generator charged the battery to a level that made it only cover the entire electrical demand starting at midnight till sunrise, where the PV starts charging the battery and powering the load simultaneously. Table A.2 shows a quantity of only 47 required batteries which is the lowest compared to previously discussed RFBs, this is because of the big capacity and high voltage of the battery which was modeled from the datasheet found in Annex B. although in this simulation both VRFB and Iron RFB have approximately similar performance in load response, VRFB uses Vanadium which is a more expensive metal than Iron which is cheap and commonly found in earth-crust, this difference in building materials will be discussed later in the economic section.

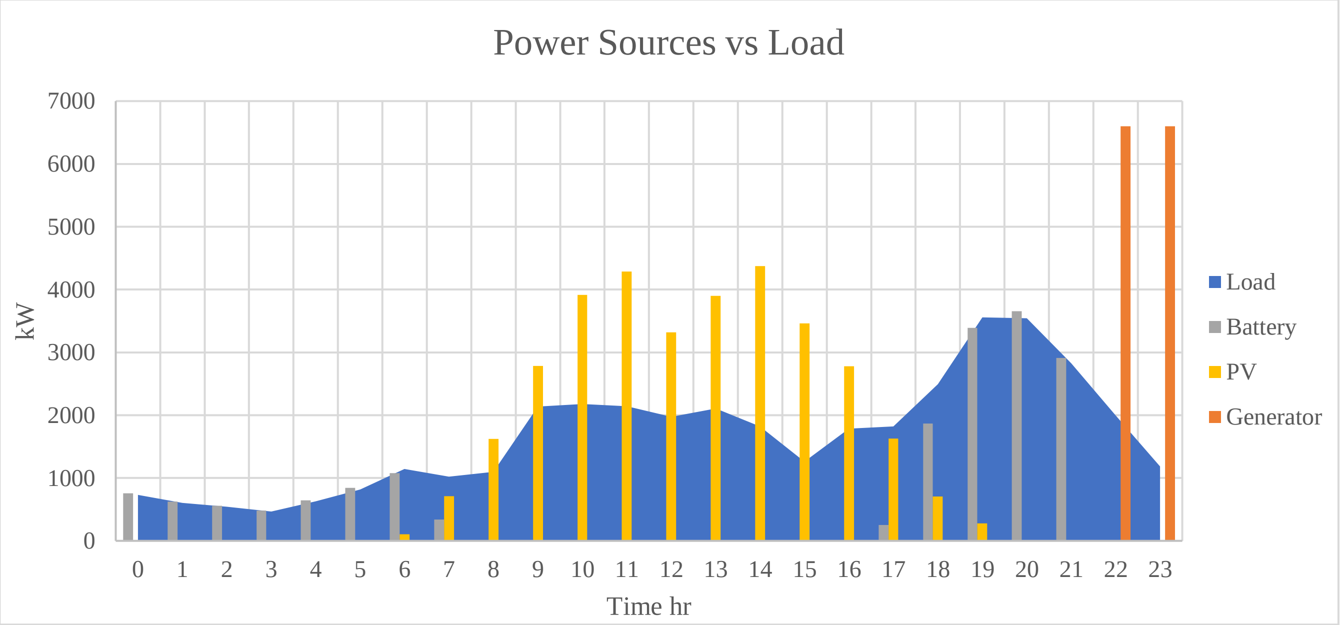

Figure 4.7 Simulating a typical day in July with Iron RFB, Power Sources vs Load

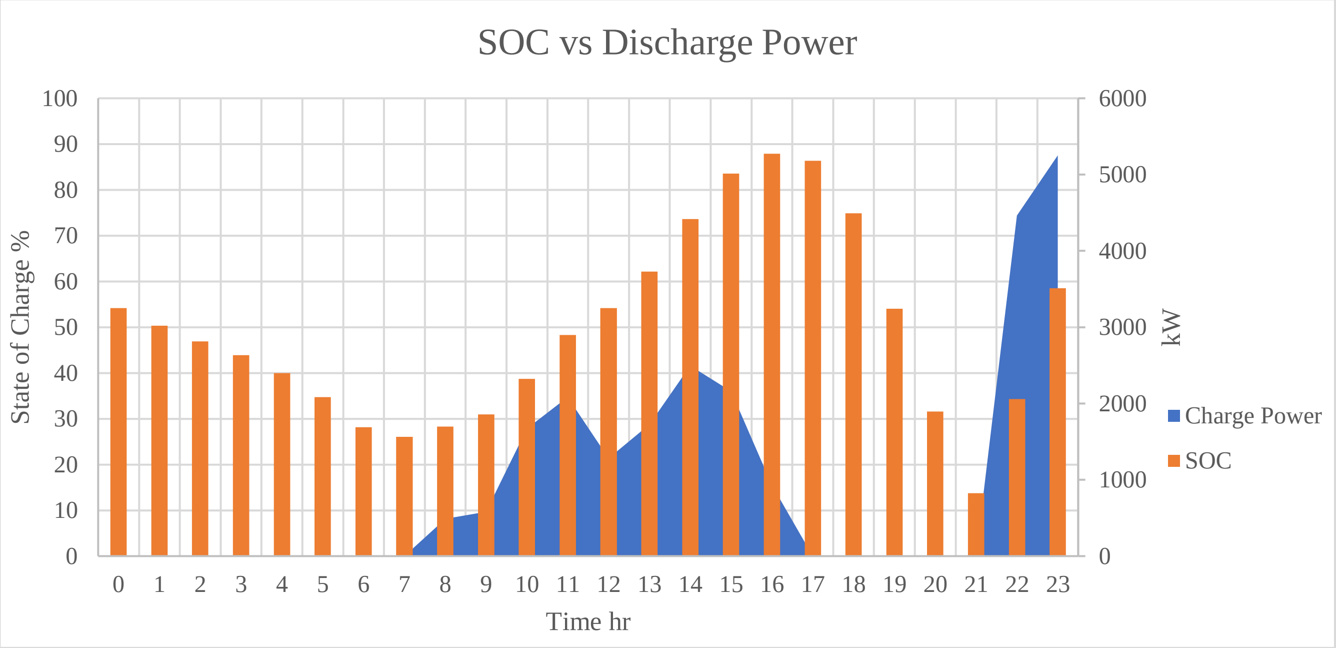

Figure 4.8 Simulating a typical day in July with Iron RFB, SOC vs Charging Power

4.2. Overall Performance Analysis

In this analysis, the three previously mentioned RFB batteries and the Li battery will be studied and compared focusing on important design parameter data such as system architectures, and will also study environmental impacts and economics.

4.2.1 Economics

The energy storage economy plays an important role to decide what is the best feasible system, energy storage that provides a low cost of energy and low price per kWh is mandatory to compete with well-known energy storage systems such as pumped hydro. According to datasheets gathered from RFBs manufacturers, figure 4.9 represents the cost of one kWh of storage by dividing the price over storage capacity. Vanadium RFB is the cheapest (200 $/kWh) among all because of that the VRFB is the most well-known, developed, and most commercialized flow battery until now. While Iron flow battery should have the lowest storage price because of the availability of Iron in the earth crust and the simplicity of the battery design. However, the Iron flow battery is slightly higher at 250 $/kWh, this is because of side reactions that happen in the electrolyte tanks causing hydrogen generation and requiring in-tank rebalancing (Selverston et al, 2019). this process raises the battery energy cost but still makes it competitive. Zinc-Bromine battery come at 480 $/kWh which is the highest in the RFBs family because of the rising zinc and bromine prices. Finally, Lithium battery is the highest at 700 $/kWh which is almost four times the price of VRFB. Moreover, this price comes higher for many reasons such as lithium mining being very costly and because lithium is being used in many applications such as batteries for electronics, EV, and many more.

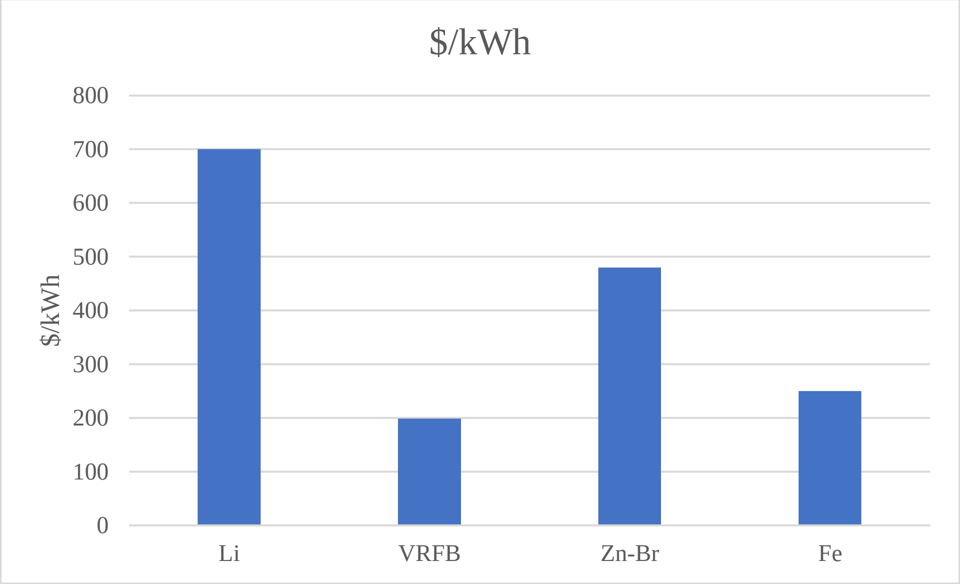

Figure 4.9 Price of batteries per kWh

The simulation analysis shows in table 4.1 that VRFB is the best-case scenario economically, it has the lowest net present cost NPC because it has the lowest cost per kWh as discussed earlier. Whereas Iron and Zn-Br RFBs are almost the same prices with Zn-Br being slightly higher, and Li battery is the highest price, again because of the high price of Lithium metal.

Cost of energy as shown in figure 4.10 shows that all discussed RFBs have a similar cost of energy, VRFB being the lowest, while Lithium battery is the highest.

Table 4.1 Simulation economic analysis

	NPC[1]	LCOE ($/kwh)	Simple Payback (yr)	Operating cost ($/yr)
VRFB	$69.7M	$0.308	0.87	$3.75M
Iron RFB	$72.1M	$0.318	1.21	$3.80M
Zn-Br RFB	$73.5M	$0.325	1.50	$3.75M
Li Battery	$87.1M	$0.384	1.45	4.85

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[1] NPC represents the total cost of the system including the price of PV, Generator, Ac-Dc convertor, and the battery storage

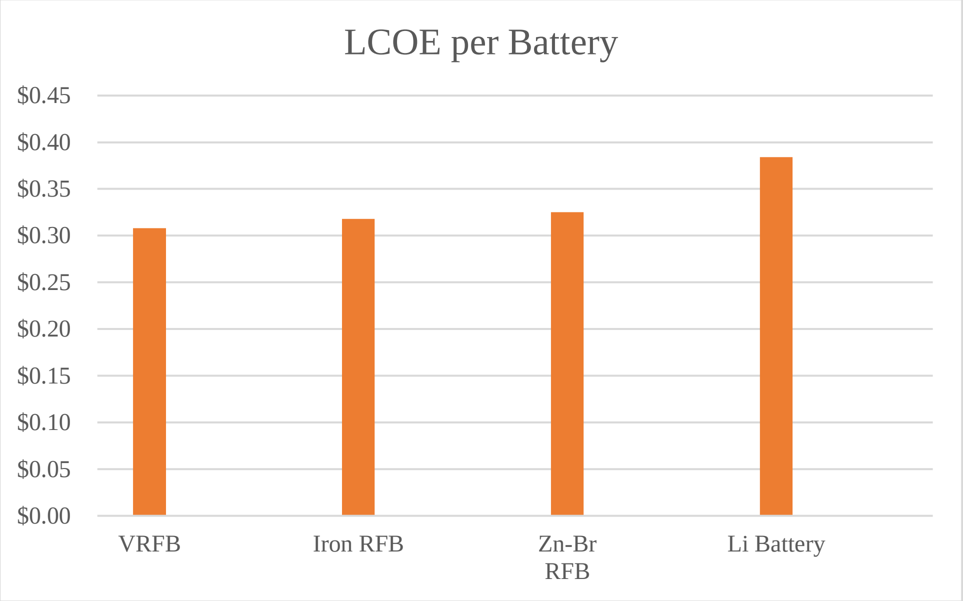


Figure 4.10 Levelized cost of energy per battery ($/kWh)

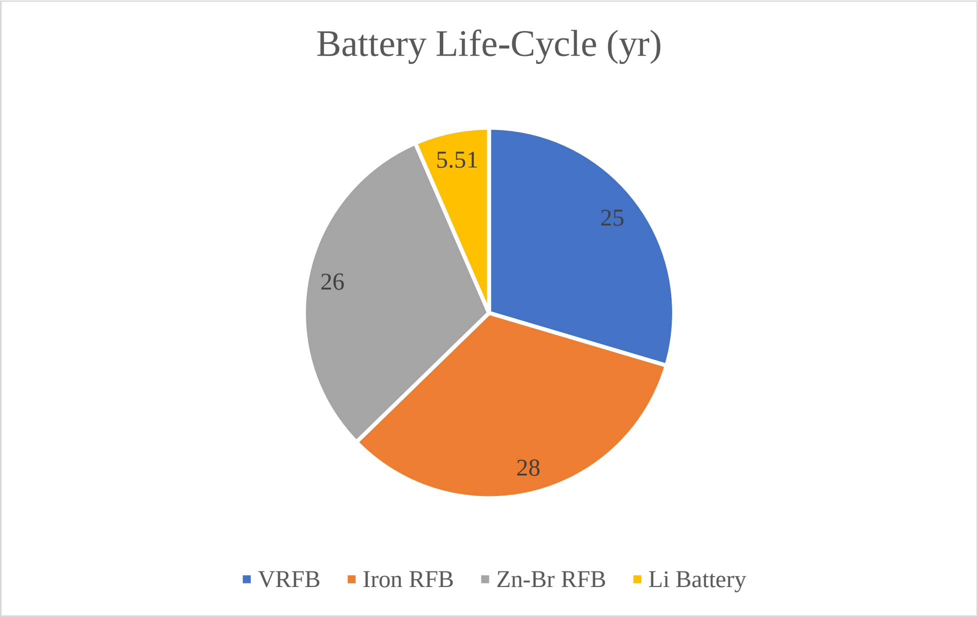


Figure 4.11 Expected life cycle of the battery models

Finally, figure 4.11 demonstrates the life cycle of the discussed batteries and it is clear that Lithium battery has the shortest life and highest cost when compared to flow batteries. The redox flow battery is providing a cheap and long-lasting energy storage system that can be easily scaled up to match a grid size maximizing the usage of renewable energy.

4.2.2 Environmental Impacts

Batteries can affect the environment directly and indirectly. The direct way is when the battery is produced, consumed, and disposed of. Although Lithium batteries contain metals that are less toxic than other batteries that contain lead or cadmium, lithium metal extraction has a high impact on the environment because it uses a lot of water and it is estimated that each one metric ton of Lithium, 500,000 gallons of water is required. “In Chile’s Salar de Atacama, one of the driest places on earth, about 65% of the water is used to mine lithium; leaving many of the local farmers and members of the community to find water elsewhere” (Liebig et al., 2020). Iron flow battery on the other hand is simply composed of iron and salt and can be easily disposed of or even transferred to another battery, unlike other batteries that use precious rare elements and require intensive and complicated recycling.

The indirect way of a battery causing damage to the environment happens when the backup generators are operating to compensate for the energy demand if the battery power is low or reached a critical state of charge. In this simulation analysis, the generator was forced to operate because the storage system was discharged and there were no energy sources left but the generator. However, further analysis shows that the round trip efficiency of the battery which is “the percentage of electricity put into storage that is later retrieved” (Dixon, 2018) has a direct effect on the generator operation hours, this means that the battery will lose some of its energy content that was gained from renewables and make the generator to operates compensating the energy loss.

In figure 4.12, the studied batteries round efficiencies are represented and, notably, the lithium battery technology has the highest efficiency “A typical lithium-ion battery will lose only 5% of energy round-trip (95% efficiency), compared to 20-25% losses for lead-acid systems.” (Jarvis, 2017). Whereas flow batteries have efficiencies lower than 80% because of the side reactions that are happening in electrolyte tanks, and because of the parasitic load caused by the battery pumps.

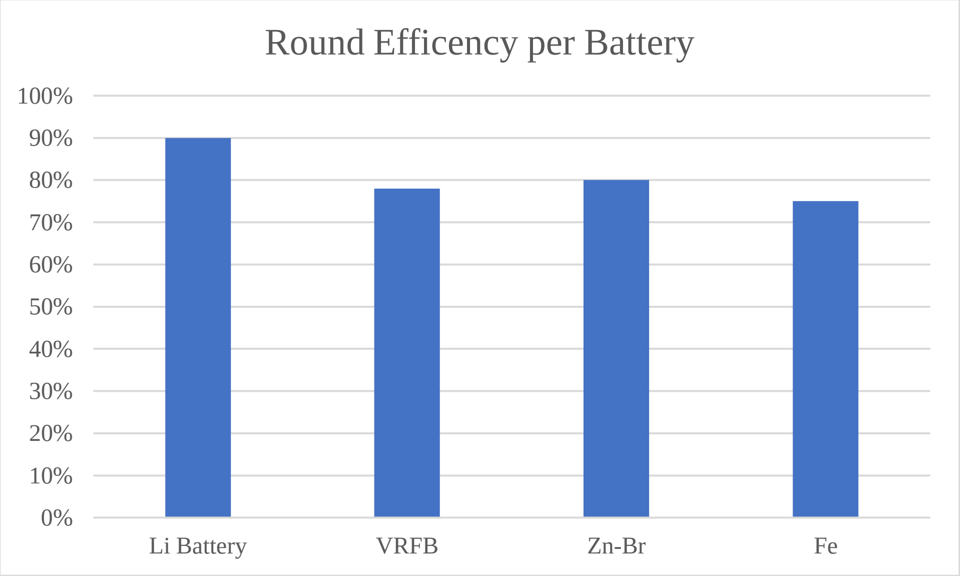


Figure 4.12 Round trip efficiency of battery models

As discussed earlier, a lower battery round trip efficiency will extend the generator operation time, which was confirmed by figure 4.13 that agrees with figure 4.12. RFBs in this case will cause the generator to burn more fuel and will have a greater impact on air pollution making it one of the main drawbacks of RFBs in this particular scenario.

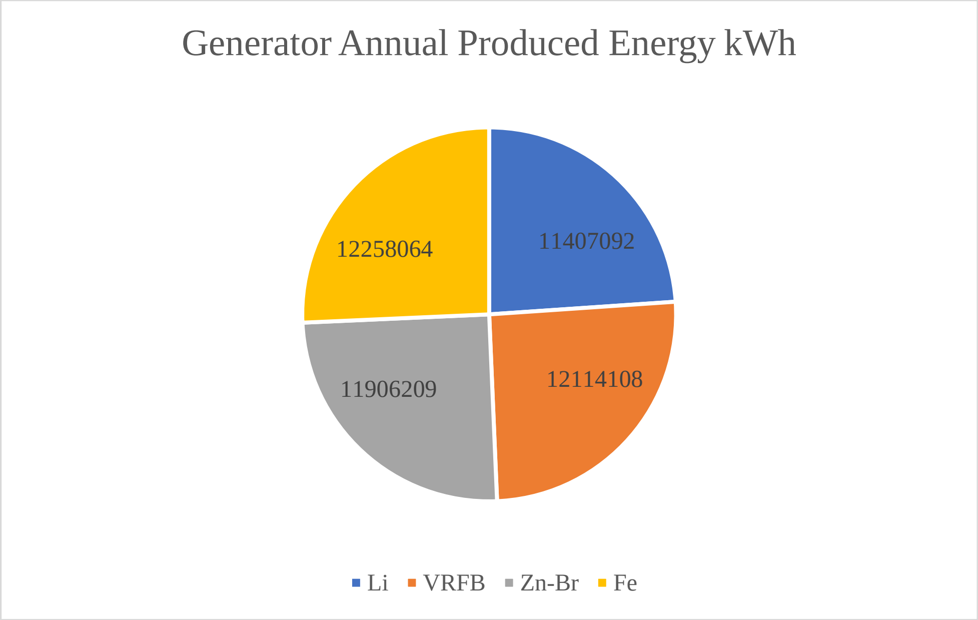


Figure 4.13 Annual amount of energy produced per battery model

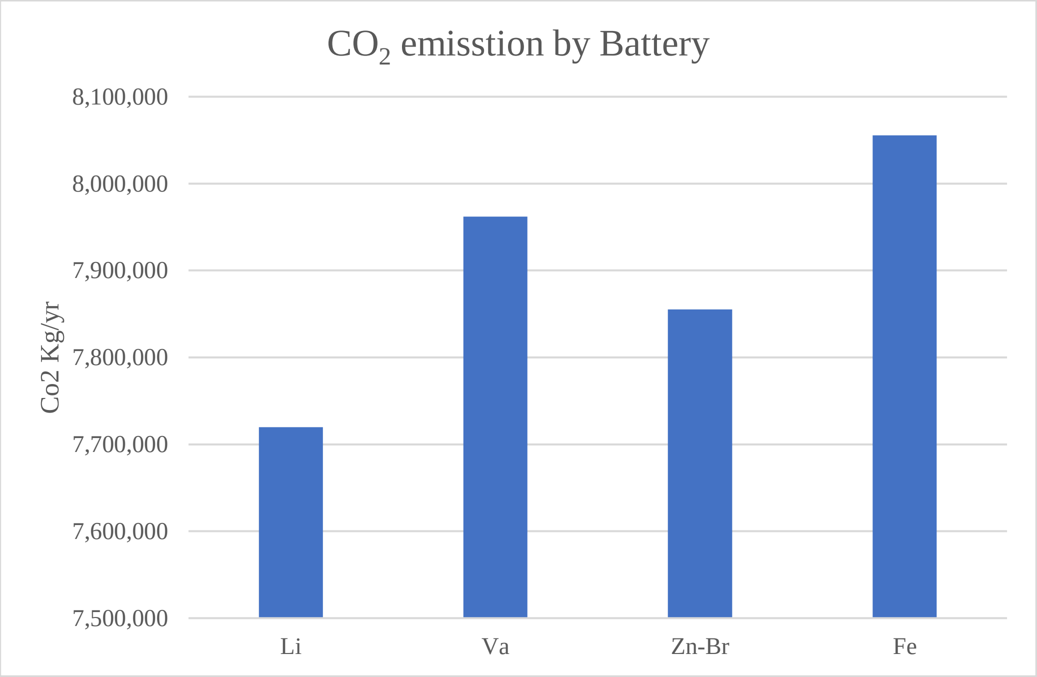


Figure 4.14 CO_2 emission caused by the generator at different simulation scenarios

The CO_2 emission analysis in figure 4.14 shows how each battery will cause the generator to emit carbon dioxide per year. In this case, lithium technology wins of being the lowest of damaging the environment, whereas the RFBs caused a higher carbon dioxide pollution. Figure 4.15 shows other polluting emissions, it is clear that carbon monoxide and nitrogen oxides are high and it is favorable to lower the emissions as much as possible to avoid impacts to the environment.

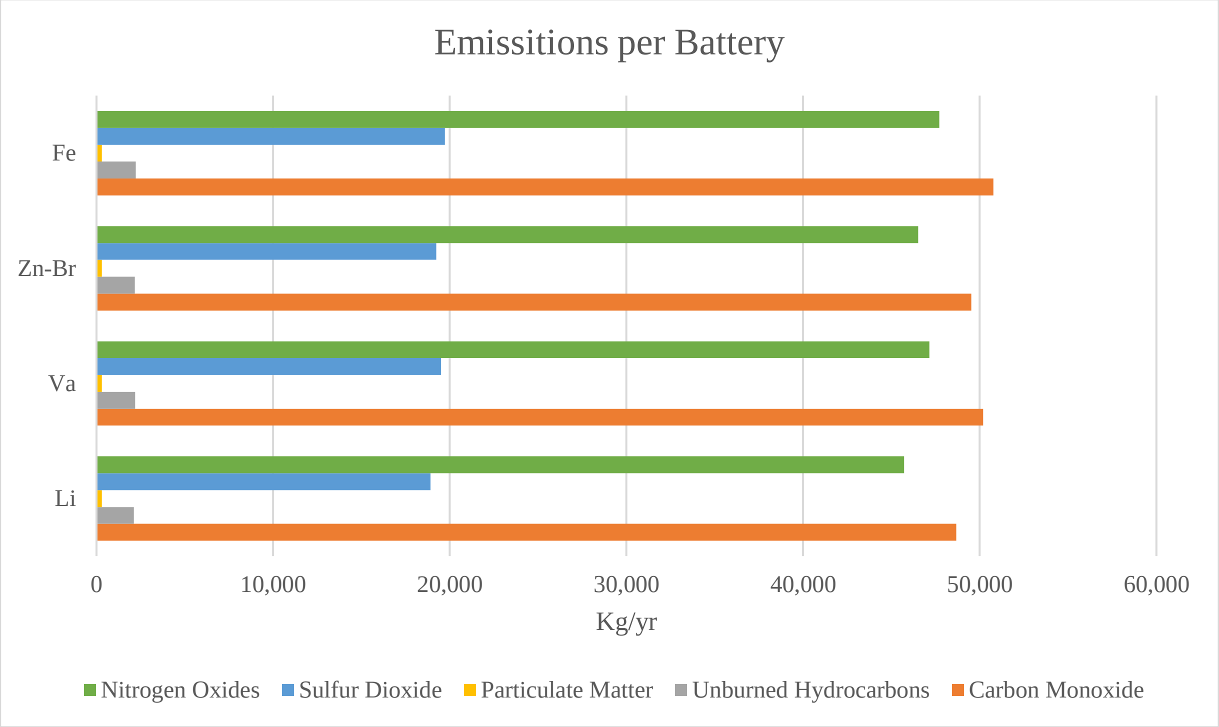


Figure 4.15 Emission analysis of each battery scenario

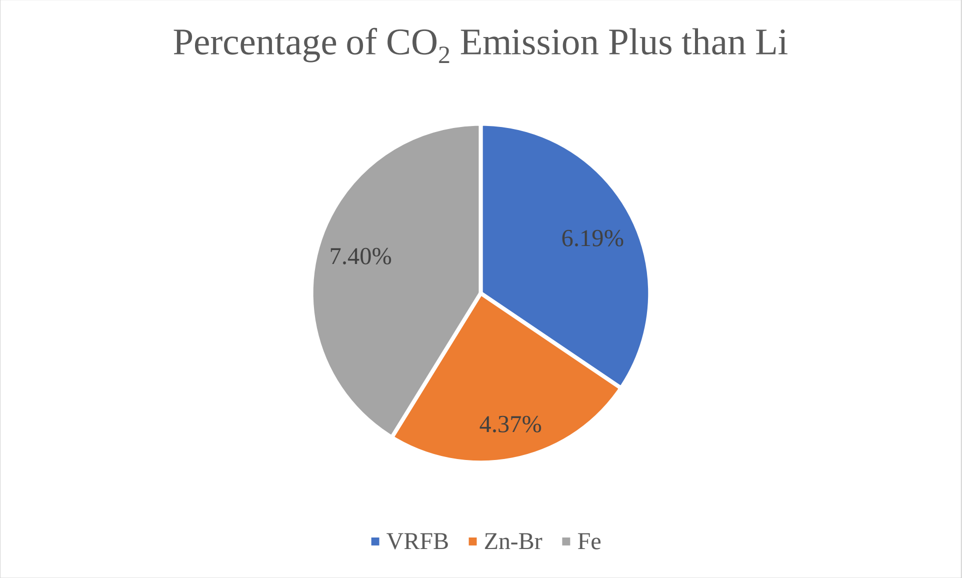


Figure 4.16 Percentage of how much RFBs are more pollutant than Li battery

In the simulation analysis, the lithium battery technology has demonstrated a lower emission. However, figure 4.16 shows that RFBs are not too polluting than the Li battery. For example, Iron RFB is only 7.4 % more CO_2 polluting than Li, and when comparing Iron RFB which is a much cheaper battery that is made from common earth-abundant metal to an expensive Lithium battery, consists of earth precious metals, and have a low life cycle, the small emission increase is not that significant. Moreover, flow batteries are still improving and scientists are working to overcome the main problems related to round trip efficiency. According to new research, scientists in the US claim to have demonstrated an Iron RFB that has 97.9 % efficiency thanks to adjusting electrolyte additives, pH level, and temperature (Bellini, 2020).

4.3. Optimum System Design

As previously discussed, RFBs made a significant performance when simulated with PV modules, the analysis showed how RFBs stored the energy that was generated from PV modules and was able to dispatch the stored energy when needed. However, the previous analysis was considering only PV to show the performance of the energy storage device which caused a lack of renewable energy generation. In this analysis, wind turbines will be integrated into the previous system to increase renewable energy generation and lower emissions by decreasing the operating time of the generator. Based on the previous simulation analysis, Iron RFB will be chosen as an energy storage device because of the following reasons:

- The battery uses simple earth-abundant materials, iron and salt
- Iron RFB is very safe and less pollutant
- Iron RFB offers a competitive cheap price per kWh
- It can maintain a very long-life cycle, even with deep discharging
- Electrolytes are easy to recycle and can be simply transferred to other new Iron RFBs

The integration of wind turbines shows a sharp decrease in the usage of the generator as shown in figure 4.17 and table A.3, this decrease will dramatically lower the cost of energy, also figure 4.18 shows a decrease in the generator operating power which will lower emissions, it is also clear that the battery had successfully powered the grid in the entire period of the peak, and the generator only starts after midnight with low power output. Finally, the renewables take over and power the load while charging the battery simultaneously as shown in both figures 4.18 & 4.19.

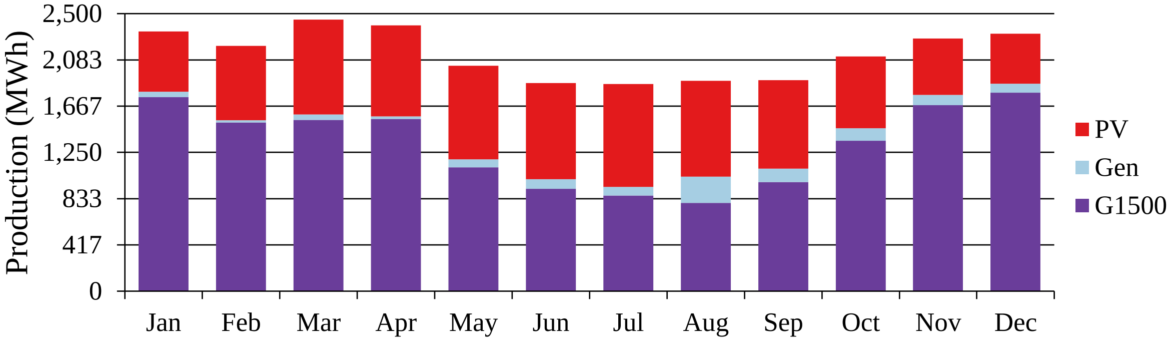


Figure 4.17 System power sources as simulated by HOMER PRO

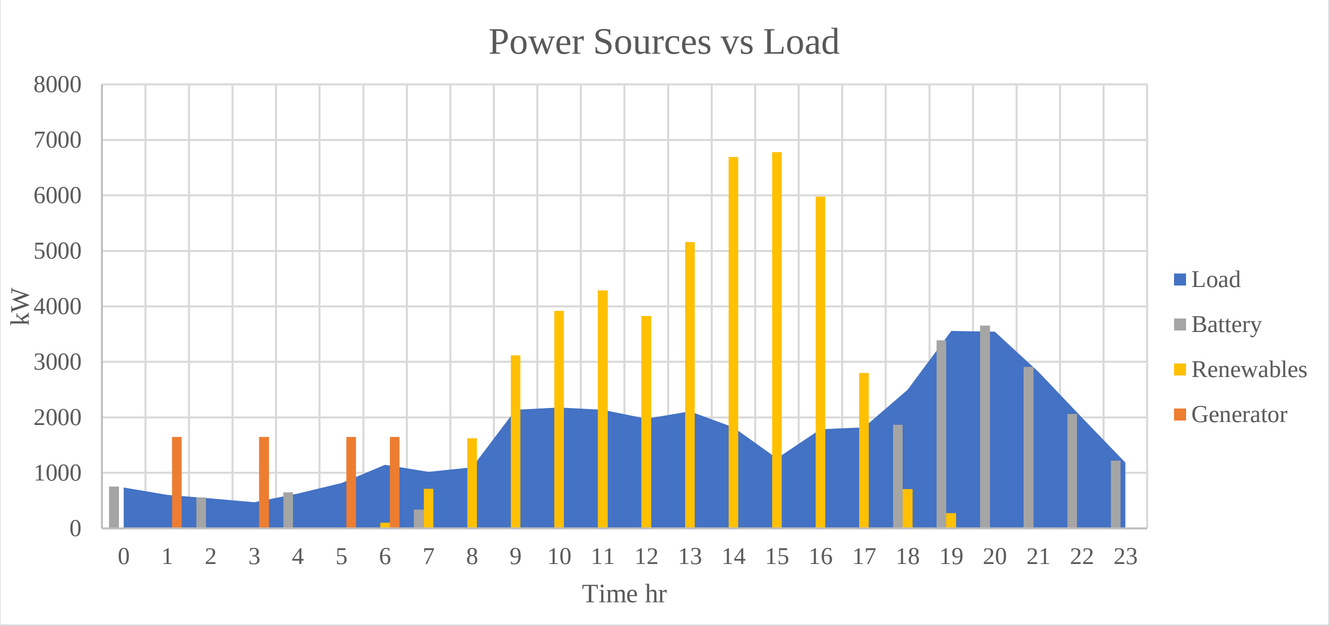


Figure 4.18 Illustration of Load against power sources and Iron RFB

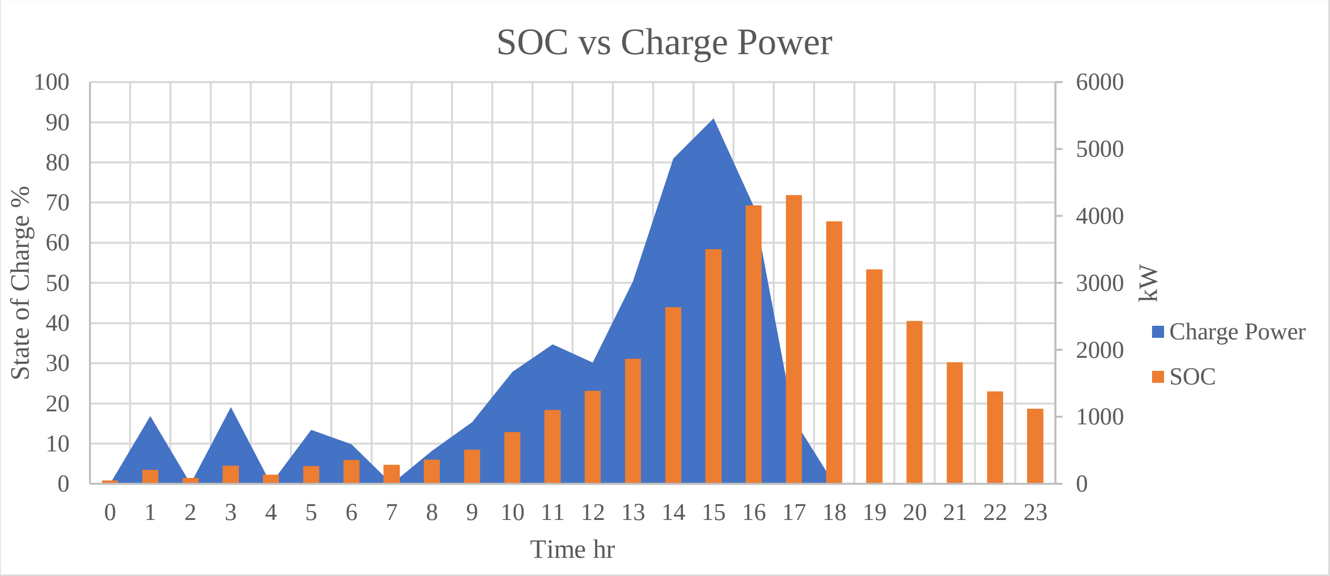


Figure 4.19 Illustration of Iron RFB state of charge and charging power

The system integrates a 6000 MW wind energy source divided into four 1.5 MW wind turbines with 6000 kW solar power. The system will include a quantity of 82 Iron RFB with a capacity of 32,800 kWh. The renewable fraction was as high as 94% which means that the operation cost will be low and the cost of energy is as cheap as $0.210 per kWh. Full system details can be found in table A.3 and figure A.4.

5. Conclusions

The capability of storing electricity and using it at a later time is one of the important keys to achieving high levels of renewable energy. The need for reliable energy storage systems is increasing to meet the upcoming renewable energy generation, ESSs are proven to improve power reliability and resilience by providing a backup power system to avoid disruptions and ensure uninterrupted power to users. ESS can also integrate diverse resources by storing excess power coming from intermittent resources such as wind and solar, and delivering the stored energy when the sun is not shining or the wind is not blowing. Moreover, ESSs minimize environmental impacts by integrating more solar and wind energy resources and lowering the usage of polluting power plants. Finally, by storing low-cost energy and using it later during high-cost peak periods, ESS can save money.

Energy storage systems are diverse in their storing mechanism and forms of energy storage, pumped hydro energy storage system is one of the most efficient ESS. According to research by the Environmental and Energy Study Institute, “Pumped-storage hydropower is more than 80 percent energy-efficient through a full cycle, and PSH facilities can typically provide 10 hours of electricity”. However, Pumped hydro requires a very high capital cost and requires a large quantity of water that many counties cannot provide. Whereas battery storage systems have high flexibility among ESSs because they can be installed anywhere without depending on the access of resources.

Flow battery is getting attention and popularity for several reasons. Mainly, because of the simplicity of scaling up the capacity by increasing the size of the electrolyte tanks, flow batteries have a longer cycle-life because the electrical current does not affect the separating membrane which was confirmed by this simulation analysis. Some flow batteries use costly materials such as Vanadium which can be a challenge. However, researchers are working to master cheap flow batteries that have their electrolytes built from cheap earth-abundant metals such as Iron flow battery. Furthermore, Organic redox flow battery can be even cheaper, those batteries are built from completely non-toxic metals or organic solvents and built from very cheap materials that cost between \$10- \$20 per kWh as confirmed by Loker Hydrocarbon Research Institute.

This work showed by simulation analysis the importance of RFBs and how they showed many advantages that make those batteries a potential for future energy storage systems, these advantages can be concluded as follows:

- Some RFBs are made from cheap materials such as iron, zinc, organic compounds which will reduce the battery price per kWh, as shown in batteries datasheets
- RFBs have longer lives and can operate for several years without requiring any maintenance which was confirmed by simulation, this way the maintenance costs are reduced making operation costs and the cost of energy cheaper.
- RFBs can be completely discharged without causing any damage to the battery, this way oversizing the battery capacity is not a necessity, consequently reducing costs
- RFBs design is flexible, battery power rating can be designed by adding more cell stacks, and battery capacity is adjusted by changing the size of electrolyte tanks.

6. References

Alighieri, A. (2017, November 1). *Zinc-bromine flow battery backs up solar rooftop PV system at SA factory*. Credible Carbon. https://www.crediblecarbon.com/news-and-info/news/zinc-bromine-flow-battery-backs-up-solar-rooftop-pv-system-at-sa-factory/

Aramendia, I., Fernandez-Gamiz, U., Martinez-San-Vicente, A., Zulueta, E., & Lopez-Guede, J. M. (2020). Vanadium Redox Flow Batteries: A Review Oriented to Fluid-Dynamic Optimization. *Energies*, *14*(1), 176. https://doi.org/10.3390/en14010176

Aubrey Ruvolo. (2011). *Common battery types*. Sd. http://butane.chem.uiuc.edu/pshapley/GenChem2/C6/3.html

Bellini, E. (2020, July 22). *New all-iron redox flow battery for renewables storage*. Pv Magazine International. https://www.pv-magazine.com/2020/07/22/new-all-iron-redox-flox-battery-for-renewables-storage/

Center For Climate And Energy Solutions. (2017, October 25). *Microgrids*. https://www.c2es.org/content/microgrids/

Colby. (2018, May 1). *A scientific approach to the economics of sustainable energy systems*. Colby. https://web.colby.edu/joules2dollars/2018/05/01/batteries/

Dixon, J. D. (2018). *Utility-scale batteries and pumped storage return about 80% of the electricity they store - Today in Energy - U.S. Energy Information Administration (EIA)*. Jeremy Dixon. https://www.eia.gov/todayinenergy/detail.php?id=46756

Dornsife. (2018). *All-Iron Redox Flow Battery > narayan Group > USC Dana and David Dornsife College of Letters, Arts and Sciences*. Dornsife. https://dornsife.usc.edu/labs/narayan/all-iron-redox-flow-battery/

Environmental and Energy Study Institute (EESI). (2019). *Fact Sheet | Energy Storage (2019) | White Papers | EESI*. EESI. https://www.eesi.org/papers/view/energy-storage-2019

GmbH, N. K. (2021, August 3). *Peak shaving*. #the_vpp. https://www.next-kraftwerke.com/knowledge/what-is-peak-shaving

Hornsdale Power Reserve. (2021, November 14). *Hornsdale Power Reserve | South Australia's Big Battery*. https://hornsdalepowerreserve.com.au/

Jarvis, R. J. (2017). *Lithium Ion – Lithium Ion Battery Test Centre*. Russell Jarvis. https://batterytestcentre.com.au/project/lithium-ion/

Kelsy Wisse. (2017). *Components of Cells and Batteries*. Battery Priniciple. https://depts.washington.edu/matseed/batteries/MSE/components.html

Liebig, G., Kirstein, U., Geißendörfer, S., Schuldt, F., & Agert, C. (2020). The Impact of Environmental Factors on the Thermal Characteristic of a Lithium–ion Battery. *Batteries*, *6*(1), 3. https://doi.org/10.3390/batteries6010003

Liu, Y., Chen, Q., Sun, P., Li, Y., Yang, Z., & Xu, T. (2021). Organic electrolytes for aqueous organic flow batteries. *Materials Today Energy*, *20*, 100634. https://doi.org/10.1016/j.mtener.2020.100634

Loker Hydrocarbon Research Institute. (2015). *An inexpensive metal-free organic redox flow battery (ORBAT) for Grid-Scale storage*. University of Southern California. https://www.energy.gov/sites/prod/files/2015/01/f19/14_2014Storage_PeerRev_Narayan_Organic_Redox_Flow_Poster.pdf

Michos, I., Cao, Z., Xu, Z., Jing, W., & Dong, J. (2019). Investigations on a Mesoporous Glass Membrane as Ion Separator for a Redox Flow Battery. *Batteries*, *5*(1), 6. https://doi.org/10.3390/batteries5010006

Nick Lavars. (2020, October 21). *Scientists build first redox flow battery made of all-organic materials*. New Atlas. https://newatlas.com/energy/first-redox-flow-battery-all-organic-materials/

Pourret, O., & Dia, A. (2016). Vanadium. *Encyclopedia of Earth Sciences Series*, 1–3. https://doi.org/10.1007/978-3-319-39193-9_272-1

The Pew Charitable Trusts. (2016, February). *Micrograids in the evolving power system*. John Keats.

Vagin, M., Che, C., Gueskine, V., Berggren, M., & Crispin, X. (2020). Ion-Selective Electrocatalysis on Conducting Polymer Electrodes: Improving the Performance of Redox Flow Batteries. *Advanced Functional Materials*, *30*(52), 2007009. https://doi.org/10.1002/adfm.202007009

Weber, A. Z., Mench, M. M., Meyers, J. P., Ross, P. N., Gostick, J. T., & Liu, Q. (2011). Redox flow batteries: a review. *Journal of Applied Electrochemistry*, *41*(10), 1137–1164. https://doi.org/10.1007/s10800-011-0348-2

Whiteaker, J. (2021, November 1). *Opinion: Let’s be honest, batteries are bad for the environment*. Investment Monitor. https://www.investmentmonitor.ai/insights/batteries-are-bad-for-the-environment

7. Appendices

Appendix A
Simulation Figures and Tables

Table A.1 Battery electrical properties and cost

Property	Value				Units
	Li Battery	VRFB	Zn-Br	Fe	
Nominal Voltage	600	850	48	850	V
Nominal Capacity	100	221	9.98	400	kWh
Round Efficiency	90	78	80	75	%
Maximum Charging Current	170	104	125	157	A
Maximum Discharging Current	500	104	125	118	A
Cost	70,000	44,000	4,800	100,000	$

Table A.2 Battery Storage Simulation Results and Data

Quantity	Value				Units
	Li Battery	VRFB	Zn-Br	Fe	
Batteries	98.0	64	1,402	47	qty.
Autonomy	3.92	7.07	7.00	9.40	hr
Nominal Capacity	9,800	14,144	13,998	18,800	kWh
Usable Nominal Capacity	7,840	14,144	13,998	18,800	kWh
Lifetime Throughput	29,400,000	242,112,000	198,114,657	200,869,678	kWh
Expected Life	5.51	25	26	28	yr
Energy In	5,619,019	9,354,196	8,852,469	9,269,087	kWh/yr
Energy Out	5,058,295	7,304,365	7,087,965	6,958,330	kWh/yr
Losses	561,966	2,058,994	1,771,201	2,318,280	kWh/yr

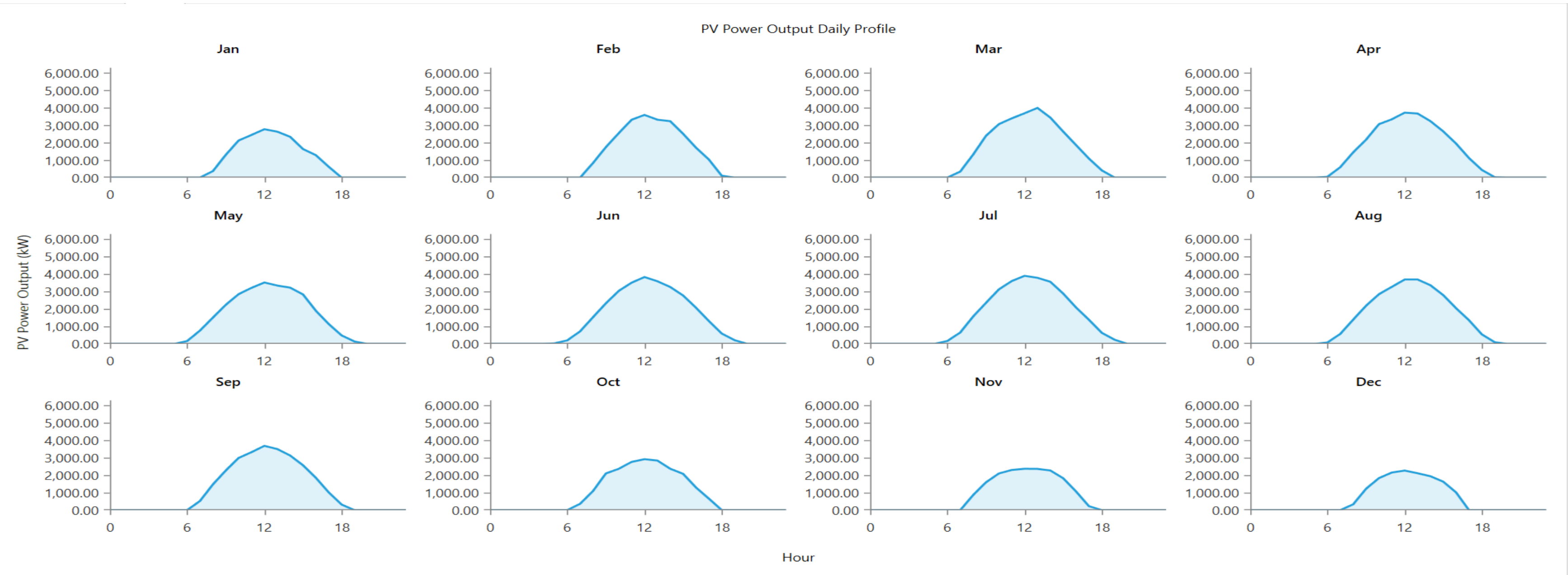


Figure A.7.1 Simulated PV modules power output profile

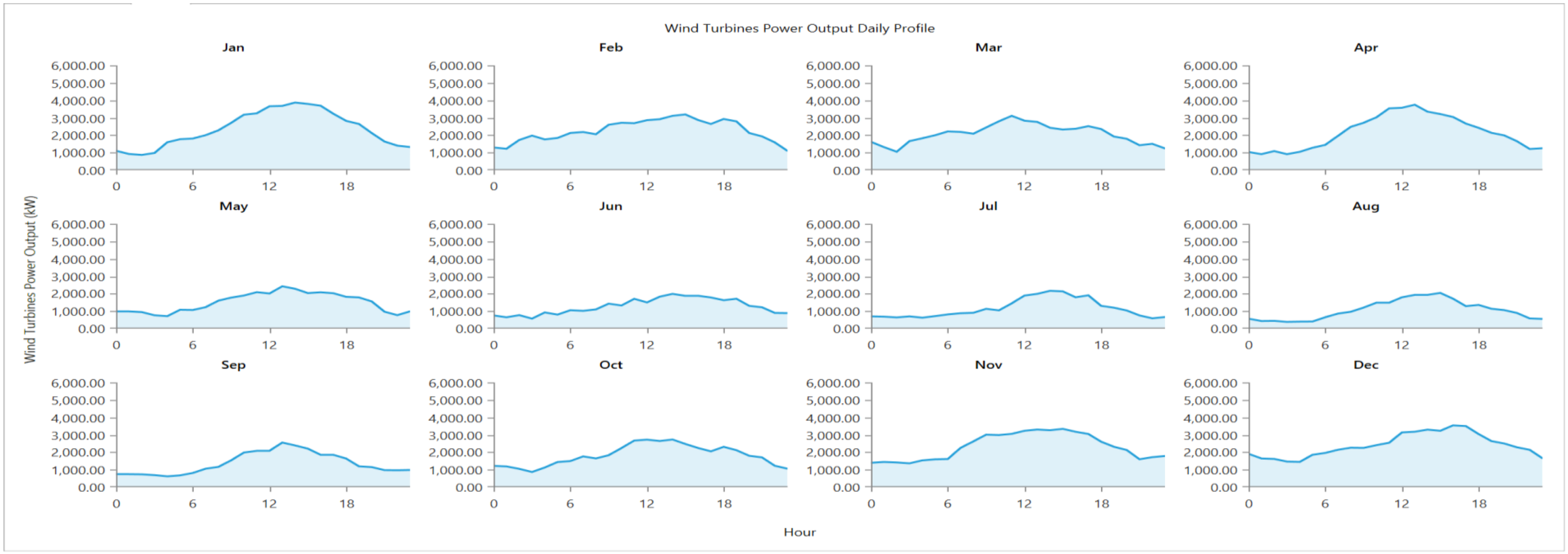


Figure A.7.2 Simulated Wind turbines power output profile

Table A.3 System Component with Generation Fractions

Component	Size	Unit	Production (kWh/yr)	Percent
Generator	6,600	kW	1,021,453	3.98
PV	6,000	kW	8,783,829	34.2
Iron RFB	82	strings	-	
Wind turbine	6	MW	15,851,914	61.8
System converter	6,263	kW	-	
			Total	100

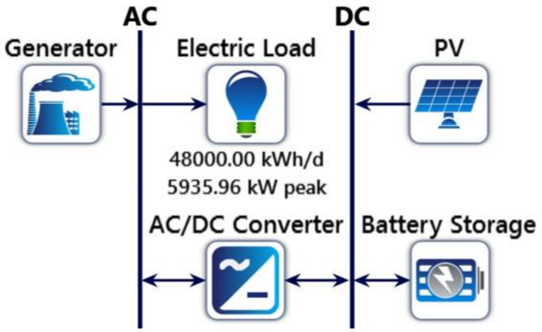


Figure A.3 Schematic of battery storage sensitivity analysis

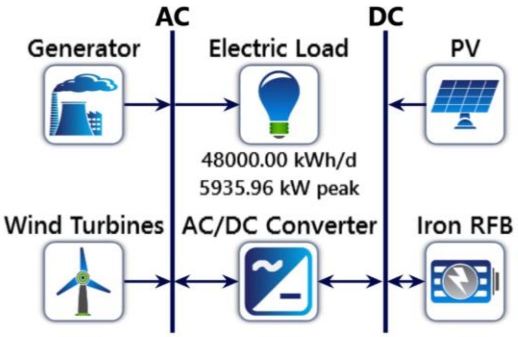
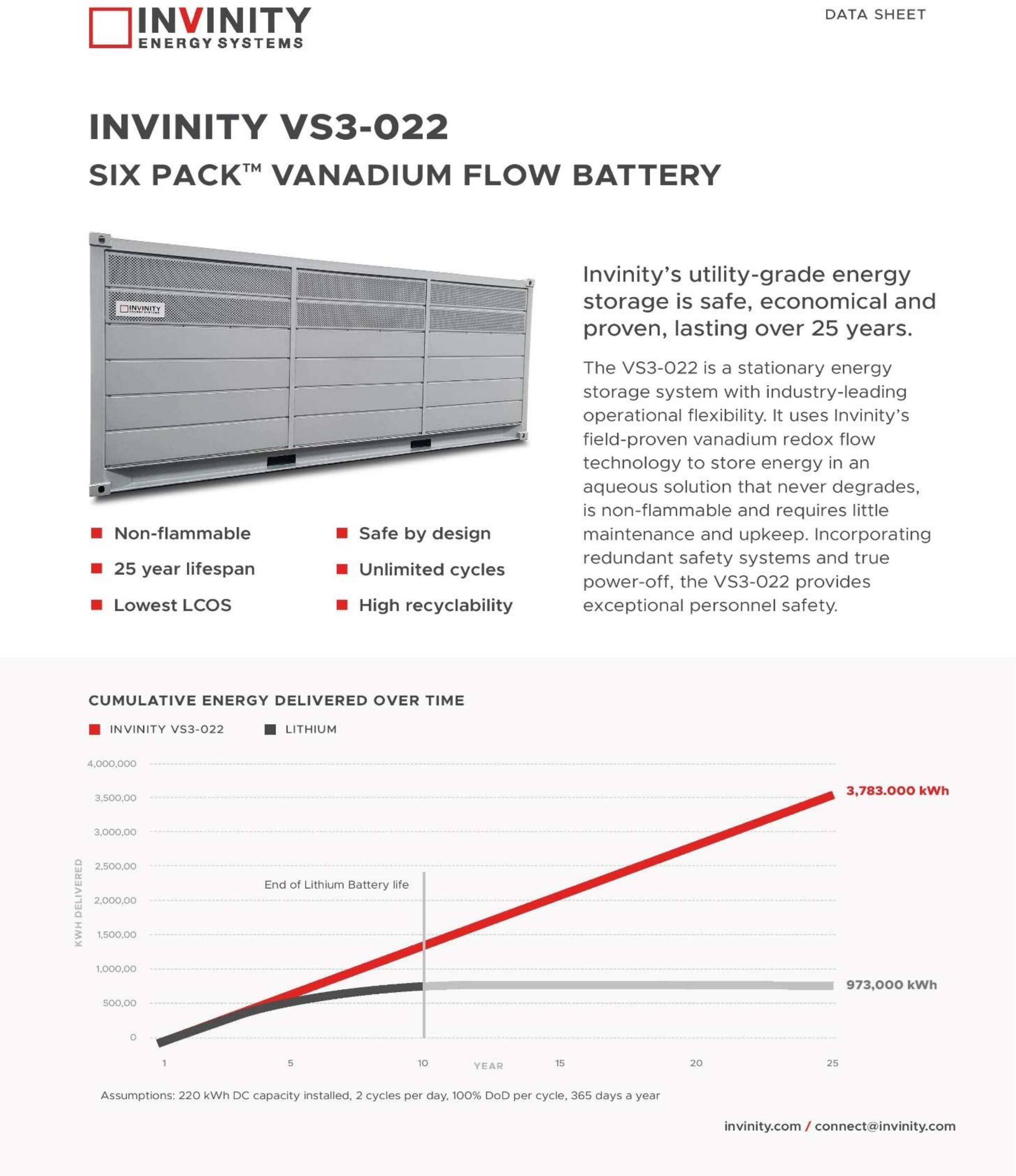


Figure A.4 The optimum system schematic considering Iron RFB as the storage device

Appendix B: RFBs Datasheets



INVINITY
ENERGY SYSTEMS

DATA SHEET

INVINITY VS3-022

SIX PACK™ VANADIUM FLOW BATTERY

- Non-flammable
- 25 year lifespan
- Lowest LCOS
- Safe by design
- Unlimited cycles
- High recyclability

Invinity's utility-grade energy storage is safe, economical and proven, lasting over 25 years.

The VS3-022 is a stationary energy storage system with industry-leading operational flexibility. It uses Invinity's field-proven vanadium redox flow technology to store energy in an aqueous solution that never degrades, is non-flammable and requires little maintenance and upkeep. Incorporating redundant safety systems and true power-off, the VS3-022 provides exceptional personnel safety.

CUMULATIVE ENERGY DELIVERED OVER TIME

Assumptions: 220 kWh DC capacity installed, 2 cycles per day, 100% DoD per cycle, 365 days a year

invinity.com / connect@invinity.com

INVINITY
ENERGY SYSTEMS

INVINITY VS3-022 VANADIUM FLOW BATTERY

PERFORMANCE SPECIFICATIONS

Nameplate Rating DC Voltage	1000 VDC
Operating Voltage, Nominal	850 VDC
Operating Voltage Range, Full Power	750 to 950 VDC
Max. Continuous DC Current	±104 A
Max. Continuous DC Power	78 kW
Energy Storage Capacity	220 kWh
Energy Storage Duration	2.5 hours @ 78 kW 4 hours @ 56 kW 8 hours @ 28 kW
Overcurrent Protection Device	Integrated
Max. Recommended Depth of Discharge	100%
Cycle Life	> 20,000 cycles
Lifetime Throughput	3,783 MWh
Annual Capacity Degradation	< 0.5% per year
Max. DC Round Trip Efficiency (RTE)	> 78%
Annual DC RTE Degradation	< 0.1% per year
Battery Management System, Fault Protection, DC Disconnect	Integrated
Third Party EMS Integration	Optional
Communications Interface	Modbus TCP
Auxiliary Input	External AC Supply
AC Auxiliary Supply	380-415 VAC, 3 Φ , 4 wire 50/60 Hz
Auxiliary Power, Nominal	3.6 kW
Auxiliary Power, Max.	7.8 kW

ENVIRONMENTAL SPECIFICATIONS

Ambient Operating Temperature	25°F to 110°F (-5°C to 45°C)
Ambient Operating Temperature with Optional Configuration	-13°F to 110°F (-25°C to 45°C)
Cooling	Integrated, Forced Air
Operating Humidity	0 to 95% RH
Environment	Indoor & Outdoor
Enclosure Rating	NEMA 3R and IP 54
Maximum Elevation	11,480 ft (3,500 m)
Wet Location Rating	Yes
Additional Cooling Required	None
Fire Suppression System Required	None
Secondary Containment	Integrated

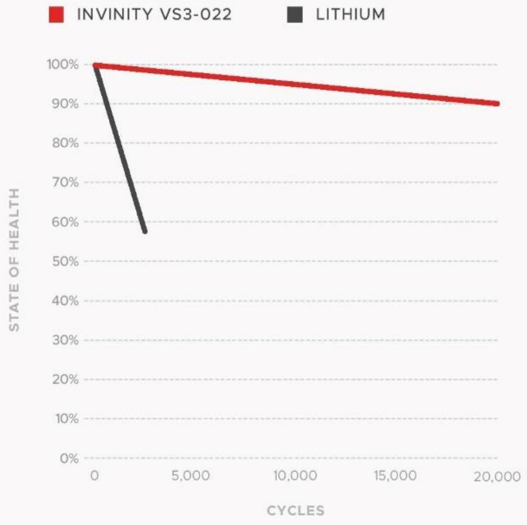
STANDARD COMPLIANCE

Safety	UL 1973, CE, IEC 62932
Energy Storage Systems and Equipment	UL 9540

PHYSICAL SPECIFICATIONS

Dimensions (L x W x H)	19.87 x 8.042 x 7.87 feet (6058 mm x 2438 mm x 2400 mm)
Weight (Flooded)	54,230 lbs (24,600 kg)
Mounting	Concrete pad mount or equivalent
Rec. Service Clearance (Long Sides)	59 inches (1500 mm)

BATTERY CAPACITY AS A PERCENT OF ORIGINAL*



*Assumptions: No capacity augmentation

Siting underway. Double-stacked configuration shown

MAR00016-2021-09 / SEPTEMBER 2021

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redflow
sustainable energy storage

ZBM2 Flow Battery

The world's smallest flow battery, monitored & managed online

10kWh

48V

- High energy density at 10kWh
- 48 Volt DC nominal batteries
- Power Rating 3kW (5kW peak)

Why Redflow **zinc-bromine flow battery** technology?

COMPETITIVE CAPEX

100% of the capacity is usable over lifetime, with no capacity fading therefore no oversizing required.

EXCELLENT LONGEVITY

Warranted electrode stack lifetime 36,500 kWh energy delivered or 10 years (whichever comes first).[1]

LONG SHELF LIFE

Sustains regular outages without battery damage and can be suspended, stored or hibernated from 0% to 100% state of charge.

RECYCLE OR REPROCESS

Excellent sustainability for all Redflow battery components and electrolyte.

CONSTANT POWER

Charge 100% of the capacity with constant power, due to a flat voltage curve and simple one stage charge profile.

COMPACT AND HIGH ENERGY DENSITY

0.34m^2 (3.7ft^2) with warranted electrode stack throughput of 36,500kWh.

GREATER SAFETY

Fire retardant electrolyte, no thermal runaway due to separated tank and stack.

INBUILT THERMAL MANAGEMENT

For the majority of systems air conditioning is not required. Lifetime and safety are not affected by temperature, within operating and storage limits.

INTUITIVE WEB BASED MANAGEMENT SYSTEM

24/7 remote self-monitoring with real-time data capture accessed via the web, through the MODBUS communications system.

Designed and developed in Australia by **REDFLOW.**

ZBM2 manufactured in Thailand by **REDFLOW.**

Installed by Redflow's global network of accredited installation partners find out more via www.redflow.com/system-integrators.

ID #0006

TELECOMMUNICATION APPLICATIONS

COMMERCIAL SOLUTIONS

GRID SCALE APPLICATIONS

RESIDENTIAL SOLUTIONS

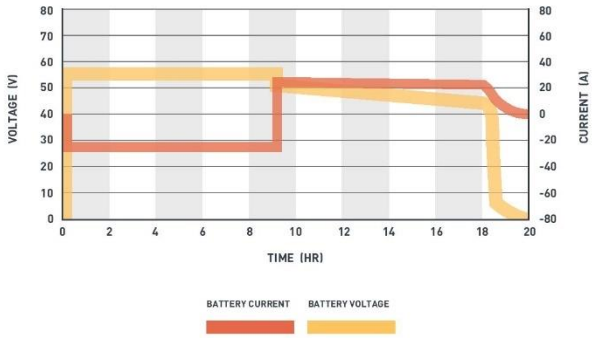
www.redflow.com

ZBM2

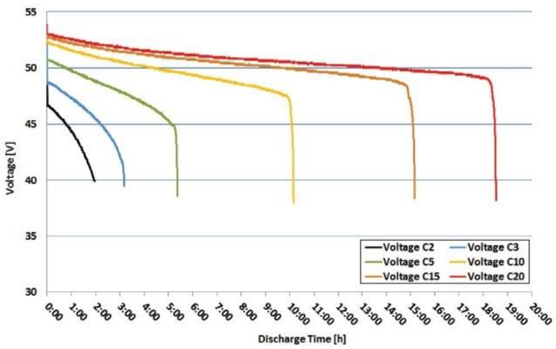
redflow
sustainable energy storage

Typical Charge and Discharge Curves

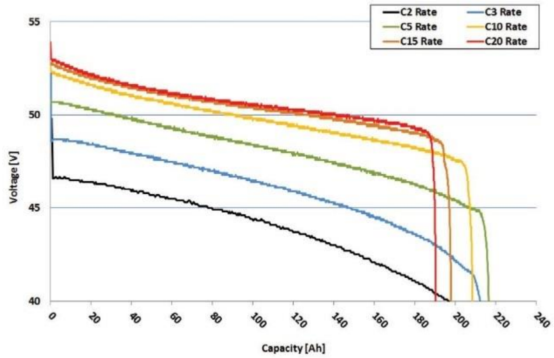
REDFLOW STANDARD CYCLE (VOLTAGE VS CURRENT)



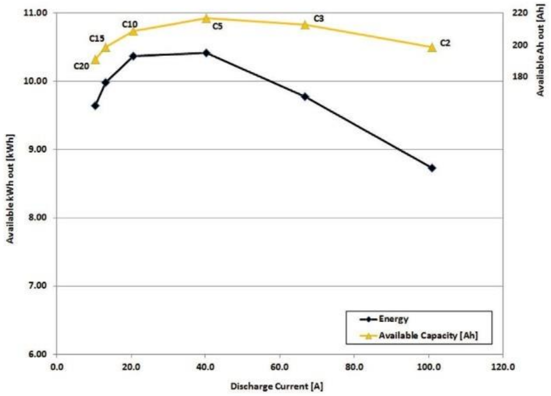
DISCHARGE CURVES[2]



DISCHARGE - CAPACITY CURVES[2]



ENERGY - CAPACITY CURVES[2]



ZBM2 Technical Specifications

VOLTAGE: 48 Volt DC nominal batteries (typical operating range 40-57V)

CAPACITY: Maximum 10kWh energy output per daily cycle. No reserved battery capacity requirement - full 10kWh cycle depth available

DIMENSIONS: 845L x 823H x 400W (mm); 33L x 32H x 16W (in)

WEIGHT: 240kg (530 lb) with electrolyte; 90kg (198 lb) without electrolyte

ELECTROLYTE VOLUME: 100L (26Gal)

STACK ENERGY EFFICIENCY: 80% DC-DC Max

OPERATING ELECTROLYTE TEMPERATURE RANGE:
15°C to 50°C (59°F to 122°F), ZBM2 can operate at ambient temperatures outside this range depending on enclosure design.

COMMUNICATION: MODBUS-TCP, CANBUS

SAFETY DATA SHEET: DG Class 8 for electrolyte

POWER RATING: 3kW (5kW peak)
+ 3kW continuous: current up to 75A (40V disconnection point)[3,4]
+ 5kW duration depending on the State of Charge (SOC): current up to 125A (40V disconnection point)[3,4]

REGULATORY COMPLIANCE MARKS: CE

WARRANTY:
+ Electrode stack: 36,500 kWh of energy delivered or 10 years (whichever comes first)[1]

Note: This is a summary document. For full details see ZBM Installation and Operation Manual and Warranty documentation.

[1] See full warranty document for details, T&Cs apply.
[2] Average results at 25°C and standard atmospheric pressure for a typical battery.
[3] Values reported for ZBM2 at 100% state of health (SOH) and at 25 °C.
[4] Redflow internal testing shows a 5kW supply for approximately 75 minutes before disconnection, for a ZBM2 starting at 100% state of charge (SOC).

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For more information visit **www.redflow.com**
Email: sales@redflow.com Phone: +61 7 3376 0008

ASX:RFX

ESS IRON FLOW BATTERIES

ESS INC
CATALYZING A CLEANER FUTURE

CLEAN, LONG-DURATION ENERGY STORAGE: THE RIGHT SOLUTION, THE RIGHT TIME

Premier technology. Unmatched sustainability. Guaranteed.

ESS ENERGY STORAGE SOLUTIONS CHECK ALL THE BOXES:

- ☑ CAPACITY FOR RESILIENCY, PEAK SHAVING & RENEWABLES INTEGRATION
- ☑ LONG DURATION FOR MAXIMIZING RENEWABLES INVESTMENTS
- ☑ THE CLEANEST LIFECYCLE OF ANY OTHER LEADING BATTERY CHEMISTRY: VANADIUM, ZINC OR LITHIUM-ION[1]

THE TIME HAS COME FOR STORAGE. THE PLACE TO COME IS ESS

ESS iron flow battery solutions are the most environmentally responsible and cost-effective energy storage systems on the market.

CLEANER

- Made with food grade, earth-abundant materials: iron, salt and water electrolyte
- No noxious fumes
- The least environmentally harmful battery chemistry to produce

SAFER

- Environmentally safe, non-toxic electrolyte
- Non-flammable, non-explosive
- No hazardous materials: no risk to personnel, no hazmat compliance plan required
- Ships in dry state and hydrated on site

MORE SUSTAINABLE AND USER FRIENDLY

- No cooling/air conditioning requirement
- Designed for 25-year operating life with minimal annual operations and maintenance (O&M) requirements
- Easy to recycle or reuse electrolyte at end of life

LOWEST COST, LONG DURATION

- Long duration (6–12 hours) for renewables shifting and demand charge reduction
- Unlimited charge/discharge cycles
- Optional power configurations between 33 kW and 100 kW

ECO-FRIENDLY

NON-TOXIC • EASILY RECYCLABLE

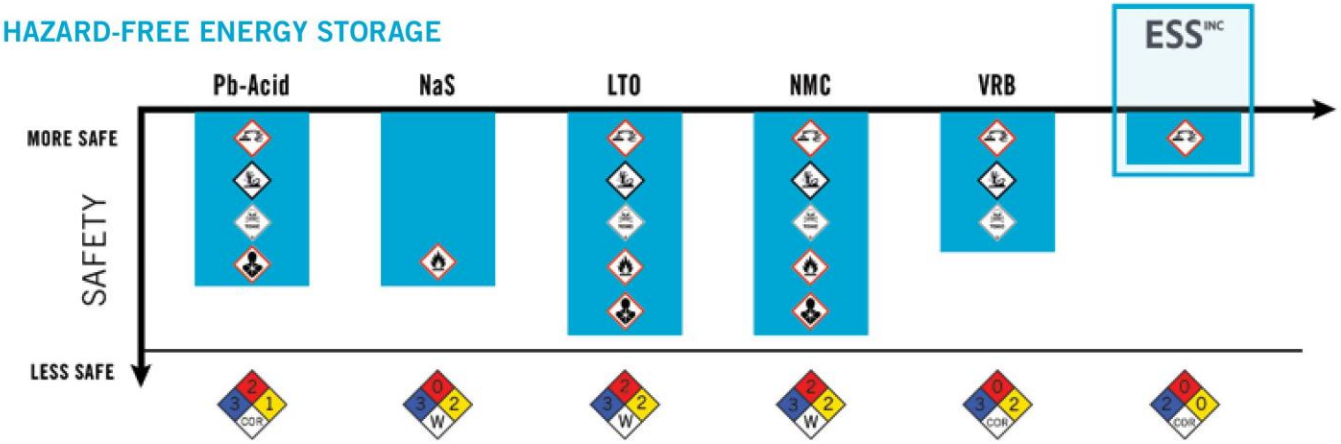
Battery chemistries matter. *Some come with high mining and environmental costs. Some are risky to work with and hard to recycle at end of life. But you don't face these problems with iron flow batteries from ESS. Ours are the greenest, lowest lifecycle cost energy storage systems you can buy.*

---

[1] Haoyang, He et. Al. Flow Battery Production: Materials selection and environmental impact. Journal of Cleaner Production, v. 269, 1 October 2020. https://www.sciencedirect.com/science/article/abs/pii/S095965262031787X?via%3Dihub

ESS: THE CLEANEST WAY TO CLEAN UP YOUR GRID

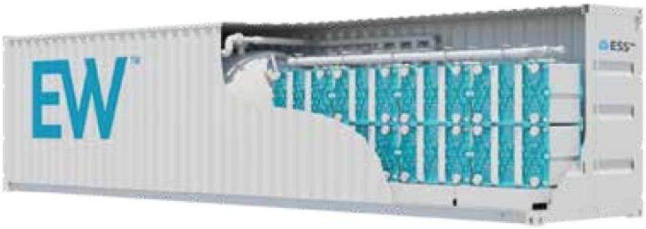
HAZARD-FREE ENERGY STORAGE



ESS SOLUTIONS SIMPLIFY INSTALLATION AND OPERATION

ESS batteries are comprised of earth-abundant iron, salt and water, not hazardous chemicals or costly rare-earth metals, making them environmentally benign to produce and the easiest-to-permit storage technology in the world. Iron flow batteries have no fire, chemical or explosive risk, eliminating the need for fire suppression, secondary containment and hazmat requirements. In addition, ESS solutions are fully recyclable at end-of-life.

VALUE ON BOTH SIDE OF THE METER: SOLUTIONS FOR UTILITIES AND C&I CUSTOMERS



The Energy Warehouse™: Designed to serve commercial and industrial customers, this compact unit has an energy storage capacity of 400 kWh and a 25-year design life. It can be configured to provide storage durations of 4 to 12 hours.

GUARANTEED PERFORMANCE

ESS Inc. has partnered with Munich RE to launch industry-first insurance coverage of our flow batteries. The innovative policy means the battery modules in our storage solutions come with up to 10 year extended warranty backed by a global investment-grade insurer.

Munich RE ®

The Energy Center™: Created for utility-scale applications, this battery-in-a-building delivers a configurable range of power capacities starting at 3 MW and energy durations ranging from 6 to 12 hours. A one-acre footprint supports up to 6 MW and 74 MWh.

ABOUT ESS INC.

ESS Inc. designs, builds and deploys the most environmentally sustainable, lowest-cost, iron flow batteries for long-duration commercial and utility-scale energy storage applications requiring from 4 to 12 hours of flexible energy capacity. The Energy Warehouse™ and Energy Center™ use earth-abundant iron, salt, and water for the electrolyte, resulting in an environmentally benign, long-life energy storage solution for the world's renewable energy infrastructure. Established in 2011, ESS Inc. enables project developers, utilities, and commercial and industrial facility owners to make the transition to more flexible non-lithium-ion storage that is better suited for the grid and the environment. For more information visit www.essinc.com.

For more information, contact:

ESS INC

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26440 SW Parkway Ave.
Wilsonville, OR. 97070

Tel: (855) 423-9920
Email: info@essinc.com
www.essinc.com

ESS Inc Sustainability Datasheet_03_04_21